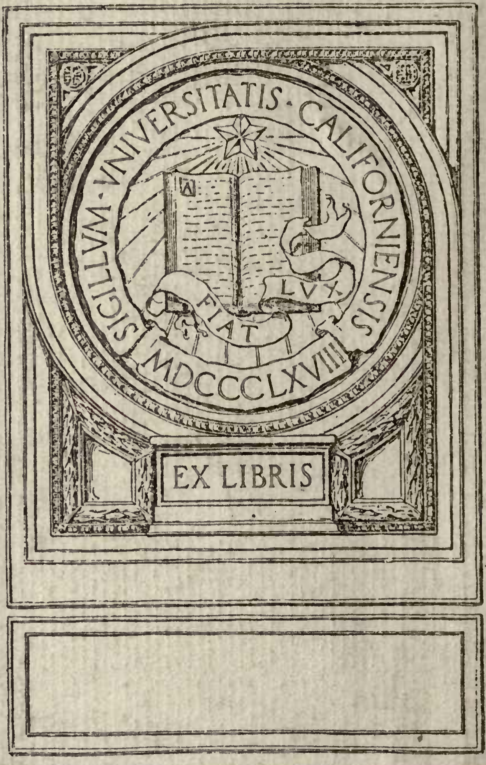
# THE MAKING, SHAPING AND TREATING OF STEEL

CARNEGIE STEEL COMPANY
BUREAU OF INSTRUCTION



# THE MAKING, SHAPING
# AND
# TREATING OF STEEL

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BY
J. M. CAMP
AND
C. B. FRANCIS

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## SECOND EDITION

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TO

HOMER D. WILLIAMS,
President of the Carnegie Steel Company

AND

HIS ASSISTANTS

For Their Valued Suggestions and Words of Appreciation

THIS BOOK IS DEDICATED

# PREFACE TO SECOND EDITION

This book has been written especially for the nontechnical employees of the Carnegie Steel Company, and others, who, seeking self instruction, may desire to secure in the shortest time possible a general knowledge of the metallurgy of iron and steel.

The book is the outcome of several years experience in attempting to teach the metallurgy of steel to our salesmen and other nontechnical employees. From the first, the method pursued in this work has been that of taking the students, under proper guidance, into the mills, where they obtain, first hand and individually, such information as they desire and are able to collect, and of supplementing the knowledge gained from these visits with talks and explanations delivered in a classroom where conditions are more favorable for this kind of instruction than they are in the mills. These talks, in a condensed form, were put in writing, and a copy given to each of the students. As the demand for these lectures increased, it was decided that, for the sake of convenience, they should be printed; and accordingly they were revised and are here assembled in the present volume.

In order to increase the value of the book as a reference book, we have aimed to condense the information and to avoid every unnecessary word, both by omitting all matter from the text not absolutely essential and by the free use of tables, drawings and diagrams, which we permit to tell their own story. However, knowing our readers will be men imbued with a desire to learn, we have not avoided discussing many scientific aspects of our subjects. But here we have tried to make it easy even for the general reader. We have aimed to use language as simple as possible, consistent with clearness, and to treat our subjects in such a way that, aside from what a limited education supplies, no prerequisites will be required. We start with the elementary subjects of Physics and Chemistry, the logical prerequisites, and build our metallurgy upon that foundation. The book will, therefore, prove of most value to those connected with the steel business, and not technically educated, who are really anxious to learn more about the wonderful industry in which they are engaged. For such as these, we have aimed to make this book at least a stepping stone to higher and better things.

With regard to the subject matter of the book, we claim but little in the way of originality. We have no new theories to advance and no new discoveries to reveal. Our aim throughout has been to describe conditions and things as they are and to explain the causes for their being as they are, rather than to tell how they might be or how they ought to be. To accomplish our first purpose, we have been compelled to rely mainly upon our personal observation and experiences, but in explaining the causes of things we have freely consulted all those whose published opinions relating to each particular subject have been available and of value. We are, therefore, indebted to many for aid, and to all these we wish to express our thanks. Wherever we have drawn upon these sources of information we have aimed to give the credit to the authors by mention in the text or by foot note references. As guides to collateral reading these references will have an additional value to our readers. We also desire to thank the superintendents and the many heads of departments of our various plants for the courtesies they have shown us and for the many bits of valuable information which they were ever ready to give.

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# PART 1.

# THE MAKING OF STEEL.

## CHAPTER I.

## SOME FUNDAMENTAL PRINCIPLES OF PHYSICS AND CHEMISTRY.

### SECTION I.

### INTRODUCTION.

**1. Iron, the Master Metal:** In beginning this very brief study of the metallurgy of the most important metal of a metallic age, it is difficult to refrain from pointing out a few of the qualities that have made iron the master metal, although its importance really needs no comment here. A little reflection shows it to be as vital to modern civilization as air and water are to life; and it has become so common that, like air and water, its true importance is lost sight of by most people, who look upon its abundance as a matter of course and value it accordingly. No other one metal has contributed so much to the welfare and comfort of man. There is scarcely an article used in our daily lives that has not been produced from iron or by means of it. Consider bread as an example. Plows made of iron turn the soil, harrows of iron level it, and drills of iron sow the seed; machines of iron harvest the wheat and thrash it; rolls of iron crush the grain to separate the flour; engines of iron bring the flour to our homes, where it is made into dough in iron pans and baked in an iron stove; finally the bread is sliced from the loaf with an iron knife, and served to us at a table made with iron tools. It has no exact substitute in nature, and without it most of our modern conveniences would have been impossible of development. The railroads, the automobile, and the watch are three of the many notable examples of such conveniences No other metal is capable of giving the great range in physical properties. that makes iron available for an almost unlimited number of purposes. Thus, from our towering skyscrapers, our massive bridges and our immense ships, where, as great beams, cables and plates, it supports loads almost greater than the mind can conceive, we can trace it even to our parlors, where, as invisible hairpins, it supports milady's tresses and, as the strings of her piano, sends forth at her magic touch sweet sounds of melody. One property which it possesses in a far greater degree than any of the other metals is that of magnetism. This property is so pronounced in iron and so slight in other metals that, from a practical viewpoint, iron and one of its compounds may be considered as the only magnetic substances. Hence, our modern magnetic and electrical appliances are dependent upon this one metal; and we find it forming the essential parts of the dynamo, the electric motor, the telegraph, the telephone, the wireless telegraph, the compass, and a large number of other instruments of less importance. And so we might continue at great length upon this one topic of the importance of iron, but our time is too short to permit our giving much of it to a theme which the reader may develop for himself. Hastening on, then, to more important matters, we find the first question that confronts us is, What is Metallurgy?

**Metallurgy:** In general, Metallurgy is defined as the science which deals with the preparation of the metals and their adaptation to the uses for which they are intended. It is an advanced and specialized science, hence a difficult one. Even a slight understanding of the subject requires a previous knowledge of the fundamental sciences of Physics and Chemistry. For those who may not have had the necessary preparation in these prerequisites, this study is becomingly introduced by a brief consideration of some of the more important principles of these two sciences. To present these principles in as concise and simple a manner as possible is the object of this chapter.

**Matter:** Through the various senses of sight, touch and hearing, the human intellect becomes aware of the existence of things which, collectively, are called matter. Limited portions of space that contain matter are termed bodies, and the different kinds of matter are, in general, spoken of as substances. Matter is a fundamental thing and cannot be accurately defined. It is described by its properties, which will be discussed later.

**The Fundamental Law and the States of Matter:** Certain facts about matter, however, are plainly evident. It occupies space, and can be neither increased nor decreased in amount. These last two facts are commonly known as the Law of the Conservation of Matter. It exists in any one of three states; solids, which have definite masses, sizes and shapes; liquids, which have definite masses and sizes but not form; and gases, which possess definite masses only. A common example is water, which at ordinary temperatures exists in all three states; namely, ice, water and vapor. Liquids and gases together are called fluids on account of their flowing properties, and in many instances they are subject to the same laws. They are distinguished from each other by their relative compressibility. Liquids are but slightly compressible, while gases are highly compressible. **The volume of a gas varies inversely as the pressure applied to it.** For example, if a certain mass of gas has a volume of 10 cu. ft. under a pressure of 100 lbs., the same mass of gas will occupy but 5 cu. ft. at 200 lbs. pressure.

**Molecules:** Furthermore, while the conception may seem difficult to establish as a fact, there are strong reasons for believing that the relatively large bodies, in which form matter makes itself evident to the human senses, are composed of minute particles, called molecules. This belief is founded upon many facts, and can be arrived at by some such process of reasoning as follows: Mental conception concerning the constitution of matter may be based on either one of two hypotheses; namely, that matter is infinitely divisible or that it is made up of small particles. According to the first hypothesis, a body of matter could be divided indefinitely, if means were available to make such a process possible, without changing any of its characteristics, except its size; that is, a piece of chalk, for example, would remain chalk even as the particles resulting from the infinite division approached zero in size and weight. This retention of original characteristics would imply that each individual kind of matter, the chalk in the present instance, is an elementary substance. But this conclusion is contrary to the facts, for it is a matter of common knowledge that many substances like iron ore, limestone, sugar, etc., are composed of substances quite different from the original. Thus, through the application of heat alone, limestone and sugar are decomposed, the former into quick lime and carbonic acid gas, and the latter into carbon, or charcoal, and water. Only the second hypothesis remains, and it agrees with these facts, for it assumes that the larger masses of limestone and sugar, so evident to our senses, are made up of small particles, each of which is composed of portions of these simpler things into which the limestone and sugar are decomposed by the heat. These ultimate particles of the different substances are called molecules, which are, therefore, defined as the smallest particles of a substance that retain the characteristics of that substance.

**Sciences of Matter:** Two great classes of matter are evident; animate or living matter, such as the living bodies of plants and animals, and inanimate matter, such as glass, water, air, etc. Animate matter is treated of by the sciences of Biology, Zoology and Botany; inanimate, by Physics and Chemistry, formerly included under the one head of Natural Philosophy. Thus, Metallurgy may be looked upon as a highly specialized branch of Natural Philosophy. All these sciences are so closely related that a knowledge of all is essential to a complete understanding of any one.

## SECTION II.

### SOME PHYSICAL PROPERTIES OF MATTER.

**Properties:** That a better understanding of matter may be obtained from a study of its properties has already been indicated. By properties is meant those characteristics by which the different kinds of matter are distinguished and by which it may be described and defined. They are of two classes,—namely, general and special. General properties are common to all matter, while special properties are peculiar to certain kinds of matter only. The general properties are as follows:

**Inertia:** This property causes matter to resist any attempt to change its state of rest or motion.

**Extension** is that property by virtue of which matter occupies space. There are two systems of measuring extension, the English and the metric. In the English system, the linear unit is the yard, while the volumetric units, as established by custom, are the gallon, the bushel, and the cubic yard. Corresponding units in the metric system are the meter=1.09361 yards=39.37 inches; the kilometer=.62137 mile; the liter=.26417 gallon=1.0567 quarts, liquid, or .908 quart, dry; and the cubic meter=1.308 cubic yards.

**Mass** refers to the amount of matter. It is measured in grams, which is the mass of one cubic centimeter of pure water at the temperature of its greatest density, 4° centigrade. Commercially, the unit is the kilogram, equal to 1000 grams. From a scientific standpoint there is no exact English equivalent, because weight involves the force of gravity, which may vary, whilst mass is constant. However, the pound has been standardized so that one kilogram=2.20462 pounds.

**Density** is the weight or mass of a unit volume of matter. It is usually expressed in grams per cubic centimeter.

**Specific Gravity** is the number of times a body is heavier than an equal volume of some substance used as a standard. For liquids and solids this standard is water; for gases it is air or hydrogen. In the metric system density and specific gravity are numerically the same, since the weight of one cubic centimeter of water is one gram.

**Porosity:** All matter is porous. The molecules, it is thought, are separated, even in the densest materials, by spaces larger than the molecules themselves.

**Impenetrability:** Two bodies of matter cannot occupy the same space at the same time, and to this property of matter the term impenetrability is applied.

**Special Properties:** The chief special properties of matter, some of which are of supreme importance in the manufacture of steel, are as follows:

**Cohesion and Adhesion:** According to the law of gravitation, every particle of matter in the physical universe attracts every other particle with a force whose direction is that of a line joining the two particles and whose magnitude varies directly as the product of the two masses, and inversely as the square of the distance between them. Applied to molecules, this attraction is known as cohesion and adhesion; the former is the attraction of molecules of the same kind for each other, the latter, the attraction of unlike molecules. The clinging of a drop of water to the end of a glass rod exemplifies both of these forces.

**Elasticity** is the power of matter to assume its original shape after having been distorted. The property of cohesion causes all bodies to resist change in form, but only solids have elasticity of form. When a solid body is deformed, the resistance it offers is called the **stress**; the deformation which produces this stress is called the **strain.** Hooke's law states that, up to the elastic limit, the strain is proportional to the stress. In practice, the stress is measured in terms of a force or forces applied externally to the body being tested. There are four methods of calling forth the elasticity of bodies:—namely, by pressure, by stretching, by bending and by twisting. Stretching and bending are the methods most commonly employed in testing the elasticity of steel.

**Plasticity** is the opposite of elasticity. A plastic body once distorted will not regain its original shape.

**Ductility** is sometimes defined as the property by virtue of which matter may be drawn into fine wires. As the term is employed in the testing of steel, ductility is the distortion or strain a body undergoes in being ruptured.

**Malleability:** Some kinds of matter, metals in particular, can be hammered or rolled into thin sheets. This property is called malleability.

**Hardness** is the ability to withstand abrasion, or resist penetration.

**Crystallization:** Some substances in changing from a liquid to a solid form, separate not as a continuous compact mass but as bodies having a definite shape and color, called crystals. That crystals may form, it is necessary that the molecules be free to arrange themselves in a definite order. This condition is secured when a substance is in solution or in a molten state. In steel manufacture this property is of great importance.

**Diffusion** is most characteristic of liquids and gases. It is the property that causes two fluids in contact to intermingle. Liquids diffuse slowly, but gases much more rapidly.

**Effusion** is the term applied to that property of gases which causes them to pass through porous solids. The rates of effusion of different gases is inversely proportioned to the square roots of their relative weights.

**Absorption:** Many porous bodies, like coke, charcoal, platinum sponge, etc., are capable of absorbing large quantities of gases. Thus, one cubic centimeter of charcoal is capable of absorbing from thirty to thirty-five times its own volume of carbon dioxide. Gases are condensed on the surface of all solids, and porous bodies offer a large surface for condensation.

## SECTION III.

### ENERGY, HEAT AND TEMPERATURE, AND THE ETHER.

**Energy:** Physics and Chemistry, however, have to do with more than matter. The senses also reveal the presence of a second factor in nature, called energy. Like matter, energy is a fundamental that cannot be satisfactorily defined. It is not a thing. It is that which gives a body the ability to move against a resistance; that is, the ability to do work.

Thus, a body may possess energy and still neither move nor do any work. Like matter, energy is conserved. It may be changed from one form to another or be transferred from one point to another, but the total energy of the Universe remains constant. This fact is known as the Law of Conservation of Energy.

**Kinds of Energy:** There are two kinds of energy; namely, potential or stored up energy, sometimes called energy of position, and kinetic energy, or the energy possessed by a body by virtue of its motion. Thus, a weight on the top of a building possesses potential energy with respect to the ground by virtue of its position; if it is permitted to fall, its energy then becomes kinetic. Energy is measured in terms of the work which it is capable of doing.

**Heat and Temperature:** One form of energy is heat. Heat must not be confused with temperature. The latter measures one of the effects of the former. The difference may be illustrated thus:—Let it be supposed that two portions of natural gas, each of a cubic foot, are burned completely, so that the heat liberated is entirely absorbed by two bodies of water initially at the same temperature, the volumes of which are a quart and a gallon, respectively. It is evident from common experience that the temperature of the smaller portion of water will be raised the higher, though the quantity of heat imparted to each is precisely the same.

**Effects of Heat:** Heat produces marked effects on matter. All matter expands by the application of heat alone, though there are many apparent exceptions. **The volume of a gas varies directly as the absolute temperature,** other conditions remaining constant. Change of state may be caused by heat. Thus, glass or iron, dense solids at ordinary temperatures, readily assume the fluid state on being heated above their fusion point. According to the kinetic theory of heat, the molecules of matter always have a certain amount of independent motion, and the effect of adding heat is to increase the energy of this motion, the molecules being thereby forced farther and farther apart. This forcing apart of the molecules accounts for the change of state as well as the expansion of bodies on being heated.

**Temperature** is determined by measuring the expansion it produces in a volume of mercury enclosed in a small glass tube, called a thermometer. The length of the tube is marked off into small divisions, which constitutes the scale of the thermometer. There are four thermometer scales in common use; the Centigrade, Fahrenheit, Reaumur and Absolute. The difference among them consists of the number of divisions between the freezing point and the boiling point of water, and the numbers applied to these divisions.

**The Centigrade** is the thermometer employed in all scientific work. In it the freezing point is marked zero and the boiling point 100°. The only difference between this scale and the Absolute is that, in the latter, the zero point is 273° below the Centigrade zero.

**In the Fahrenheit** thermometer, the space between the freezing and the boiling points is divided into 180 equal parts, and zero is 32 of these parts below the freezing point of water. The boiling point, therefore, is 212°.

**In the Reaumur** scale, the freezing point is marked zero and the boiling point 80°. For high temperatures, instruments called pyrometers are used. These relations of the various scales are shown in the accompanying diagram: From this diagram the following formulas are readily developed:

Temp. A=Temp. C+273.

Temp. C=Temp. A—273.

Temp. F=Temp. $\frac{9}{5}$C+32.

Temp. C=Temp. (F—32°)$\frac{5}{9}$.

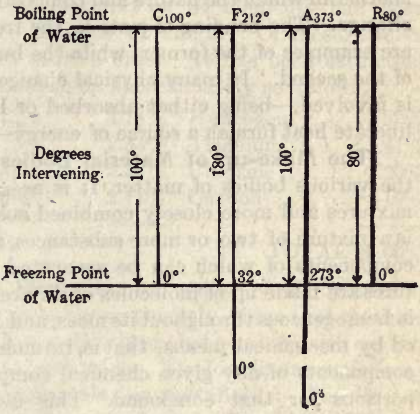

Fig. 1. Diagram showing relations of the various thermometer scales.

**Measurement of Heat:** Heat is measured in calories. A calorie (cal.) is the heat required to raise the temperature of one gram of water one degree centigrade. In practice the large calorie (Cal.) is employed. It is the amount of heat required to raise one kilogram of water through one degree centigrade. The corresponding unit in the English system is the B. t. u. (British thermal unit), which is the heat required to raise the temperature of one pound of water one degree Fahrenheit. These units may be converted from one to the other by use of the following factors:

1 Calorie=3.968 B. t. u. or
1 B. t. u.= .252 Cal.

**The Ether:** A third factor composing the Universe is the Ether. Little is known about it except that it fills all space, permeates all matter and transmits light, heat, and electric waves. Its properties are very difficult to analyze, because the senses are not directly affected by it. Its presence was first suspected through the study of the transmission of light. By comparatively simple experiments, it was shown as early as 1802 that light is transmitted by a wave motion, and since light is transmitted through a vacuum, something other than matter must act as the medium. The same conclusion is arrived at by a study of heat radiation. The development of wireless telegraphy was based on this supposition, and its success is further evidence of the existence of the Ether.

## SECTION IV.

### CHANGES IN MATTER.

**Physical and Chemical Changes:** Matter is constantly undergoing changes. A close observer soon discerns that these changes are of two kinds,—namely, one in which the nature and composition of the matter undergoing the change remains the same, called a **physical change,** and another in which the nature and composition are affected, called a **chemical change.** The bending of a stick, the freezing of water, the fusion of steel are examples of the former, while the burning of coal is a common example of the second. In many physical changes and in all chemical changes heat is involved,—being either absorbed or liberated. Chemical changes that liberate heat furnish a source of energy— **chemical energy.**

**The Make-up of Material Bodies:** In considering the make-up of the various bodies of matter, it is necessary to distinguish between mere mixtures and more closely combined substances. **A mechanical mixture** is a mixture of two or more substances, which is not homogeneous and the components of which can be separated by mechanical means. Such mixtures are made up of molecules of different kinds. **A chemical compound** is homogeneous throughout its mass, and its components cannot be separated by mechanical means, that is, its molecules are all of the same kind. The components of any given chemical compound are always in the same proportions for that compound. This fact distinguishes compounds from **alloys** and **solutions** which, though they are practically homogeneous and sometimes are practically impossible of separation by mechanical means, are never constant in composition. An **alloy** is a solid solution of one metal in another.

**Kinds of Chemical Compounds:** A close study of a great number of chemical compounds will show that all substances fall into four classes; namely, acids, bases, salts and non-electrolytes.

**Acids** are characterized by the fact that they all have a sour taste when in water solution and change the color of certain chemicals, called indicators. One of the most common of these indicators is litmus, of which there are two colors, a blue and a red. Acids change the color of blue litumus to red. Vinegar is chiefly a dilute solution of acetic acid.

**Bases** have the power of neutralizing acids, and may be looked upon as their opposites. Examples are quick lime, lye, etc. Bases change the color of red or neutral litmus to blue.

**A Salt** is the product formed when an acid is neutralized by a base, Common table salt, made by neutralizing hydrochloric acid with sodium carbonate, is an example. As a rule acids, bases, and salts are electrolytes, that is, their water solutions will conduct the electric current.

**Non Electrolytes:** There are some compounds that do not resemble either acids or bases, nor can they be classed as salts. They are characterized by the fact that their water solutions will not conduct the electric current, so are termed non-electrolytes. Benzene, methane and distilled water are examples.

**Chemical Elements:** Notwithstanding the fact that chemical compounds are homogeneous and cannot be separated by mechanical means. they are readily divided into simpler substances by chemical processes, These simpler substances are called elements, and each and every chemical compound is composed of two or more chemical elements. While the number of chemical compounds is almost unlimited, there are comparatively few elements. In 1918, the discovery of 84 elements had been reported. The total number lies between 92 and 97. Of these, twelve compose about 99 per cent. of the earth's crust. It has been estimated that the solid crust of the earth is made up approximately as follows:

| | | | | | |
|---|---|---|---|---|---|
| Oxygen | 49.85% | Calcium | 3.18% | Hydrogen | .97% |
| Silicon | 26.03% | Sodium | 2.33% | Titanium | .41% |
| Aluminum | 7.28% | Potassium | 2.33% | Chlorine | .20% |
| Iron | 4.12% | Magnesium | 2.11% | Carbon | .19% |

TOTAL 99.00%

**Classification of Chemical Elements:** A study of the elements reveals the fact that there are two great classes; namely, those that combine with oxygen and hydrogen to form bases, and those that combine with oxygen and hydrogen, or hydrogen alone, to form acids. The former are sometimes called **metals** and the latter **non-metals, or metalloids.** The line of division is not a sharp one. Some elements form both acids and bases, but the tendency is more pronounced in the one direction than in the other. Furthermore, like plants or animals, these two divisions may be sub-divided into families or groups, the members of which possess similar properties. These divisions and groups are shown in a subjoined table.

**Symbols:** For convenience and brevity, each element is represented by a symbol. These symbols are composed of the first letter, capitalized, of the English or Latin names of the elements, combined, where necessary as a distinguishing mark, with some succeeding letter. Thus, C=carbon, Ca=calcium, Cd=cadmium, F=fluorine, Fe=ferrum (iron), etc.

**Fundamental Laws of Chemical Changes:** Now, **where the elements combine to form a compound they always do so in definite proportions by weight.** Thus, fifty-six parts by weight of iron will combine with sixteen parts by weight of oxygen, or fourteen parts by weight of nitrogen with sixteen parts by weight of oxygen. This fact is known as the **Law of Definite Proportions,** and the definite weights are called combining weights. Further investigation along this line shows that some pairs of elements form more than one compound and that the combining weights of the elements in these different compounds are simple multiples of each other. Concisely stated, the law is this: **Whenever two elements unite to form more than one compound, if we consider a fixed weight of the one, the weights of the other which combine with it are integral multiples of one another.** This fact is known as the **Law of Multiple Proportions,** or Dalton's second law. The following compounds formed by the two elements nitrogen and oxygen are well known examples:

| Compound | Parts by Weight of Nitrogen | Parts by Weight of Oxygen |
|---|---|---|
| Nitrous Oxide | 28 | 16 |
| Nitric Oxide | 28 | 32 |
| Nitrogen Trioxide | 28 | 48 |
| Nitrogen Peroxide | 28 | 64 |
| Nitrogen Pentoxide | 28 | 80 |

## SECTION V.

### THE ATOMIC AND ELECTRON THEORIES.

**Atoms:** Upon the facts just stated in the preceding section, the English chemist Dalton founded a very important hypothesis, now known as the atomic theory. In order to explain the laws stated above, reasoning led to the following assumptions:

1st: The molecules of matter are themselves made up of small particles.

2d: These particles possess the power of attracting other particles or otherwise attaching themselves to them.

3d: These particles do not subdivide in taking part in chemical changes.

These particles are called atoms. All the atoms of the same element have the same mass or weight, the same form, and the same combining power, while atoms of different elements differ in one or more of these respects.

**Atomic Weights:** The atom is so small that it is useless to hope that its mass or weight will ever be determined absolutely. However, the weight of one atom of an element must be proportional to the combining weight of that element. Since the combining mass or weight of hydrogen is the least of all the other elements, it is assumed that its atom is the lightest. Therefore, the atomic weight of hydrogen was made one by Dalton and the atomic weight of the other elements multiples of it. However, since hydrogen forms with other elements comparatively few compounds that can be used for atomic weight determinations and oxygen more than any other element, it was decided later to make the latter element the standard. Accordingly, the atomic weight of oxygen is made 16, and the atomic weights of other elements are compared with it as a standard, thus making hydrogen 1.008. This system of comparative weights is known as the international table of atomic weights.

**Valence:** Concerning the attractive power of the atoms of the various elements, it may be pointed out that the law of multiple proportions indicates that the atom of an element may combine with one or more atoms of another element in forming compounds with it. Here, again, hydrogen is used as a standard, for since its combining weight is the least of all the other elements, it is assumed that the holding power of its atoms must also be the least. Therefore, **the valency of an atom is properly defined as the number of hydrogen atoms it is capable of combining with or replacing.** The valencies of the atoms of the elements are by no means fixed quantities, but vary—in some cases from one to seven.

The following table is intended to furnish a complete list of the elements, with their symbols and atomic weights, and to show, also, the classification and valencies of the more common ones. Very rare elements are placed in a separate list. Elements that ordinarily are both acid and basic are marked with an *, and those important in the manufacture of steel are printed in Italics.

### Table I—The Chemical Elements.

Showing Physical Constants of the More Common Ones.

| Class | Group | Name | Symbol | 1920 Atomic Weight | Valence | Specific Gravity | | Melting Point | Boiling Point |
|---|---|---|---|---|---|---|---|---|---|
| | | | | O=16 | | Water | Air | °C | °C |
| BASE FORMING | Potassium | Lithium | Li | 6.94 | I | .59 | .... | 186 | 1400 |
| | | _Potassium_ | _K_ | _39.1_ | _I_ | _.87_ | .... | _62.5_ | _667_ |
| | | _Sodium_ | _Na_ | _23.0_ | _I_ | _.97_ | .... | _97.6_ | _742_ |
| | Calcium | _Calcium_ | _Ca_ | _40.07_ | _II_ | _1.58_ | .... | _810_ | ...... |
| | | Barium | Ba | 137.37 | II | 3.8 | .... | 850 | 950 |
| | | Glucinum | Gl | 9.1 | II | 1.85 | .... | 960 | ...... |
| | | Strontium | Sr | 87.63 | II | 2.5 | .... | 900 | ...... |
| | Magnesium | _Magnesium_ | _Mg_ | _24.32_ | _II_ | _1.7_ | .... | _650_ | _1120_ |
| | | Zinc | Zn | 65.37 | II | 7.1 | .... | 419 | 918 |
| | | Cadmium | Cd | 112.40 | II | 8.6 | .... | 321 | 778 |
| | Silver | Silver | Ag | 107.88 | I | 10.5 | .... | 961 | _1955_ |
| | | _Copper_ | _Cu_ | _63.57_ | _I-II_ | _8.9_ | .... | _1083_ | _2100_ |
| | | Mercury | Hg | 200.60 | I-II | 13.60 | .... | —38.8 | 357 |
| | Aluminum | *_Aluminum_ | _Al_ | _27.1_ | _III_ | _2.58_ | .... | 657 | 1800 |
| | | Gallium (rare) | Ga | 70.1 | ........ | 5.95 | .... | 30 | ...... |
| | | Thallium " | Tl | 204.0 | ........ | 11.85 | .... | 302 | ...... |
| | | Scandium " | Sc | 44.1 | ........ | ...... | .... | _1200_ | ...... |
| | Lead | *Lead | Pb | 207.2 | II-IV | 11.3 | .... | 327 | 1525 |
| | | *Tin | Sn | 118.7 | II-IV | 7—7.3 | .... | 232 | 1525 |
| | Chromium | *_Chromium_ | _Cr_ | _52.0_ | _II-III-VI_ | _6.9_ | .... | _1505_ | _2200_ |
| | | *_Molybdenum_ | _Mo_ | _96.0_ | ........ | _8.8_ | .... | _2500_ | ...... |
| | | *_Tungsten_ | _W_ | _184.0_ | ........ | _18.8_ | .... | _1700_ | ...... |
| | Manganese | *_Manganese_ | _Mn_ | _54.93_ | _II-IV_ | _7.4_ | .... | _1225_ | _1900_ |
| | Iron | _Iron_ | _Fe_ | _55.84_ | _II-III_ | _7.78_ | .... | _1520_ | _2450_ |
| | | _Cobalt_ | _Co_ | _58.97_ | _II_ | _8.7_ | .... | _1610_ | ...... |
| | | _Nickel_ | _Ni_ | _58.68_ | _II_ | _8.7_ | .... | _1450_ | ...... |
| | Palladium | *Palladium | Pd | 106.7 | ........ | 11.8 | .... | _1550_ | ...... |
| | | Ruthenium (rare) | Ru | 101.7 | ........ | 8.6 | .... | _1950_ | ...... |
| | | Rhodium (rare) | Rh | 102.9 | ........ | 12.1 | .... | _1940_ | ...... |
| | Gold | *Platinum | Pt | 195.2 | IV | 21.5 | .... | 1753 | ...... |
| | | *Gold | Au | 197.2 | I-III | 19.3 | .... | 1062 | 2530 |

## Table I—The Chemical Elements—Continued.

| Class | Group | Name | Symbol | 1920 Atomic Weight O=16 | Valence | Specific Gravity Water | Specific Gravity Air | Melting Point °C | Boiling Point °C |
|---|---|---|---|---|---|---|---|---|---|
| ACID FORMING | Chlorine.. | *Fluorine*.......... | *F* | *19.0* | *I* | ...... | *1.26* | *—223* | *—187* |
| | | *Chlorine*.......... | *Cl* | *35.46* | *I* | ...... | *2.49* | *—102* | *—37.6* |
| | | Bromine........ | Br | 79.92 | I | 3.1 | .... | —7.3 | 59 |
| | | Iodine.......... | I | 126.92 | I | 4.9 | .... | 114 | 184 |
| | Sulphur... | *Sulphur*.......... | *S* | *32.06* | *II-IV-VI* | *2.0* | .... | *116.5* | *444.6* |
| | | Selenium (rare).. | Se | 79.20 | ........ | 4.3 | .... | 218.5 | 690 |
| | | Tellurium " .. | Te | 127.50 | ........ | 6.2 | .... | 451 | 1390 |
| | Carbon... | *Carbon*........... | *C* | *12.0* | *IV* | *1.7-3.5* | .... | Infusible | *3500* |
| | | *Silicon*........... | *Si* | *28.3* | *IV* | *2.49* | .... | *1420* | 3500 |
| | | Boron.......... | B | 10.9 | III | 2.40 | .... | *2250* | 3500 |
| | | *Titanium*......... | *Ti* | *48.10* | *IV* | *3.54* | .... | *1795* | ...... |
| | Nitrogen.. | *Nitrogen*.......... | *N* | *14.01* | *I to V* | ...... | *.96* | *—213* | *—196* |
| | | *Phosphorus*....... | *P* | *31.04* | *III-V* | *1.8* | .... | *44.1* | *290* |
| | | *Arsenic......... | As | 74.96 | III-V | 5.7 | .... | 185 | 449.5 |
| | | *Antimony....... | Sb | 120.20 | III-V | 6.6 | .... | 630 | 1460 |
| | | *Bismuth....... | Bi | 208.0 | III-V | 9.7 | .... | 269 | 1485 |
| | | **Vanadium*....... | *V* | *51.0* | *III-V* | *5.9* | .... | *1680* | ...... |
| | | Oxygen | O | *16.0*<br>*(15.97)* | *II* | ...... | *1.10* | *—218* | *—182* |
| | | Hydrogen | H | *1.008*<br>*(1.)* | *I* | ...... | *.07* | *—259* | *—252* |

### Very Rare Elements.

| | Name | Symbol | Atomic Weight | | Name | Symbol | Atomic Weight |
|---|---|---|---|---|---|---|---|
| 51 | Argon......... | A | 39.9 | 68 | Neon.......... | Ne | 20.2 |
| 52 | Caesium....... | Cs | 132.81 | 69 | Niton......... | Nt | 222.4 |
| 53 | Cerium........ | Ce | 140.25 | 70 | Osmium....... | Os | 190.9 |
| 54 | Columbium.... | Cb | 93.1 | 71 | Praseodymium | Pr | 140.9 |
| 55 | Dysprosium.... | Dy | 162.5 | 72 | Polonium...... | Po | 210.0 |
| 56 | Erbium........ | Er | 167.7 | 73 | Radium....... | Ra | 226.0 |
| 57 | Europium...... | Eu | 152.0 | 74 | Rubidium...... | Rb | 85.45 |
| 58 | Gadolinium.... | Gd | 157.3 | 75 | Samarium..... | Sa | 150.4 |
| 59 | Germanium.... | Ge | 72.50 | 76 | Tantalum...... | Ta | 181.5 |
| 60 | Helium........ | He | 4.0 | 77 | Terbium....... | Tb | 159.2 |
| 61 | Holmium...... | Ho | 163.5 | 78 | Thorium....... | Th | 232.15 |
| 62 | Indium........ | In | 114.8 | 79 | Thulium....... | Tm | 168.5 |
| 63 | Iridium........ | Ir | 193.1 | 80 | Uranium....... | U | 238.2 |
| 64 | Krypton....... | Kr | 82.92 | 81 | Xenon......... | Xe | 130.2 |
| 65 | Lanthanum.... | La | 139.0 | 82 | Ytterbium..... | Yb | 173.5 |
| 66 | Lutecium...... | Lu | 175.0 | 83 | Yttrium....... | Yt | 89.33 |
| 67 | Neodymium... | Nd | 144.30 | 84 | Zirconium..... | Zr | 90.6 |

**Electrons:** Until 1900 all the elements had resisted all efforts to break them up into simpler substances, and atoms were considered to be the smallest divisions of matter. With the discovery of radium and other radio-active substances, however, a new field for investigation was opened, and subsequent discoveries indicate that the atom is divisible. These very small particles are called electrons. It is thought that electrons, in some intimate relation to the Ether, are the fundamental particles of which all matter is composed.

## SECTION VI.

### CHEMICAL FORMULA AND REACTIONS.

**Chemical Formulas of Compounds:** The method of representing the elements by symbols, together with the system of atomic weights, affords a convenient and concise method of representing chemical compounds, or to be more explicit, the molecules of chemical compounds. Thus, by analysis, water is found to be composed of hydrogen and oxygen in the proportion of eight parts of oxygen to one part of hydrogen by weight. These facts are completely expressed by the formula $H_2O$, which indicates a molecule of a compound composed of two atoms of hydrogen and one atom of oxygen, or, since the atomic weight of hydrogen is 1 and of oxygen, 16, 2 parts of hydrogen to 16 parts of oxygen (1 to 8). Likewise, the formula $Fe_2O_3$ represents a compound, the molecule of which is made up of 111.68 parts of iron to 48 parts of oxygen.

**Molecules of Elements:** In studying chemical changes in which elements are set free, it is found that they are much more active at the instant of their liberation than afterwards, and are, therefore, said to be in the **nascent state** at that instant. This fact leads to the belief that the instant an element is set free from its compounds it exists in the atomic condition, but if there is nothing else present with which the atoms can combine, they combine with each other to form molecules of the element. This idea cannot be proven in the case of solids, but its correctness is easily shown in the case of gases. From many facts, Avogadro was able to show **that equal volumes of all gases, under the same conditions of temperature and pressure, contain the same number of molecules.** Hence, the molecular weight in grams of all gases give a constant volume of 22.32 liters, called the gram-molecular volume. Now, the weight of 22.32 liters of oxygen=32 gms., of hydrogen, 2 gms., of nitrogen, 28 gms. Dividing these weights by the respective atomic weights of the elements, the quotient is 2 in each case. Hence, the molecules of these elements contain two atoms each, and the correct formulas for these elements are $O_2$, $H_2$ and $N_2$, respectively.

**Chemical Equations:** This system of symbols and weights also simplifies the representation of chemical changes. Suppose it is desired to represent the chemical change that takes place when a common substance, like coal for instance, burns. Coal is largely made up of carbon; the element which combines with it is oxygen in the air; an invisible gas, $CO_2$, is formed and diffuses into the air. This change, spoken of as a reaction, is represented in the form of an equation; thus, $C+O=CO_2$.

**Balancing Reactions:** Since matter is conserved, there must be as many atoms on one side of the equation as on the other. This is shown by placing a 2 before O on the left side of the equation, thus, $C+2O=CO_2$. This process is called balancing. Thus, reactions tell not only the names of the reacting substances and of the products formed, but also give the proportions by weight, and in the case of gases, volume relations as well.

**Radicals:** In the molecules of many chemical compounds, certain groups of atoms appear to be more closely bound together than others in the same molecule. In these groups the atoms composing them appear to bear a fixed relation to each other, which remains unchanged during a chemical reaction. Thus, in many wet reactions in which $H_2SO_4$ is employed as a reagent, the sulphur and oxygen do not separate but remain closely combined, as illustrated in the reaction that takes place between this acid and barium chloride:

$$H_2\,(SO_4)+Ba\,Cl_2=Ba\,(SO_4)+2\,HCl$$

Such groups of atoms are called radicals.

**Ions and Electrolysis:** In electrolytes these radicals are readily identified as ions. From a study of the effect of dissolved electrolytes on the boiling and freezing points of the water in which they are dissolved, and on their osmotic pressures, evidence is obtained to show that each of the dissolved molecules breaks up or dissociates into two parts.

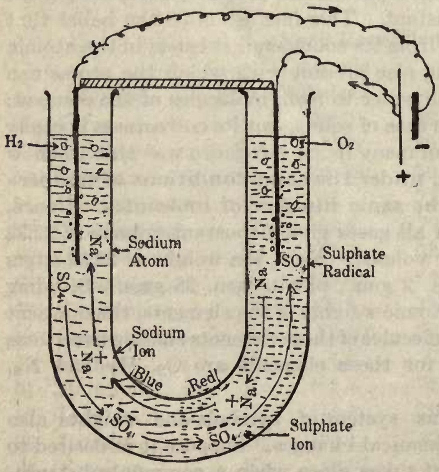

Fig. 2. Showing decomposition of water and formation of sodium hydroxide and sulphuric acid from sodium sulphate by electrolysis.

The following simple experiment may be employed to throw additional light upon this subject. Into the U-tube of Fig. 2 is placed a solution of sodium sulphate and some neutral litmus, into which is immersed two small platinum rods to act as electrodes for an electric current, as shown in the figure. Upon closing the circuit, bubbles of hydrogen are given off at the cathode and bubbles of oxygen at the anode, while the solution about the cathode becomes deep blue in color, showing it is basic, and that about the anode becomes red, showing it to be acid. These facts are explained by assuming that the molecules of dissolved $Na_2SO_4$ dissociate into parts, called ions. This dissociation is indicated thus: $Na_2SO_4 = \overset{+}{Na} + \overset{+}{Na} + \overset{--}{SO_4}$. The sodium ions, $\overset{+}{Na}$, carrying a positive charge of electricity, are propelled by the current toward the cathode, while the negatively charged sulphions, $\overset{--}{SO_4}$, go to the anode. Here they give up their charges and become chemically active, decomposing the water thus:

$$2Na + 2H_2O = 2NaOH + H_2 \qquad 2SO_4 + 2H_2O = 2H_2SO_4 + O_2$$

This experiment is but one example of electrolysis. Any inorganic acid, base or salt may be substituted for the sodium sulphate; and any conductor of electricity, such as iron, may be used instead of platinum. It is to be noted, however, that if iron had been used in this experiment, the anode would have been corroded away by the acid radical; thus, $Fe + SO_4 = FeSO_4$. Electrolysis has been advanced to explain the corrosion of iron.

**Dry and Wet Chemistry:** Chemical changes take place under constant conditions. Substances that will react in one way under one set of conditions will not react, or react in an entirely different way, under another set of conditions. Some substances react simply by contact, as quick lime and water. Many reactions will take place only in a water solution, while many other substances, being insoluble in water, must be heated almost to their point of fusion before they react. A study of reactions between substances in solution is called "wet chemistry" while the study of reactions brought about by heat is termed "dry chemistry." However, under the same conditions, the same substances will always produce the same results. This fact is known as the law of constancy of nature.

**Acids, Bases and Salts of Dry Chemistry:** Most substances dealt with in wet chemistry lose water when heated. This statement is particularly true of inorganic acids, bases and salts. Thus, in the case of acids and bases, heat breaks up these compounds into water and oxides, called **anhydrides.** Acids give **acid anhydrides**, and bases, **basic anhydrides.** These anhydrides constitute the acids and bases of dry chemistry. They have the same power of neutralization that their corresponding wet compounds possess, and form neutral compounds to which the term **slag** is applied instead of **salt.** Many salts, in crystallizing from aqueous solutions, unite with, or better, take up a definite amount of water, which does not go to form a new compound, but to form crystals, and is called, therefore, **water of crystallization.** This water is held very loosely by the molecule and is readily given up by it. In some crystals, like those of washing soda, for example, this tendency is so pronounced that they give up their water of crystallization to the air, if its humidity is low. Such substances are said to be **efflorescent.** On the other hand, many dry substances absorb moisture from the air and are, therefore, said to be

**hygroscopic.** A few substances will absorb enough water from a very moist air to become wet and actually go into solution in the water they absorb. These substances are said to be **deliquescent.** The following reactions will serve to illustrate these facts in so far as they involve chemical changes:

$H_2SiO_3 + heat = H_2O + SiO_2$
Metasilicic Acid Water Silica, or silicic anhydride

$Mg\ (OH)_2 + heat = H_2O + MgO$
Magnesium hydroxide Magnesia—a basic anhydride

$Na_2SO_4 \cdot 10H_2O + heat = 10H_2O + Na_2SO_4$
Glauber Salt Sodium Sulphate
(Crystallized) (Dry Powder)

In this connection a study of the following table will also prove helpful.

**Table 2. Acids, Bases and their Anhydrides with Salts Resulting from Neutralization.**

| Name of Compound | Formula of Compound | Formula of Anhydride | Salt With | | |
|---|---|---|---|---|---|
| | | | Univalent Base | Divalent Base | Trivalent Base |
| Sodium hydroxide | $NaOH$ | $Na_2O$ | | | |
| Calcium hydroxide | $Ca(OH)_2$ | $CaO$ | | | |
| Ferric hydroxide | $Fe(OH)_3$ | $Fe_2O_3$ | | | |
| Sulphuric Acid | $H_2SO_4$ or $H_2O \cdot SO_3$ | $SO_3$ | $Na_2O \cdot SO_3$ or<br>$Na_2SO_4$ | $CaO \cdot SO_3$ or<br>$CaSO_4$ | $(Fe_2O_3) \cdot (SO_3)_3$<br>or $Fe_2(SO_4)_3$ |
| Nitric Acid | $HNO_3$ or<br>$H_2O \cdot N_2O_5$ | $N_2O_5$ | $Na_2O \cdot N_2O_5$ or<br>$NaNO_3$ | $CaO \cdot N_2O_5$ or<br>$Ca(NO_3)_2$ | $Fe_2O_3 \cdot (N_2O_5)_3$<br>or $Fe(NO_3)_3$ |
| Orthophosphoric Acid | $H_3PO_4$ or<br>$3H_2O \cdot P_2O_5$ | $P_2O_5$ | $3Na_2O \cdot P_2O_5$ or<br>$Na_3PO_4$ | $(CaO)_3 \cdot P_2O_5$<br>or $Ca_3(PO_4)_2$ | $Fe_2O_3 \cdot P_2O_5$<br>or $FePO_4$ |
| Orthosilicic Acid | $H_4SiO_4$ or<br>$2H_2O \cdot SiO_2$ | $SiO_2$ | $2Na_2O \cdot SiO_2$ or<br>$Na_4SiO_4$ | $(CaO)_2 \cdot SiO_2$<br>or $Ca_2SiO_4$ | $Fe_2O_3)_2 \cdot (SiO_2)_3$<br>or $Fe_4\ (SiO_4)_3$ |

**Kinds of Reactions:** As already indicated, all reactions may be placed under one of two heads; namely, those that liberate heat, called exothermic, and those that absorb heat, called endothermic. A more detailed classification, such as the following, is sometimes employed:

1. Direct combination (synthesis)—$2H + O = H_2O$ or $2H_2 + O_2 = 2H_2O$.
2. Direct decomposition (analysis)—$2HgO = 2Hg + O_2$.
3. Simple replacement or substitution—$2H_2O + 2Na = 2NaOH + H_2$.
4. Double replacement or metathesis—$BaCl_2 + H_2SO_4 = BaSO_4 + 2HCl$.
5. Oxidation—$\begin{cases} 3\ Fe + 4O = Fe_3O_4. \\ Fe\ Cl_2 + Cl = Fe\ Cl_3. \end{cases}$
6. Reduction—$\begin{cases} Fe_3O_4 + 8H = 3\ Fe + 4H_2O. \\ Fe\ Cl_3 + H = Fe\ Cl_2 + HCl. \end{cases}$

The two processes of oxidation and reduction are of great importance in metallurgy. They have a triple meaning. Primarily, oxidation means the taking on of oxygen by an element or compound, and reduction means the giving up of oxygen. In the case of elements that form more than one compound, if the number of atoms of one that combines with a fixed number of the other be increased, the process is oxidation; if decreased, reduction. In metallurgy an element in the metallic state is said to be reduced. The two processes are inseparable; when one thing is reduced, another is oxidized. In metallurgical operations these two processes are of paramount importance, for all the substances reduced constitute the metallic product and all in oxidized form make up the slag.

**Some Laws Controlling Chemical Reactions:** In writing reactions considerable knowledge of a specific character is essential. Thus, suppose it is required to write the reaction that represents the action of iron brought in contact with water. First, it will be necessary to know under what conditions the substances are brought together, for at ordinary temperatures no reaction will take place. At a high temperature, a reaction takes place, and it is necessary to know that ferroso-ferric oxide and hydrogen are produced, and the formulas of all these substances. This knowledge can then be indicated thus: $Fe+H_2O=Fe_3O_4+H_2$. Balancing the reaction, which is done by inspection and arithmetic, is the next step. Finally, the reaction is reversible, for if instead of steam over hot iron, hydrogen be passed over hot iron oxide, iron and water are the products. The reaction is, therefore, correctly written thus: $Fe_3O_4+4H_2 \rightleftharpoons 3Fe+4H_2O$, or $3Fe+4H_2O \rightleftharpoons Fe_3O_4+4H_2$. Many reversible reactions, under conditions which do not permit the products to escape from the field of action, do not proceed to completion, but reach a balanced condition after a time and seem to stop, though as a matter of fact they are progressing in one direction as rapidly as in the other, hence are described as being in dynamic equilibrium. In practical chemical work it is usually desirable to have reactions go to an end. As an aid in writing reactions the following laws may be found of value:

A. The reaction of two or more substances will go to an end, that is, will be complete, provided,

1. One of the products is volatile at the temperature of the reaction.
2. One of the products is insoluble in the solvent in which the reaction takes place.
3. One of the products is a non-electrolyte, that is, does not ionize in the solvent.

B. The speed of a chemical action in a given direction may be increased by effecting a greater concentration of one of the reacting substances. This is a simple, non-mathematical statement of the law of mass action.

C. Chemical reactions always tend to proceed in the direction that will liberate the most heat, and without the addition of heat from an external source those substances that have the greatest heats of formation will tend to form.

## SECTION VII.

### CHEMICAL NOMENCLATURE.

**General Principle:** A brief description of the nomenclature of chemical compounds will be found of great assistance to those not familiar with the subject. The names of the elements first discovered, and, therefore, unfortunately, the more common ones, are not based on any principle; but of the more recently discovered elements the metals have received names ending in **um** or **ium**, and the metalloids, in **n** or **ne**. In the naming of compounds, however, the old names have been discarded and new ones substituted. The system employed in assigning these new names is this: **The name of a compound should show the elements of which it is composed, and as far as possible their relative proportions.**

**Terminology of Binary Compounds:** The simplest compounds are those composed of only two elements. The names of all such compounds are made up of the name of the basic element, if one is present, succeeded by the name of the acid element, which ends in **ide**: examples; ferrous (iron) sulphide, FeS; sodium chloride, NaCl; calcium oxide, CaO.

In such cases as iron and sulphur where the same two elements combine to form more than one compound, the compounds, when two in number, are distinguished by changing the ending of the metallic part of the name from **ous** to **ic**; thus, ferrous sulphide, FeS; ferric sulphide, $FeS_2$; stannous chloride, $SnCl_2$; stannic chloride, $SnCl_4$. Often, the prefixes **mono-**, **di-**, **tri-**, **tetra-**, **pent-**, **per** are used, especially if the name will not permit the ending **ous** and **ic**, or if more than two compounds are formed by the same two elements. Carbon dioxide, $CO_2$; nitrous oxide, or nitrogen monoxide, $N_2O$; nitric oxide or nitrogen dioxide, $N_2O_2$; (NO); nitrogen trioxide, $N_2O_3$; nitrogen tetroxide or nitrogen peroxide, $N_2O_4$; nitrogen pentoxide, $N_2O_5$ are examples.

**Terminology of Ternary Compounds:** The names of compounds that contain three elements, provided they are not derived from acids, may end in **ide**, also, in which case all three of the elements appear in the name, as sodium aluminum fluoride, ($Na_3AlF_6$), bismuth oxychloride, (BiOCl). A few ternary compounds have names ending in **te** (from **ter**, three), as potassium chlorplatinate, ($K_2PtCl_6$).

**Terminology of Acids:** Acids are composed of the acid-forming elements in combination with hydrogen or with hydrogen and oxygen. The name of a given acid is derived from the name of the acid forming element. The best known acid of an element has the ending **ic**. Example, chlor**ic** acid, $HClO_3$. Then the acid the molecule of which contains one less atom of oxygen has the ending **ous**. Example, chlor**ous** acid, $HClO_2$. If the element also forms an acid containing one more atom of oxygen in its molecule than the **ic** acid, it is designated by the prefix **per**. Example.

perchloric acid, $HClO_4$. Acids, like sulphuric ($H_2SO_4$) and ortho phosphoric ($H_3PO_4$), which contain more than one replacable hydrogen atom are called, as a class, polybasic acids; and, in individual cases, the different acids are referred to as **di basic, tri basic,** etc., because such acids may be neutralized by more than one base at once. For example, potassium and sodium may replace the two hydrogens in $H_2SO_4$ to form sodium potassium sulphate, $NaKSO_4$. In all such double salts both the base forming elements must appear in the name of the salt.

**Terminology of Bases:** The base forming elements form compounds with hydrogen and oxygen in which these two elements appear as a radical, OH, called hydroxyl. Hence, these compounds are called hydroxides in wet chemistry. Thus, sodium hydroxide, Na OH, and calcium hydroxide Ca $(OH)_2$ are examples. In dry chemistry the hydrogen and part of the oxygen are driven off, leaving the oxides which still act as acids and bases.

**Terminology of Salts:** Salts take their names from those of the base forming elements and the acids of which they are composed, changing the endings of the acids. Salts of acids that end in **ic** change this ending to **ate,** and those that end in **ous,** to **ite.** Thus, sodium chlorate $NaClO_3$, derived from chloric acid, sodium perchlorate $NaClO_4$, from perchloric acid, and sodium chlorite, $NaClO_2$, from chlorous acid, are examples. Other systems of nomenclature are in use, but the ones just noted cover the largest field.

## SECTION VIII.

### CHEMICAL CALCULATIONS.

**Kinds of Problems:** Chemical calculations constitute a very important branch of study in the training of the metallurgist. They are of three general classes; namely, those involving weight, those involving the volumes of gases, and those involving both weight and volume. Further subdivisions of these classes may be made, the principles of which are best taught from specific examples, as follows:

### PROBLEMS INVOLVING WEIGHT ONLY.

**Calculation of the Molecular Weight from the Formula:** Problem: The formula of copper sulphate is $CuSO_4$. Find its molecular weight. Solution: From the table of atomic weights and the formula, we find

Atomic weight of copper =63.57
" " " sulphur=32.06
" " " oxygen =16

| Atomic Weights | | No. of Atoms | | Combining Weights |
|---|---|---|---|---|
| 63.57 | x | 1 | = | 63.57 |
| 32.06 | x | 1 | = | 32.06 |
| 16. | x | 4 | = | 64.00 |

Molecular weight of $CuSO_4$= 159.63 Ans

**Calculation of Percentage Composition of a Compound from its Formula:** Problem: Find the percentage composition of a compound, the formula of which is $CuSO_4$.

**Solution:**

$$\underline{\text{Cu} \quad \text{S} \quad \text{O}_4}$$

Molecular weight=63.57+32.06+(4 x 16)=159.63.

$$159.63 \,\underline{\big| \; 63.57 \qquad 32.06 \qquad 64.00 \qquad}$$

Percentage Composition=39.83% Copper, 20.09% Sulphur, 40.09% Oxygen. Ans.

**Calculation of Formula from the Analysis of a Compound:** Problem: By analysis a pure compound is found to be composed of calcium 29.41%, sulphur 23.53% and oxygen 47.06%. What is its simplest formula?

**Solution:**

| Element | | Parts in a Hundred | | Atomic Weights | Atomic Ratios | | Number of Atoms |
|---|---|---|---|---|---|---|---|
| Ca | — | 29.41 | ÷ | 40.07 | = .735— | ÷.735= | 1 Ca |
| S | — | 23.53 | ÷ | 32.06 | = .735+ | ÷.735= | 1 S |
| O | — | 47.06 | ÷ | 16. | =2.941— | ÷.735= | 4 O |

Formula of compound is $CaSO_4$. Ans.

**Calculation of Relative Weights from the Chemical Equation:** Problem: Five per cent. of a certain limestone is non-volatile impurities and 95% is pure calcium carbonate. What will be the weight of lime obtained from calcining 2000 lbs. of this stone?

**Solution:**

Weight of impurities =5% of 2000= 100 lbs.

" " calcium carbonate =1900 lbs.

Reaction on calcining........ $CaCO_3 = CaO + CO_2$

Combining or atomic wts..$\underline{40.00+12+(3x16)=40.+16+12+(2x16)}$

Relative or molecular wts.. 100.00 = 56.00 + 44

100 lbs. $CaCO_3$ gives 56 lbs. CaO

1 " " " .56 " "

1900 " " " 1064 " "

1064 lbs. CaO+100 lbs. non-volatile impurities=1164 lbs. of lime. Ans.

PROBLEMS INVOLVING VOLUME ONLY.

**Calculation of Relative Volumes of Gases:** From Avogadro's hypothesis, it is known that molecular weights of all gases give the same volume under standard conditions of 0°C and 760 mm. barometric pressure. Problems involving volumes of gases only are, therefore, very simple to solve, because the relative volumes are identical with the coefficients of the molecules, as will be evident from an inspection of the following examples:

$H_2+Cl_2=2HCl$

1 vol. hydrogen+1 vol. chlorine gives 2 volumes hydrochloric acid gas

$CH_4+2O_2=CO_2+2H_2O$

1 vol. methane+2 vol. oxygen gives 1 vol. carbon dioxide+2 vol. water vapor

$N_2O_2+O_2=2NO_2$

1 vol. nitric oxide+1 vol. oxygen gives 2 volumes nitrogen peroxide.

### PROBLEMS INVOLVING BOTH WEIGHT AND VOLUME.

**Indirect Method:** This method necessitates finding the relative weights of the gases involved, from which the volumes may be calculated from the specific gravity, or the weight of a unit volume.

**Problem:** How many cubic feet of carbon dioxide measured under standard conditions would be given off by 2000 lbs. pure calcium carbonate during the process of calcination?

**Solution:**

Reaction $CaCO_3 = CaO + CO_2$

$$\frac{40+12+48}{100} = \frac{40+16}{56} + \frac{12+2x16}{44}$$

100 lbs. $CaCO_3$ give 44 lbs. $CO_2$

2000 " " " 880 " $CO_2$

Wt. 1 cu. ft. $CO_2$=.1235—lbs.

880÷.1235 = 7125—cu. ft. Ans.

**Direct Method:** The fact that molecular weights of gases give constant volumes at standard conditions affords a simple direct method for calculating volumes from the equation. If the weights are expressed in grams, each gram-molecule of the gases involved represents 22.32—liters; if in kilograms, each kilogram-molecule stands for 22.32—cubic meters; and if in avoirdupois ounces, each ounce-molecule gives a volume of 22 32+ cubic feet. By this method the problem above would be solved as follows:

2000 lbs.=32000 ozs.

$$CaCO_3 = CaO + \overset{?\ \text{cu. ft.}}{CO_2}$$

$$\frac{40+12+(3x16)}{100} = \frac{40+16}{56} + 22.32\ \text{cu. ft.}$$

100 ozs. $CaCO_3$ gives 22.32 cu. ft.

1 " " " .2232—

32000 " " " 7142 —cu ft. Ans.

## SECTION IX.

### A DESCRIPTION OF ELEMENTS COMMONLY MET WITH IN THE MANUFACTURE OF STEEL.

### Oxygen.

**Occurrence:** This element is most widely distributed in nature; 49.85% of the solid crust of the earth, 88.89% of water and 20.8% of air is oxygen. In air it exists in a free state. In a combined state, it exists in limestone, sand, marble, clay, quartz, iron ore, and many other substances.

**Preparation:** It is prepared by merely heating certain of its compounds, some of which are mercuric oxide, potassium chlorate and manganese dioxide; by the decomposition of water by electrolysis; and from the air by purifying processes.

**Properties:** Oxygen is a colorless, odorless, tasteless gas, heavier than air (sp. gr.=1.1056) and slightly soluble in water. At a low temperature and a high pressure it is converted into a liquid which boils at—181°C.

The phenomenon of ordinary burning or combustion is due to the combination of oxygen with other substances. It unites with many elements to form a class of compounds, the oxides. It is necessary to life. Animals die in an atmosphere of less than 16% oxygen.

**Compounds:** Some important oxides are: carbon dioxide, $CO_2$, carbon monoxide, $CO$, calcium oxide, $CaO$, magnesium oxide, $MgO$, ferric oxide, $Fe_2O_3$, and ferroso-ferric oxide, $Fe_3O_4$. The last two are important as ores of iron.

### Hydrogen.

**Occurrence:** Hydrogen does not occur in nature in a free state, but combined with oxygen it forms water, of which it constitutes 11.11%. In a combined state it occurs also in the bodies of plants and animals, hence, in the volatile matter of coal, in petroleum, and in natural gas of which it constitutes almost 25%. Water is always one of the products of combustion when a fuel containing hydrogen is burned.

**Preparation:** It can be prepared by decomposing water with sodium, potassium, hot iron, hot coke, or the electric current; by treating certain metals with certain acids; and by treating aluminum with sodium or potassium hydroxide.

**Properties:** Hydrogen is a colorless, tasteless, odorless gas, almost insoluble in water. It can be converted into a liquid that boils at—252°C. It is the lightest substance known, being about $\frac{1}{15}$ as heavy as air and $\frac{1}{16}$ as heavy as oxygen. Its specific gravity, air standard, is .0696. It is combustible and explosive. It combines with oxygen in the proportion of 1:8 to form water. Its great tendency to combine with oxygen makes it an intense reducing agent.

### Sulphur.

**Occurrence:** This element occurs free in the neighborhood of volcanoes and in underground deposits, from which it may be prepared by purifying processes. In combined state it is found as $FeS_2$, $FeCuS_2$, ZnS, and PbS, the last three being valuable ores of copper, zinc, lead, respectively. It also occurs as the sulphates $CaSO_4$, $BaSO_4$ and $PbSO_4$, and in animal and vegetable matter. Compounds of sulphur occur in iron ores, in limestone, and in coal; and these are reduced in the blast furnace, when a varying part of the sulphur combines with the iron, in which form it is very undesirable, if present in large amounts, on account of its injurious effects on steel and cast iron.

**Properties:** Sulphur is a brittle, yellow crystalline solid which melts at 114.5°, forming a straw colored liquid. It is allotropic, i. e., can exist in different physical forms. These forms are prismatic, rhombic and amorphous. When heated to a sufficiently high temperature, it combines with oxygen to form sulphur dioxide, $SO_2$, with iron to form ferrous sulphide, FeS, and with most of the metals, forming sulphides. The sulphur in iron or steel is in the forms of FeS and MnS, distributed almost uniformly throughout the metal while in the molten state. Upon solidifying, however, owing to the difference in density and fusion temperature between these compounds and the metal, they may, under normal conditions, segregate to some extent, causing some parts of the solidified mass to show a higher content of this impurity than the average, or of the whole in the molten state. With hydrogen it forms a gas, hydrogen sulphide, $H_2S$,—very important in Chemistry.

**Uses:** Sulphur is used in the manufacture of matches and black gun powder, also for disinfecting purposes and for vulcanizing rubber. Its chief use, however, is in the manufacture of sulphuric acid; and the amount of this acid consumed by a nation is a measure of its scientific advancement.

**Compounds:** Besides compounds already mentioned, sulphur forms several acids, one of which, sulphuric acid, $H_2O \cdot SO_3$ ($H_2SO_4$) is a most important compound. It is obtained by oxidizing sulphur dioxide, $SO_2$, which is given off as a gas from the roasting of $FeS_2$, ZnS, CuS, and from the burning of sulphur.

### Carbon.

**Occurrence:** This element occurs free in nature in crystalline forms as diamonds and graphite and in the amorphous form as coal. It is the chief constituent of the bodies of plants and animals, of all natural fuels, and of nearly all prepared fuels. It occurs in combined state in limestone, magnesite, marble and other carbonate rocks.

**Properties:** Carbon is allotropic; diamond and graphite have been mentioned. The common amorphorous forms are coal, lampblack, charcoal, coke, bone black and gas carbon. Its density varies with its form.

**Compounds and Uses:** Carbon forms many compounds with hydrogen, called hydrocarbons, as methane $CH_4$, ethylene $C_2H_4$, benzene $C_6H_6$, acetylene $C_2H_2$, each of which is but the first member of a series of related compounds. With oxygen it forms carbon dioxide, $CO_2$ which is a product of combustion and of respiration. $CO_2$ is also given off when carbonates, such as limestone, are heated. The reaction is, $CaCO_3 = CaO + CO_2$. Carbon monoxide is formed in combustion when the supply of oxygen is insufficient for the formation of $CO_2$. Thus, in the blast furnace, a fixed amount of air is blown against an excess of hot carbon, which act results in this reaction: $2C + O_2 = 2CO$. Owing to its tendency to combine with oxygen, forming $CO_2$, CO is a good reducing agent. So, the CO formed before the tuyeres of the blast furnace reacts with the iron oxide thus:

$$3\,CO + Fe_2O_3 = 3CO_2 + 2\,Fe.$$

Carbon alone acts as a reducing agent in the metallurgy of iron.

$$3C + Fe_2O_3 = 2\,Fe + 3\,CO.$$

Iron forms a carbide with carbon, the formula of which is $Fe_3C$. In pig iron it is also found uncombined in the form of tiny flakes of graphite, hence the term graphitic carbon. Carbon has a marked effect upon iron. The varying properties of steel and the many uses to which it can be applied are due largely to the influence of this element. Carbon in steel, then, up to a certain limit, is not to be considered as an impurity but as an essential factor.

## Silicon.

**Occurrence:** Next to oxygen, silicon is the most abundant element in nature. It is the most important constituent of the mineral part of the earth. Sea sand, quartz, jasper, opal and infusorial earths are almost pure forms of $SiO_2$. As silicates, it occurs in clay, mica, talc, hornblend and feldspar. On account of its wide distribution it forms the chief impurity of iron ore, as well as of nearly all natural mineral deposits.

**Compounds:** As already indicated silica, $SiO_2$, is one of the chief compounds of silicon. It also forms several acids, chief of which is silicic acid, $2H_2O.SiO_2$ ($H_4SiO_4$) which loses water when heated and forms $SiO_2$.

$$H_4SiO_4 = SiO_2 + 2H_2O.$$

Thus, in whatever form silicon may occur in an ore, it is looked upon as $SiO_2$. This substance is the great acid of dry chemistry and at high temperatures will neutralize any base with which it comes in contact. In the blast furnace some of the silica ($SiO_2$) contained in the charge is reduced to silicon. The amount so reduced varies with the working conditions of the the furnace, mainly the temperature. Once reduced, the silicon alloys with the iron and becomes a part of the metallic bath. All but traces of this silicon is re-oxidized and removed in the various processes of making steel. However, a little is beneficial to steel, so it is sometimes added in small amounts in the form of an iron alloy.

### Nitrogen.

**Occurrence and Properties:** This element occurs in niter beds as saltpeter, $KNO_3$, and Chili saltpeter, $NaNO_3$, also in organic compounds and in coal. It is an odorless, tasteless, colorless gas that constitutes about 78% of the atmosphere.

**Compounds:** With hydrogen it forms ammonia, $NH_3$; with oxygen a series of oxides, $N_2O$, $NO$, $N_2O_3$, $N_2O_5$ and $NO_2$; and with hydrogen and oxygen, an important acid, $H_2O{\cdot}N_2O_5$ ($HNO_3$). It is a very inert element and has very slight effects in the manufacture of steel. Nevertheless, its presence in the air in so large amounts makes it an important factor in blast furnace practice.

### Phosphorus.

**Occurrence:** Phosphorus, always combined with other elements, occurs widely distributed in limited amounts, particularly in soils. It is, therefore, found in all iron ores. It occurs in deposits as phosphorite and apatite, and is an important constituent of bone.

**Properties and Compounds:** While phosphorus belongs in the same group of elements as nitrogen, it does not much resemble it from a physical standpoint. It is allotropic and exists in two forms, as a pale yellow solid that melts readily at the low temperature of 44.1°C, and as a red form quite different in properties. While it is a much more active element, it closely resembles nitrogen chemically. It forms compounds with hydrogen and oxygen, such as $PH_3$ and $P_2O_5$, and an acid, $H_2O.P_2O_5$ ($HPO_3$), called metaphosphoric acid. It generally is found in nature as salts of orthophosphoric, $3H_2O.P_2O_5$ ($H_3PO_4$), and pyrophosphoric, $2H_2O.P_2O_5$ ($H_4P_2O_7$), acids. With iron it forms a phosphide, $Fe_3P$. It is completely reduced in the blast furnace, hence all the phosphorus occurring in the raw materials is found in the pig iron. In steel it is a very undesirable impurity, but fortunately it is oxidized readily, when it can be neutralized with lime and easily removed as part of a slag.

### Calcium and Magnesium.

While these two elements belong to different groups, they are very similar so far as the manufacture of iron and steel are concerned. With few exceptions one may be substituted for the other without great inconvenience. Their oxides are the more important bases of dry chemistry.

**Occurrence and Chief Compounds:** Both elements occur as insoluble carbonates; limestone, marble, chalk and marl are forms of calcium carbonate, $CaO.CO_2$ ($CaCO_3$). Magnesite is magnesium carbonate, $MgCO_3$. When heated, both these compounds decompose into the oxides and carbon dioxide, thus:

$$CaCO_3 = CaO + CO_2.$$
$$MgCO_3 = MgO + CO_2.$$

CaO represents quick lime, and MgO, magnesia.

These elements also occur together as a double salt of carbonic acid, calcium magnesium carbonate, $CaMg(CO_3)_2$, commonly called dolomite, which gives calcium magnesium oxide $CaO \cdot MgO$ when calcined.

$$CaMg(CO_3)_2 = CaO \cdot MgO + 2\,CO_2.$$

**Uses of Lime and Magnesia:** Lime, $CaO$, Magnesia, $MgO$, and the double oxide, $CaO \cdot MgO$, are all very refractory. But on account of its tendency to slake in air, $CaO$ is not used as such. Practically, $MgO$ is the best basic refractory known, and calcined dolomite is the best available substitute.

The oxides are reduced with difficulty, and on account of their cheapness constitute the principal basic fluxes. As $MgO$ is the leading basic refractory, $CaO$ is the leading basic flux. It combines with both silica and phosphoric acid to form readily fusible slags, which have a lower density than iron and consequently lie upon the surface of the metallic bath.

## Aluminum.

**Occurrence and Properties:** This element in combined form is very widely distributed, occurring as one of the constituents of feldspar, granite, mica, cryolite, and all clays. It is reduced from the oxide, $Al_2O_3$, by an electrolytic process, in which state it is applied to many uses. It has a strong affinity for oxygen, violently reducing iron oxide, and on this account it is added to steel as a deoxidizing agent.

**Compounds:** In its compounds aluminum displays decidedly basic properties, forming salts with all the common acids except carbonic acid. It forms neither a carbonate nor a sulphide. Aluminum hydroxide, $Al(OH)_3$, however, acts like both an acid and a base. When this compound is heated, it loses water and forms alumina, $Al_2O_3$. It is found in varying amounts in all the raw materials that enter into the metallurgy of iron. In the blast furnace it is never reduced. Its presence, however, has a marked influence on the slag, affecting its fluidity and fusion temperature, important considerations in blast furnace practice. In its purer states alumina is a good refractory, but its scarcity prohibits its extensive use as such.

## Chromium.

**Occurrence:** This element is somewhat rare. In small deposits it is found as chromite, $Cr_2O_3 \cdot FeO$. This substance is the best neutral refractory known. In its purer states it melts at about 2175°C.

**Properties and Uses:** Chromium is both acid and basic in character. It is very important in the manufacture of alloy, or special steels. Its chief effect is one of hardening, hence it is employed to increase the hardness of projectiles, armor plate, automobile steel, and tool steels.

### Manganese.

**Occurrence:** This element occurs in nature as $MnO_2$, its deposits being somewhat limited in the United States. In very small amounts it is widely distributed, and is found in nearly all raw materials of iron manufacture. About 75% of this manganese is reduced in the blast furnace, so it is a constituent of all pig iron. But it is readily oxidized in the purifying processes, and except for almost traces, that found in steel is added to it in the process of manufacture. Its effect in steel up to 1.0% is good, because it offsets the evil effects of oxygen and sulphur. Higher percentages, 7% to 15%, are employed to produce the special steel known as manganese steel.

### Iron.

**Occurrence:** This most important metal occurs in combined states and, in slight amounts, in nearly all earthy matter, as clays, soils, sands, etc. In deposits, it is found as the sulphide, $FeS_2$, as silicates, as a constituent of chromite, as the carbonate, $FeCO_3$, and as the oxides, $Fe_2O_3$ and $Fe_3O_4$. The compound last named is magnetic.

**Properties:** Pure iron, almost unknown, is somewhat unlike the ordinary commercial forms. It is grayish-white in color and relatively soft when compared with steel of high carbon content. It is malleable, ductile, and magnetic. Its specific gravity is 7.78, and its melting point in its purest commercial form is about 1520 °C. The presence of certain elements, notably carbon, silicon, phosphorus or sulphur, in the metal lowers the melting point rapidly.

**Compounds:** Iron forms two series of compounds, the ferrous and the ferric. The more important ferrous compounds are $FeO$, $Fe(OH)_2$, $FeCl_2$, $FeSO_4 \cdot 7H_2O$; corresponding ferric compounds are $Fe_2O_3$, $Fe(OH)_3$, $FeCl_3$, $Fe_2(SO_4)_3$. Most of these compounds are of the highest commercial importance, and many will receive much fuller treatment as this course advances.

# CHAPTER II.

# REFRACTORIES.

## SECTION I.

### NATURE OF REFRACTORIES.

**Importance:** The problem of obtaining refractories suitable for each particular operation is one of supreme importance in the metallurgical arts, especially in the manufacture of steel. They form the chief materials of which all furnaces and retaining vessels are made, as well as flues and stacks through which hot gases are conducted. This equipment is expensive, and any failure in the refractories results in a great loss of time, equipment and product, and, too often, in loss of life as well.

**Requirements of Refractories:** A refractory may be defined as any substance which is infusible at the highest temperature it may be required to withstand in service. In any particular application however, this definition is incomplete, because the fact that a substance is infusible does not alone determine its value as a refractory. An almost infusible brick, for example may be so fragile as to be worthless, since bricks are generally required to support a load in addition to resisting the effects of great heat. A perfect refractory would meet the following requirements at any temperature: (1) it would not fuse or soften; (2), it would not crumble or crack; (3), its contraction and expansion would be the minimum; (4), it would not conduct heat; (5), it would be impermeable to gases and liquids; (6), it would resist mechanical abrasion; (7), it would not react chemically with substances in contact with it. Needless to say, an absolutely perfect refractory has never been discovered. However, there are a number of substances which closely approach the first six requirements, at temperatures commonly employed in metallurgical work, and whether or not they will meet the seventh depends upon their chemical composition and the nature of the substances with which they are in contact.

**Classes of Refractories:** Refractory substances, in common with matter in general, are of three classes: namely, acid, basic and neutral. Recalling the chemical action of acids and bases toward each other, it is at once apparent that a refractory of an acid character is useless in contact with a basic slag, and vice versa. In selecting a refractory for a specific purpose, the first question to be decided is what class of refractory will be required. Other factors affecting its life and usefulness are the amount of impurities it contains and the uniformity of its composition; and, in the case of brick, to these will be added strength, toughness, porosity, or other special qualities. In the manufacture of prepared refractories these factors are all under control, depending upon the selection of materials and the method of manufacture.

## SECTION II.

### ACID REFRACTORIES.

**Chemical Composition:** Acid refractories owe their acid character only to silica, $SiO_2$, and are of two kinds, namely, those composed mainly of silica and those composed of aluminum silicate, or clay. In the pure state silica fuses at a very high temperature, about 1830° C, a temperature much above that obtained in ordinary furnaces, but when heated in contact with basic substances it forms silicates, some of which are easily fused. Hence, in refractories composed of silica the presence of impurities, alumina as well as the stronger bases, must be guarded against. As a refractory, silica is used in the natural forms of sand and cut stone and in the prepared form of brick. Sand (90%to 99.5% $SiO_2$) is used to make up the bottoms of acid open hearth furnaces and of some types of heating furnaces. Ganister, a very superior material for lining converters, is a highly silicious rock. It has a silica content of about 98%.

**Silica Bricks** are prepared from quartzite rock found in Pennsylvania, Wisconsin and Alabama. The rock is first crushed fine, then intimately mixed with a binding material which acts as a cement to hold the particles of silica together and to give the brick the necessary strength. For this purpose either clay or lime, usually in the form of milk of lime, is used, the former to produce quartzite brick and the latter, "silica" or ganister brick. The mixture, in a moist condition, is next compressed and moulded into the shape desired for the bricks, which are allowed to dry slowly and then are burned at high temperatures,about 1500° C.,in large kilns. From seven to ten days are required to complete the burning. Silica brick expands slightly when heated.

**Clay** is a natural occurring earthy material which has the property of plasticity when wet but becomes hard when burned. The ordinary varieties are more or less impure silicates of aluminum, formed by the decomposition, or weathering, of feldspathic rock, and contain high percentages (10% to 15%) of combined water. They may be residual or sedimentary. Fire clays are of two varieties, known as plastic and flint clays; the latter is very hard, even when ground, but very refractory. The most refractory clays are associated with the coal measures of Pennsylvania.

**The impurities in clays** are alkalies, due to undecomposed feldspar; sand; gravel; iron oxide, silicate or sulphide; calcium and magnesium silicates or carbonates; titania; and organic matter. Of these impurities, the basic oxides are the most harmful, as they lower the fusion point decidedly. This is due to the fact that aluminum silicate combines with bases, forming double silicates.

**The process of making fire clay brick** is similar to that for silica brick. The clay, in a finely crushed condition, is moistened with a definite amount of water and thoroughly mixed. When flint clay is being used, some plastic clay is used as a binder. Upon being dried, clay begins to shrink and continues to do so during the burning, when the combined water is driven off and the brick becomes hard. Thus, a brick, 9 inches in length after being burned, may measure from 9½ to 9¾ inches when moulded, depending on the mixture used. Calcined, or burnt clay is employed in the mixtures to control the shrinkage. Once burned, the brick ceases to shrink and permanently loses the property of plasticity, which latter fact would indicate that the plasticity is due to combined water. The refractory properties of a brick depend upon the nature and amount of impurities and the ratio of silica to alumina. Besides its use as brick, clay is important as a refractory mortar to be used in laying bricks in furnaces and ladles, and as plaster where seamless linings are required.

## SECTION III.

### BASIC REFRACTORIES.

**Magnesia**, with a melting point of 2165°C is, for practical purposes, the most satisfactory basic refractory. It is prepared by calcining the mineral magnesite, a natural carbonate of magnesium. Large deposits are somewhat rare. In this country very pure deposits had long been known to exist in the states of California and Washington, but up to the outbreak of the World War the entire supply was obtained from Austria and Hungary. Now, however, the demand is supplied almost wholly from the State of Washington. For this reason it is an expensive material, which fact accounts for its not being used except where a basic substance of the highest refractoriness is required. It makes an ideal brick for the construction of basic furnaces, and is used for the inner courses of bottoms and walls to slightly above the slag line. In a coarsely crushed form, described as pea size, it is very desirable material for making up bottoms in basic furnaces, as, mixed with a small percentage of basic cinder, it is readily fritted, forming a solid mass that resists chemical and mechanical action of the charge and the buoyant force of the bath.

**Lime** is even more refractory than magnesia, resisting the intense heat of the oxyhydrogen flame, but on account of its slaking properties it is of little practical value as a refractory. Mixed with magnesia it gives satisfactory results.

**Dolomite,** fortunately, furnishes such a mixture and occurs in this country in abundant quantities. Upon calcining the mineral, a mixture of lime and magnesia in the best proportions is obtained. It cannot be fritted on a bottom as well as magnesite, and the lime content fastens upon it a tendency to slake. In the steel industry it is used chiefly for making up the banks of basic open hearth furnaces.

**Bauxite** is a natural form of the sesquioxide of aluminum, mixed with varying amounts of earthy matter and the corresponding oxide of iron. It usually contains one per cent. or more of titania, $TiO_2$. It is but feebly basic and, when free from silica, is highly refractory. In pure form alumina melts at 2010°C., but the fusion temperature of the natural bauxite will seldom exceed 1820°C. Recent trials indicate that it may prove to be an excellent lining material, but its scarcity precludes its general use.

## SECTION IV.

### NEUTRAL REFRACTORIES.

**The Ideal Furnace Lining** is a neutral material, a substance that will permit of changing from acid to basic, or basic to acid, processes on the same lining. Two such substances are well known, but unfortunately the conditions of natural deposits will not permit of their use except in restricted quantities. These, are graphite and chromite.

**Graphite:** This substance is a natural product, though it can be prepared artifically in small quantities. It occurs mixed with calcareous or silicious rocks in Ceylon, Siberia, Austria, England, Brazil and New York. It requires expensive purification. It is infusible even at the temperature of the electric arc, but burns rapidly at that temperature, forming CO or $CO_2$. At the temperature of the open hearth it would be very slowly consumed. It is used in making special brick, crucibles, etc. Clay may be used as a binding material.

**Chromite** most nearly approaches the ideal refractory. Experience proves it to give equally satisfactory results in either an acid or a basic process. Its fusion point, about 2180°C., is far above the highest working temperature of the open hearth or blast furnace. It is difficult to set or sinter. In a finely ground condition and mixed with the proper proportion of slag also finely ground, it is used regularly in the open hearth to daub ports and jambs and patch walls near the slag line. In the form of brick it is used as dividing courses to separate acid from basic bricks, and in the bottoms of soaking pits, because it is impervious to pit cinder. The binding material for chromite brick is lime, or clay and lime.

**Protection for Refractories:** The fusion temperature of the materials discussed is amply high to withstand the temperatures of carbon heated furnaces, if resistance to heat were the only requirement. But the refractory must possess strength, resistance to abrasion and corrosion, etc., and as these properties decrease rapidly with increase of temperature, it is desirable, in some cases necessary, to protect them as much as possible from the heat. This end is accomplished by backing the brick work with hollow metal forms through which water is kept constantly flowing. These forms are made of cast iron, steel, copper, or bronze, depending upon their use and position in the furnace, and may be in the shape of coiled pipes, hollow boxes, or sprayed jackets. As this course progresses, these devices will be frequently met with and their value demonstrated.

For purposes of comparison typical analyses of the various refractories will be found in the following table:

**Table 3. Chemical Analyses of Refractories.**

| NAME | PERCENT OF | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Silica | Iron Oxides | | Alumina | Lime | Magnesia | Soda | Potash | Water | Titania | Chromic Oxide | Manganese Oxide | Carbon |
| | $SiO_2$ | $Fe_2O_3$ | FeO | $Al_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | $H_2O$ | $TiO_2$ | $Cr_2O_3$ | MnO | C |
| Ganister | 98.20 | .30 | ..... | .90 | .15 | .10 | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| Low Grade Silica Sand.. | 91.60 | 3.48 | ..... | 3.68 | .10 | .05 | Trace | Trace | ..... | ..... | ..... | ..... | ..... |
| High Grade Silica Sand.. | 99.25 | .31 | ..... | .20 | Trace | Trace | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| Silica Brick... | 96.42 | .50 | ..... | .75 | 2.01 | .08 | ..... | ..... | ..... | .06 | ..... | ..... | ..... |
| Low Grade Fire Clay.... | 60.50 | 2.35 | .40 | 24.95 | .25 | .05 | .15 | ..... | 10.00 | 1.40 | ..... | ..... | ..... |
| High Grade Fire Clay.... | 50.35 | .75 | ..... | 33.65 | .10 | .05 | .10 | .40 | 13.75 | .80 | ..... | ..... | ..... |
| Low Grade Fire Clay Brick... | 61.72 | 6.43 | ..... | 28.70 | .46 | 1.04 | .05 | .05 | ..... | 1.60 | ..... | ..... | ..... |
| High Grade Fire Clay Brick... | 53.52 | 2.00 | ..... | 41.00 | .30 | .30 | .90 | .20 | ..... | 1.60 | ..... | ..... | ..... |
| Calcined Magnesite... | 3.96 | 5.81 | ..... | 1.95 | .40 | 87.45 | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| Calcined Dolomite.... | 1.66 | .94 | ..... | 1.24 | 55.01 | 38.26 | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| Bauxite....... | 4.10 | 3.20 | ..... | 60.80 | .04 | .04 | .10 | ..... | 30.08 | 1.62 | ..... | ..... | ..... |
| Bauxite Brick.. | 8.82 | 6.30 | ..... | 78.01 | .98 | 4.41 | ..... | ..... | ..... | 1.16 | ..... | ..... | ..... |
| Chromite...... | 9.36 | ..... | 13.50 | 10.60 | Trace | 21.06 | ..... | ..... | ..... | ..... | 43.97 | .80 | ..... |
| Artificial (Coke—tar) Graphite.... | 5.95 | ..... | 2.15 | 3.04 | .43 | .20 | ..... | ..... | ..... | ..... | ..... | ..... | 88.20 |
| Natural Graphite Brick...... | 13.04 | ..... | .44 | 6.12 | ..... | ..... | ..... | .43 | 1.95 | ..... | ..... | ..... | 77.80 |

## SECTION V.

### TESTING REFRACTORIES.

**Trial Tests and Laboratory Tests:** The best test for a refractory is a trial test in which the material is placed in actual service under the most trying conditions it will be expected to stand up under. As such tests can seldom be made on material for new work and as there may be considerable variation in raw materials and in methods of manufacture, laboratory tests are necessary. Such tests are not always conclusive, owing to the difficulty of obtaining laboratory conditions identical to those in actual practice. They are, however, very useful for the purpose of comparisons, and, if the conditions of the tests are sufficiently severe, the more serious defects will be revealed. These tests are chemical and physical. From the chemical analysis the composition of the material is determined and its quality is judged. As the method of manufacture and the care with which it is carried out affect the properties of the refractory, the chemical test should be, and usually is, supplemented by physical tests. Chief among these tests are the fusion or softening point, crushing strength, expansion and contraction, slagging, porosity, density, resistance to compression, impact, abrasion and spalling tests. Each of these tests may be made in a comparatively simple manner, but care and judgment are required to see that the conditions of the tests conform closely with those to which the brick are to be subjected in actual service. On this account some of the tests usually employed will not be applicable to the iron and steel industry, while others must be modified to conform to its conditions. The tests here described are those particularly suited to this industry.[1]

**The fusion temperature,** in ordinary practice, is usually determined by means of Seger cones. These are small triangular pyramids, 6 cm. high, with a base of 2 cm. They are composed of aluminum silicates. Cone number 28 contains ten parts silica to one part alumina and corresponds to a temperature of 1630° C. The fusion temperatures of succeeding cones up to number 40, which corresponds to a temperature of 1920° C, are increased by decreasing the proportion of silica to alumina. For lower temperatures varying amounts of alkali or lime are added. By this means the melting point is so controlled, that a series of cones may be prepared with melting points between the limits of 500° and 1900°. Upon being gradually heated to a sufficiently high temperature, these cones will soften and slowly bend until their tops touch the floor, which point is taken as their fusion point. In making a test, a pyramid of the material to be tested, having the same shape and dimensions as the standards, is placed in a furnace with two or more standards having melting points estimated to be near that of the material to be tested. As the temperature of the furnace is raised, the standard cone that melts at the same time as the test will register the temperature of the fur-

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[1] See Practical Methods for Testing Refractory Fire Brick by C. E. Nesbitt and M. L. Bell. Proceedings of the American Society for Testing Materials. Vol. XVII, 1916.

nace and the fusion point of the test. The softening temperature is considered to be that at which the specimen bends, sags or puffs out of shape. Instead of the standard cone, the more accurate pyrometer is coming into use for making this test.

**Resistance to Compression:** The ability of brick to withstand pressure at a high temperature is a very important property. This test is made on a modified form of Brinell ball testing machine. The ball is made of steel and is 2½ inches in diameter. In making this test, the brick is uniformly and slowly heated from atmosphoric temperature to 1350° and held in the furnace at this temperature for three hours or longer, when it is removed and placed flat under the ball of the machine, and a pressure of 850 lbs. is immediately applied, which is gradually and uniformly increased at such a rate that a maximum load of 1600 lbs. is attained at the end of five minutes. The depth of the depression made by the ball is taken as the measurement of the resistance of the brick to compression.

**Expansion and Contraction:** A brick must be prepared for this test by grinding the ends so that they will be parallel to each other and at right angles to the sides. Its length is then measured by means of a specially constructed micrometer. The brick is next heated to the temperature at which it is to be used, removed from the furnace and immediately measured. The expansion or contraction is expressed in inches per lineal foot.

**Slagging Test:** By this test the impermeability of the brick to molten slag is determined. The brick is prepared by drilling two circular cavities, 2½ inches in diameter, each at the intersection of the diagonals of the rectangles formed by bisecting transversely the unbranded face of the brick, to such a depth that the area of the greatest cross section is 1.7 inches. The brick is then heated as in the compression test. When the temperature has reached 1350°, 35 grams of a standard blast furnace slag is placed in one cavity and 35 grams of a standard heating furnace slag in the other. Both slags are pulverized to pass a 40 mesh sieve. The temperature of 1350° is maintained for two hours after the slag is added, at the end of which time the brick is removed from the furnace and, when cold, sawed lengthwise so as to bisect both cavities, thus exposing the part of the brick subject to slag penetration. The area penetrated by the slag is measured with a planimeter and expressed in square inches.

**Density:** The density is determined from the weight of the brick in air and its dimensions. This method gives the apparent specific gravity. This test is greatly influenced by the method of manufacture, being affected by both the amount of water used in pugging and the pressure in moulding. While in manufacturing practice the amount of water added is determined by the plasticity of the clay, investigations have shown that the moisture content should be about 8% and the pressure about 1500 lbs. per square inch to secure the greatest density.

**The Impact Test:** This test is important in the case of brick to be used in blast furnace tops, where they are subject to much impact from lumps of ore, stone, and coke in charging. The test is greatly affected by temperature. A brick heated to 260°C. was found to be 20% weaker than one of the same brand tested at 20°C., and 40% weaker when tested at 540°C. In carrying out the test, the brick is first heated from atmospheric temperature to 260°C., the temperature being raised gradually through a period of one hour. The brick is then placed end up in a machine, by means of which a steel ball 2½ inches in diameter and weighing 2.34 lbs. is dropped upon the longest axis of the brick from heights successively increasing by two inches until the brick breaks. The height in inches of the ball in the last test is taken as the measure of the resistance of the brick to impact.

**The Abrasion Test:** This test aims to determine the wearing qualities of the brick at the temperature to which it is subjected in actual service. The brick is heated to the required temperature, and its end then pressed against a carborundum wheel for a given time and with a fixed pressure. The brick must be ground to uniform thickness and a preliminary cut made, so the wheel will cut through the entire thickness from the beginning of the test. The depth of the cut made on the hot brick measures the abrasion. It is obvious that the test will be affected by the width of the cutting wheel, the speed at which it revolves, also the grade and grit of the carborundum, all of which must be fixed and constant.

**Spalling Test:** Spalling in a brick is usually produced by temperature changes, often accelerated by mechanical pressure. The drawbacks with this test are the fact that it must be made much more severe than the conditions of actual service and that it concerns the brick only as made, thus neglecting the effect of slag penetration and the resulting vitrification that often causes brick to spall in service. The test is usually made on several bricks. The bricks are dried at 100° C. for 5 hours or more, weighed, and then placed in the door of a furnace, heated to 1350° C., so that one end only is exposed to the interior heat of the furnace. The remainder of the door space, if any, is then filled with other brick. After heating for one hour at this temperature the bricks are removed, and each one is immediately plunged into two gallons of water at 20° C. to a depth of four inches and held there for three minutes. It is then withdrawn from the water, allowed to dry three minutes, and returned to the furnace as before. This operation is repeated until the bricks have been plunged ten times, when they are dried at 100° C. for five hours or more and again weighed. The percentage of loss in weight, which is taken as a measure of the spalling, is claculated from the original weight.

## CHAPTER III.

## IRON ORES.

### SECTION I.

### ORES AND THE IRON BEARING MINERALS.

**Minerals and Ores:** Any homogeneous inorganic substance that occurs naturally in the solid state is called a mineral. A mineral, therefore, may be either an element or a compound. While a few elements, like gold and platinum, occur for the most part native, and others, like silver, copper, mercury, sulphur and carbon, may be found both native and combined, most minerals, of which some 800 varieties have been discovered and named, such as quartz, feldspar, hematite, hornblende, calcite, mica, etc., or their species, represent definite chemical compounds. Owing to the many forces that are constantly at work in nature and the wide distribution of some of the minerals, it is seldom a deposit consisting of but a single mineral is encountered. It is of such natural deposits that the ores are constituted. In general, then, an ore is defined as a mineral or a mixture of minerals from which one or more elements may be extracted with profit.

**The Iron Bearing Minerals:** While there is a vast number of mineral species that contain iron, there are only a few that are of any importance commercially, because, in most cases, either the iron content is too low to justify the extraction of the metal or the mineral itself does not occur in sufficient abundance to make it available for use as an ore. Grouped according to their chemical composition, the iron bearing minerals of chief importance are divided into four classes; namely, the iron oxides, iron carbonates, iron silicates, and iron sulphides. Of these, only the first class may be considered as a factor in the manufacture of steel in the United States. These oxides go to form a large number of minerals, which have been grouped and named as shown in the following table:

**Table 4. Chief Iron Bearing Minerals.**

| Chemical Name | Mineralogical Name. |
|---|---|
| 1. Ferroso-ferric Oxide | Magnetite |
| 2. Anhydrous Ferric Oxide | Hematite |
| 3. Hydrous Ferric Oxides | Limonite and others |
| 4. Ferrous Carbonate | Siderite |
| 5. Iron Silicates | Chloropal and others |
| 6. Iron Sulphides | Pyrite and others |

**Magnetite Group:** The only important mineral of this group is magnetite, chemical formula $Fe_3O_4$, composed of iron, 72.4%, and oxygen, 27.6%. The mineral is found in Arkansas, Pennsylvania, New Jersey, and New York. It varies in color from gray to black, has a specific gravity of about 5.0, and is magnetic. This last named property is taken advantage of in locating ore bodies below the surface of the ground and in mechanically purifying ores of this group by magnetic concentration. It is often found closely associated with igneous rocks, when it is apt to contain appreciable amounts of chromium or titanium oxides which cannot be removed from it by magnetic concentration. The remaining magnetic ores of the United States are, for the most part, of a low grade and require dressing, but the magnetite ores of Sweden represent the purest ores in the world and are of a grade approaching that of the pure mineral.

**Hematite Group:** The typical mineral of this group is hematite, which contains the equivalent of 70% metallic iron, based on the chemical formula $Fe_2O_3$. It furnishes the base of the world's most important ores. Being associated with rocks of various geological periods, these ores occur widely distributed, and in a variety of forms, which differ greatly in their iron content. Many of these varieties are known, from their outstanding characteristic, as red hematite, specular hematite, oölitic hematite, fossil ore, etc.

**Limonite or Brown Ore Group:** The minerals of this group are all hydrous ferric oxides, and may be represented, as a group, by the general formula $m Fe_2O_3 \cdot n H_2O$. There are five of these minerals, and they have been named, in the order of their progressive increase in water content, turgite, $2Fe_2O_3 \cdot H_2O$; goethite, $Fe_2O_3 \cdot H_2O$; limonite, $2 Fe_2O_3 \cdot 3 H_2O$; xanthosiderite, $Fe_2O_3 \cdot 2 H_2O$; and limnite, $Fe_2O_3 \cdot 3 H_2O$. On a theoretical basis the iron content of this series will vary from 52.31% to 66.31%. These minerals are widely distributed throughout the United States. In southern Virginia they make up the greater part of the available ores, all of which are low in iron content and high in silica.

**The Carbonate Group:** The representative member of this group is the mineral known as siderite, or iron carbonate, $FeCO_3$, which contains 43.8% of iron. Owing to the fact that carbonic acid is dibasic, a part of the iron required to neutralize it may be replaced by other metals, thus giving rise to a series of minerals, such as iron-calcium carbonate, iron-magnesium carbonate, etc. Some of the names commonly applied to these ores are spathic iron ore, kidney ore, blackband ore, etc. The ore deposits in which this group appears are of little commercial importance in the United States. In England they make up the ores of the Cleveland district. Usually, carbonate ores are calcined before they are charged into the blast furnace.

**The Mineralogical Make-up of Iron Ores:** As was indicated at the beginning, an ore deposit at best represents but a mixture of different minerals, only a part of which will contain the element or elements sought. All iron ores, then, may be looked upon as being made up of these two parts: One part is composed of the iron bearing minerals, which represent definite compounds of iron; the other part includes all the other substances mixed with these compounds, and is known as the gangue of the ore. Evidently, the richness of the ore, by which term is meant the proportion by weight of iron to all other elements in the ore, depends on the composition of the iron bearing minerals it contains and upon the amount of gangue associated with them. In working up the ores, their physical condition must also be taken into consideration. In this respect, they are subject to the widest variation, ranging from soft clay-like or earthy matter to hard compact masses. Both extremes tend to give trouble in the blast furnace. Thus, the soft fine ores are so apt to choke up a furnace, not designed to use them, that they were once considered practically worthless. The successful smelting of these ores represents one of the great achievements of American furnacemen. One objection to very fine ores, and one that has not yet been overcome, is that they give rise to large amounts of flue dust, which interferes seriously with the economical utilization of the furnace gases. On the other hand, the very hard and dense ores, which enter the furnace in the form of comparatively large lumps, are difficult to reduce and require an excessive amount of fuel.

## SECTION II.

### VALUATION OF ORES.

**Factors in the Valuation of Ores:** Omitting relative property valuations, prices of competitive ores, costs of transportation, and other considerations of a purely business nature, the chief factors that determine the value of an ore are its richness, its chemical composition and its accessibility. The richness of the ore will, of course, be made the basis for the valuation. For this purpose a unit system is employed, a unit of iron corresponding to one per cent. But the prices of ores do not rise and fall parallel with the number of units of iron they contain, because the gangue to be disposed of must also be considered. For example, suppose two hematite ores containing 63% and 42% iron are being considered. In the first, 90% of the ore is pure mineral, leaving only 10% as gangue to be disposed of, but the second represents only 60% pure mineral with 40% of its weight as gangue to be fluxed and transported. Next to richness comes the consideration of the chemical composition of the ore as a whole, for certain impurities, when present in only relatively small amounts, may make a rich ore worthless. Without taking the time to consider all the possibilities in this connection, the more common impurities in ore may be classed as follows:

1. **Those impurities that are never reduced in the blast furnace** and so do not affect the composition of the iron are alumina, $Al_2O_3$; lime, CaO; magnesia, MgO; and the alkalies, soda, ($Na_2O$), and potassia, ($K_2O$). All these substances, it will be observed, are strong bases, with the exception of alumina which may be either an acid or a base. Therefore, the presence of these substances in the ore may not be objectionable, for the lime and the magnesia, in particular, are valuable as fluxes. Alumina, also, up to about 5%, may play a useful part in regulating the blast furnace. The alkalies for the most part are driven off with the flue dust, and with modern appliances they may be recovered, when present in sufficient amount to justify the installation of the necessary apparatus, so that they may form a valuable by-product.

2. **Those impurities that may be partially reduced** in the furnace and give elements that enter the pig iron are silica, or the silicates, sulphates and manganese compounds. Of these, the silica, which term includes both the free silica and the silicates, constitutes a large part of the gangue of most ores, and as it requires an equal weight of lime or magnesia to flux it, it must be considered in fixing the value of an ore. Owing to the fact that the amount reduced in the blast furnace is subject to control to a considerable extent and that the element is readily removed during the process of purifying the pig iron, it is not considered of much importance from the standpoint of its effect on the steel produced from the iron. This attitude toward silica is just the opposite of that displayed toward the sulphur compounds. All these compounds are reduced in the furnace to sulphides, in which form the sulphur enters either the metal as ferrous or manganese sulphides or the slag as calcium sulphide. Now, there is a limit to the quantity of sulphur a given slag can absorb, the highest figures given being less than 5%, and, naturally enough, the nearer this limit is approached, the more difficult it becomes to keep the sulphur out of the metal. Since even comparatively small amounts of this element exert an evil influence in steel, and it can be removed from the metal only partially and with much difficulty, the importance of this element in fixing the value of an ore is evident. As to the manganese compounds, the amount of this element that enters the iron varies with the manganese content of the ore and takes place to the extent of nearly 75% of the manganese charged. The per cent. of this element is, therefore, considered in its relation to the iron content. An ore is available for the manufacture of the ordinary grades of pig iron when the manganese content does not exceed 2% of the iron content; between 2% and 10%, calculated on the same basis, it is necessary to mix the ore with others containing little of this element; but if the manganese content is 15% to 20% of the iron content, then the ore becomes available for the manufacture of spiegel.

3. **The impurities always reduced** in the furnace are all the compounds of phosphorus, which element enters the pig iron only. While this element is easily removed from the metal by basic processes, none at all is eliminated by the acid processes, with the result that acid steels contain a higher percentage of this element than the average of the charge from which the steel is produced. This element, therefore, is the basis for the separation of all ores into the two great classes, known as **Bessemer** and **basic.** This division, like that for manganese, is made on the basis of the relation of the phosphorus content to iron content of the ore. Since it is desirable to produce Bessemer steel that will contain not more than .100% of its weight as phosphorus, a true Bessemer ore would be one whose phosphorus content plus the phosphorus content of the coke and limestone required to smelt and flux it would produce a pig iron with a phosphorus content not exceeding .090%. Allowing 10% for conversion loss, such a pig iron would give a steel containing less than .100% of its weight of phosphorus. Commercially, however, since commercial tolerances usually permit the phosphorus in the steel to rise as high as .110%, no allowance is made for conversion, and a commercial Bessemer ore is one whose phosphorus content plus some arbitrary figure, usually about .015%, to allow for the phosphorus acquired from the flux and fuel, is less than one one-thousandth of its iron content. Thus, the per cent. of phosphorus in an ore containing 60 units of iron must be .045, or less, to be classed as a Bessemer ore, for 1/1000 of 60=.060 and .060—.015=.045. Another method for determining the grade of an ore is explained by the following example:

Question: To what class does an ore containing 60% iron and .045% phosphorus belong?

Solution:

045÷.60=.075=per cent. phosphorus in the pig iron, acquired from the ore.
.020=Estimated per cent. phos. in pig iron, acquired from coke and stone.
——
Ans. .095=per cent. phosphorus in the pig iron. Therefore, the ore is of Bessemer grade.

**Water** or moisture is another factor to be considered in the valuation of ores, because it adds to the weight of ore to be handled and transported. The importance of this matter in fixing the value of an ore is seen at once when it is pointed out that many of the soft ores of the Lake Superior region carry as much as 12% of their weight as hygroscopic water, and a few as much as, or more than, 15%. This moisture content for any particular ore is much more nearly constant under varying weather conditions than might be expected; but in the case of different ores there is a wide variation, ranging from .40% in some of the hard red hematites to 16.80% in a few of the soft red ores. These points are well illustrated by the table below, the examples in which have been selected because they show about the same iron content when dry.

**TABLE 5. Analyses of Ores Illustrating Dry and Wet Basis.**

| ORE | STATE | % Iron, Fe | % Phos, P. | % Silica $SiO_2$ | % Mang. Mn. | % Alumina, $Al_2O_3$ | % Lime, CaO | % Magnesia, MgO | % Sul. S. | % Ignition Loss | % Moisture, $H_2O$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A. (Marquette Range) | Dry | 57.36 | .137 | 15.62 | .08 | 1.26 | .68 | .33 | .007 | .03 | ..... |
| | Natural | 56.82 | .135 | 15.47 | .08 | 1.25 | .67 | .327 | .007 | .03 | .944 |
| B. (Missabe Range) | Dry | 57.03 | .042 | 12.48 | .56 | 1.69 | .21 | .32 | .010 | 2.80 | ..... |
| | Natural | 52.54 | .039 | 11.50 | .52 | 1.56 | .19 | .29 | .009 | 2.58 | 7.87 |
| C. (Missabe Range) | Dry | 57.06 | .081 | 7.33 | 1.72 | 1.00 | .30 | .40 | .010 | 2.00 | ..... |
| | Natural | 47.47 | .067 | 6.09 | 1.43 | .83 | .25 | .32 | .008 | 1.66 | 16.80 |

The marketing of the ores and all the metallurgical calculations involving them are based on the analyses of samples dried at 100°C. It will be observed that drying at this temperature may not drive off water of crystallization and that in the case of the brown hematites a much higher temperature than the drying temperature is required to drive off all the combined water.

**Accessibility;** It is evident that the economic importance of an ore deposit depends to a great extent upon its size and its location, both geologic and geographic. Thus, an ore that is very desirable from the standpoint of chemical composition and physical condition, may be so located as to be practically inaccessible; or granting it can be made accessible, the amount of ore in the deposit may not justify the expense of opening it up. On the other hand, a poor ore may be so conveniently located that it may be concentrated at a profit. A thorough discussion of this topic cannot be undertaken in the brief space allotted to this chapter. Suffice it to say, that the working of any ore body under modern conditions presents difficult engineering problems both in mining and in transportation. Perhaps the best way to impart some understanding of these problems is through a brief description of the ore mining operations of the Steel Corporation, itself. With the exception of the Tennessee Coal, Iron & Railroad Company, which obtains its ore from the Birmingham District in Alabama, all the constituent companies of the Corporation depend upon the Lake Superior district for their ore supply.

## SECTION III.

### THE BIRMINGHAM DISTRICT.

**Location and General Geology:** The Birmingham District includes the area from which the furnaces at Birmingham, Ensley, and Bessemer secure their iron ores, and is co-extensive with Birmingham Valley. This Valley extends from the City of Birmingham in both a northeast and southwest direction for a total length of about 75 miles and a width of about six miles. The ore, which is a variety of red hematite, occurs in the Clinton formation, which consists of shale, sandstone, iron ore, and a little ferruginous limestone. Geological researches conducted by the government[1] indicate that the ore was formed at the same time as the rocks with which it is associated. The valley lies within the area originally covered by this formation, which, therefore, occurs on both sides and dips away from it on each. But it is only in Red Mountain that the ore bed has been found of sufficient thickness and purity to justify its being worked on a large scale, and nearly all of the most productive mines are located in a section, about 62 miles long, of this mountain between Narrow Gap and Sparks Gap.

**Method of Mining:** All of the red ore mines in the Birmingham district were started as open cuts along the outcrop, and the product of these surface mines, having been leached, were at first soft ore. At a few points these simple mining operations are still carried on, but, owing to the dip of the ore beds, all mines from which any large quantity of ore has been taken are now completely underground and are operated by means of slopes or inclines. At these greater depths the ore is very hard and compact. On account of the fact that the southern portion of the ridge is overlaid by more recent formations, the ore gradually becomes more and more deeply buried on passing southward, and all the deepest slopes are in the strip of mountains south-west of Birmingham. The deepest slope at this southern extremity of the district extends downward on beds whose average dip is about 22°. The co-existance of the ore with limestone and the proximity of coal beds suitable for making coke give this district an advantage over other districts of the country. The ore contains phosphorus to the extent of about .8%, which is much higher than other basic ores of the country. By employing the duplex or the triplex processes in refining the pig iron, a slag with a high phosphorus content is produced that is available as fertilizer for agricultural use.

## SECTION IV.

### THE LAKE SUPERIOR DISTRICT.

**Importance, Location and General Geology:** During recent years the Lake Superior district has provided approximately four-fifths of the entire iron ore output of the United States, and there is nothing to indicate but that the region will, for many years to come, continue to be the nation's

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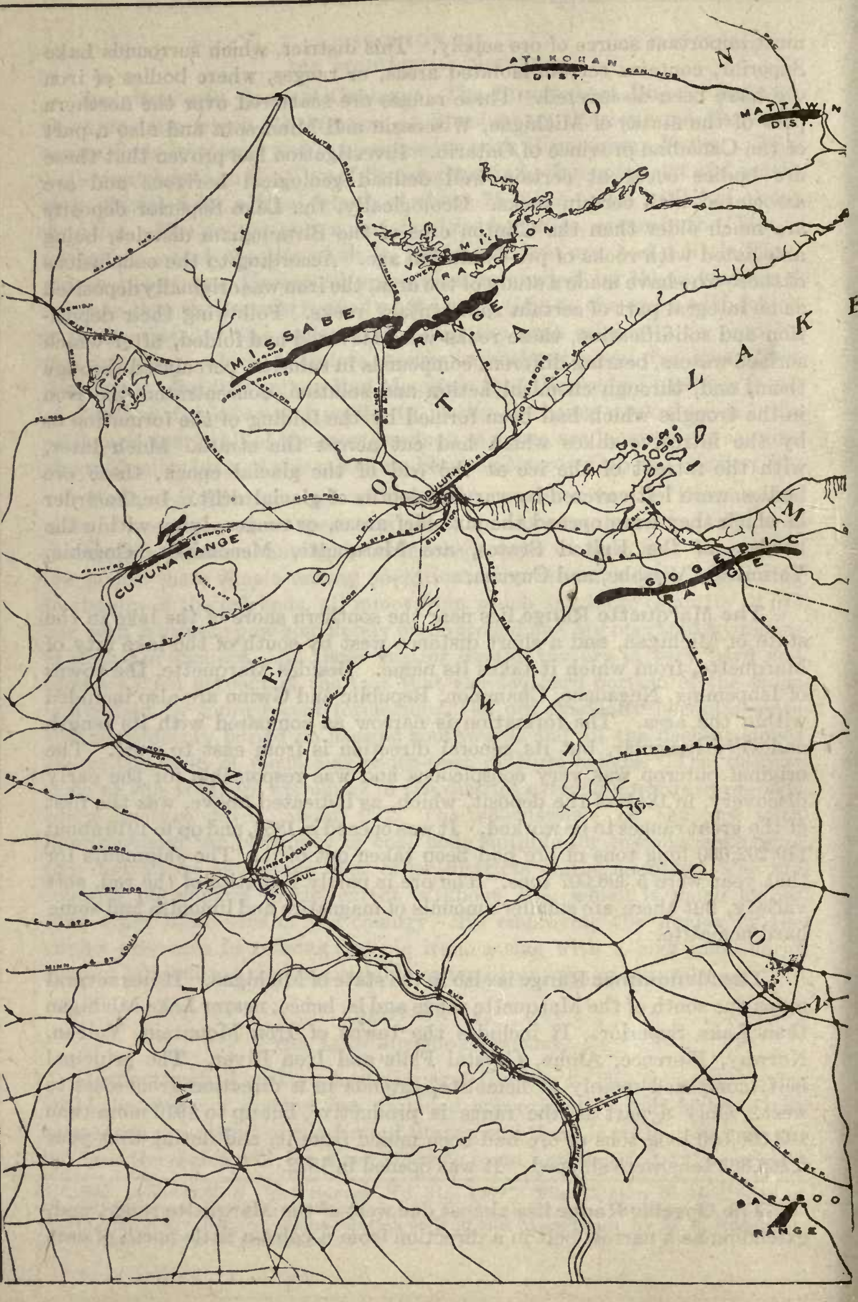
[1] Sec. Bulletin U. S. Geol. Survey No. 315, 1907. The Clinton or Red Ores of the Birmingham District, Alabama, by E. F. Burchard, also Bulletin U. S. Geol. Survey No. 340. Investigations relating to Iron and Manganese, by E. F. Burchard, A. C. Spencer, W. C. Phalen.

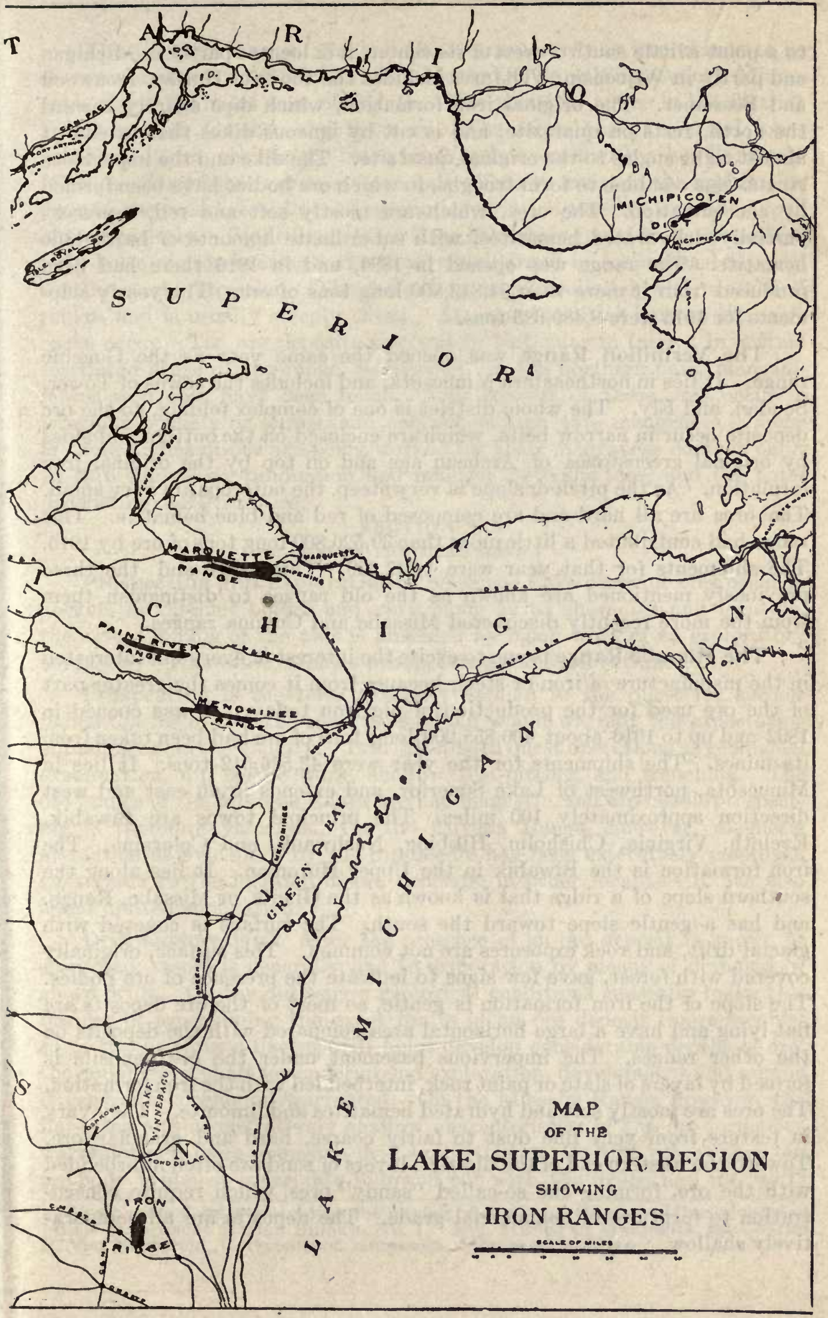
most important source of ore supply. This district, which surrounds Lake Superior, contains certain isolated areas, or ranges, where bodies of iron ore have been discovered. These ranges are scattered over the northern part of the states of Michigan, Wisconsin and Minnesota and also a part of the Canadian province of Ontario. Investigation has proven that these ore bodies occur at certain well defined geological horizons and are associated with certain rocks. Geologically, the Lake Superior deposits are much older than the Clinton ores of the Birmingham district, being associated with rocks of pre-Cambrian age. According to the conclusions of those who have made a study of the area, the iron was originally deposited as an integral part of certain sedimentary rocks. Following their deposition and solidification, these rocks were elevated and folded, after which surface waters, bearing different compounds in solution, percolated through them, and, through chemical action and solution, concentrated the iron in the troughs which had been formed by the folding of the formation or by the intrusive dikes which had cut across the strata. Much later, with the retreat of the ice at the end of the glacial epoch, these ore bodies were left covered by varying depths of glacial drift. In the order in which they were opened the six chief areas, or ranges, lying within the borders of the United States, are Marquette, Menominee, Gogebic, Vermilion, Missabe, and Cuyuna.

**The Marquette Range** lies near the southern shore of the lake in the state of Michigan, and a short distance west by south of the lake city of Marquette, from which it takes its name. Besides Marquette, the towns of Ishpeming, Negaunee, Champion, Republic and Gwinn are also included within the area. The formation is narrow as compared with its length and very irregular, but its general direction is from east to west. The original outcrop was very conspicuous and was responsible for the early discovery, in 1844, of the deposit, which, as indicated above, was the first of the great ranges to be worked. It was opened in 1854, and up to 1916 about 119,292,000 long tons of ore had been taken out of it. The shipments for that year were 5,396,007 tons. The ore is partly hematite of the red, soft variety, but there are smaller amounts of magnetite and limonite and some hard hematite.

**The Menominee Range** is also in the state of Michigan. It lies several miles due south of the Marquette range and is, hence, nearer Lake Michigan than Lake Superior. It includes the towns of Iron Mountain, Vulcan, Norway, Florence, Alpha, Crystal Falls and Iron River. The principal belt, composed mainly of hematite, extends in a direction from east to west. Only a part of the range is productive, but up to 1916 more than 103,600,000 long tons of ore had been mined from it, and during that year 6,365,363 tons were shipped. It was opened in 1872.

**The Gogebic Range** lies almost due west of the Marquette range, and, extending as a narrow belt in a direction from a point a little north of east


ATIKOKAN DIST.
MATTAWIN DIST.
VERMILION RANGE
TOWER
MISSABE RANGE
COLERAINE
GRAND RAPIDS
BEMIDJI
DEERWOOD
CUYUNA RANGE
TWO HARBORS
DULUTH
SUPERIOR
GOGEBIC RANGE
MINNEAPOLIS
ST. PAUL
BARABOO RANGE
MINNESOTA
WISCONSIN
ONTARIO
LAKE
MICHIGAN



MAP
OF THE
LAKE SUPERIOR REGION
SHOWING
IRON RANGES

to a point a little south of west of its center, it is located partly in Michigan and partly in Wisconsin. The area includes the towns of Hurley, Ironwood and Bessemer. The original iron formation, which dips sharply toward the north, rests on quartzite, and is cut by igneous dikes that extend at almost right angles to the original quartzite. The dike and the impervious strata thus combine to form troughs, in which ore bodies have been formed by concentration. The ores, which are mostly soft and red, represent partially dehydrated hematites, with subordinate amounts of hard, blue hematite. The range was opened in 1884, and in 1916 there had been produced from it more than 94,812,800 long tons of ore. The yearly shipments for 1916 were 8,489,685 tons.

**The Vermilion Range** was opened the same year as the Gogebic range. It lies in northeastern Minnesota, and includes the towns of Tower, Soudan, and Ely. The whole district is one of complex folding, so the ore deposits occur in narrow belts, which are enclosed on the bottom and sides by original greenstones of Archean age and on top by the original iron formation. As the pitch or slope is very steep, the outcrops are very small. The ores are all hard and are composed of red and blue hematite. This range had contributed a little more than 39,526,800 long tons of ore by 1916. The shipments for that year were 1,947,200. This range and the three previously mentioned are known as the old ranges to distinguish them from the more recently discovered Missabe and Cuyuna ranges.

**The Missabe Range** is one to excite the interest of every one interested in the manufacture of iron or steel, because from it comes the greater part of the ore used for the production of pig iron today. It was opened in 1892 and up to 1916 about 406,855,200 long tons of ore had been taken from its mines. The shipments for the year were 42,526,612 tons. It lies in Minnesota, northwest of Lake Superior, and extends in an east and west direction approximately 100 miles. The principal towns are Biwabik, Eveleth, Virginia, Chisholm, Hibbing, Nashwauk, and Coleraine. The iron formation is the Biwabik in the Upper Huronian. It lies along the southern slope of a ridge that is known as the Giants, or Missabe, Range, and has a gentle slope toward the south. The surface is covered with glacial drift, and rock exposures are not common. This surface, originally covered with forest, gave few signs to indicate the presence of ore bodies. The slope of the iron formation is gentle, so most of the ore deposits are flat-lying and have a large horizontal area compared with the deposits on the other ranges. The impervious basement under the ore deposits is formed by layers of slate or paint rock, interbedded with the iron formation. The ores are mostly soft and hydrated hematites and limonite. They vary in texture from very fine dust to fairly coarse, hard and granular ore. Toward the western end of the district, layers of sand are often interbedded with the ore, forming the so-called "sandy" ores, which require concentration to form ore of commercial grade. The deposits are all comparatively shallow.

**The Cuyuna Range**, which is the last range of any importance to be discovered, was opened in 1911. It is located in Crow Wing County, Minnesota, about 100 miles west of Duluth. The principal towns in the district are Deerwood, Crosby, and Brainerd. The range has no marked topographic features, the surface being level and covered with a heavy mantle of sand. Since there are no surface indications to assist in the exploration for ore, the presence of lines of magnetic variation must be depended upon almost entirely. By drilling, these lines have been found to be associated with belts of iron-bearing formations which trend in a northeasterly and southwesterly direction. The formation is interfoliated with slate and schist, and is usually steeply tilted. At some localities igneous intrusive rocks occur. The ore deposits are usually lenticular in form. In certain restricted areas of the range, particularly in the northern part, manganiferous iron ores have been found. The deposits of these ores occur in irregular pockets or lenses, and contain as high 45% manganese. Some of these bodies of ore are being worked for their manganese content only. In 1916 the yearly production had reached 1,716,218 tons, and the total production, 4,897,298 tons.

## SECTION V.

### MINING THE LAKE ORES.[1]

**Prospecting and Exploration:** Since the Lake Superior ores occur in pockets or distinct bodies and vary much as to character and location, the actual mining of the ores is preceded by much work of an exploratory character. This work includes **prospecting** and **exploration.**

**Prospecting** is the term generally applied to the quest for surface indications of ore, or the conditions which would warrant the expectation of finding ore in the vicinity. It includes such quest operations as geological examination, dip needle work, shallow test-pitting, and trenching. The ore bodies of the Missabe Range are non-magnetic, and dip needle prospecting is therefore valueless. On the Cuyuna Range, however, magnetic attraction as evidenced by the dip needle has been extensively employed as a guide to the location of ore deposits; in other localities it has also found limited application.

**Drill Exploration:** After the presence of an ore deposit is known or suspected, resort is generally had to exploration by means of diamond or churn drills. On the old ranges geological conditions generally make this manner of ascertaining the exact limits of an ore deposit impracticable; so, if two or three adjacent drill holes develop considerable depths of ore, the sinking of a shaft for underground exploration, development and mining is generally considered warranted. On the Missabe Range, however, the flat-lying and comparatively shallow characteristics of the ore formation warrant much more extensive drill explorations. On this range, then, an ore body is almost invariably followed out with the drills, and its limits

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[1] For further details concerning the mining of the Lake Ores, see Minn. School of Mines Experiment Station Bulletin No. 1, Iron Mining in Minnesota, by Charles E. Von Barneveld, University of Minnesota, Minneapolis, Minn.

FIG. 4. Open Pit Mining

FIG. 4. Open Pit Mining

are determined to the point where the complete plan of development can be worked out in advance of actual mining operations.

**Methods of Mining:** Both open pit and underground methods of mining are employed in the mines of the Lake Superior District. On the old ranges, where the ore bodies often extend to great depths and usually lie at angles so steeply inclined to the horizontal that the surface exposures, or outcrops, are small, underground mining methods are employed almost without exception. On the Missabe Range the ore bodies are, as a rule, flatlying with relatively large areas of outcrop, and open pit mining is, therefore, general. Of course, there are many deposits on this range that, on account of limited operating area, excessive depth of over-burden, or for other reasons, must be mined by underground methods, and there are, therefore, a large number of underground mines also. But by far the greater part of the tonnage produced from the Missabe Range comes from open pits.

**Open Pit Mining:** Before deciding whether an ore body should be mined by underground methods or as an open pit, a detailed operating-analysis is made of the proposition to determine by which method the ore can be mined most economically. Estimates are made determining the yardage of overburden, or "stripping", that must be removed to uncover the ore body, the tonnage of ore which can then be mined by steamshovel, and the additional tonnage which can be "scrammed" or "milled" in the pit after the limits of steamshovel operation have been reached. Then the cost of the entire operation, including interest-charges on the necessarily large investment in stripping removal, is calculated and reduced to a final cost per ton of ore recoverable. If this figure is less than the probable cost per ton of underground mining, and if the other operating conditions are satisfactory, open pit operation is, of course, deemed advisable. The laying out of an open pit mine involves the following engineering problems: first, outlining the area of ore which it will pay to strip, i. e., considering the two factors of depth of ore and thickness of overburden; second, planning the disposal of stripping which it will be necessary to remove to uncover the ore body, for this material must often be hauled considerable distances from the pits to dump grounds; third, locating the track systems outside the pit for the transportation of stripping and the hauling of ore; fourth, designing the system of railroad tracks within the pit that will make available the maximum quantity of ore accessible by steamshovel, which designing generally involves a series of switchbacks on limiting operative grades and curvature; fifth, providing for drainings of the pit; and sixth, planning in advance for the mining of the ore that cannot be mined by steamshovel. The general term **open pit mining** covers three recognized methods of mining, i. e., steamshovel, milling and scramming. **Steamshovel mining,** of course, needs no description; it is simply the loading of ore directly into railroad cars by steamshovel.

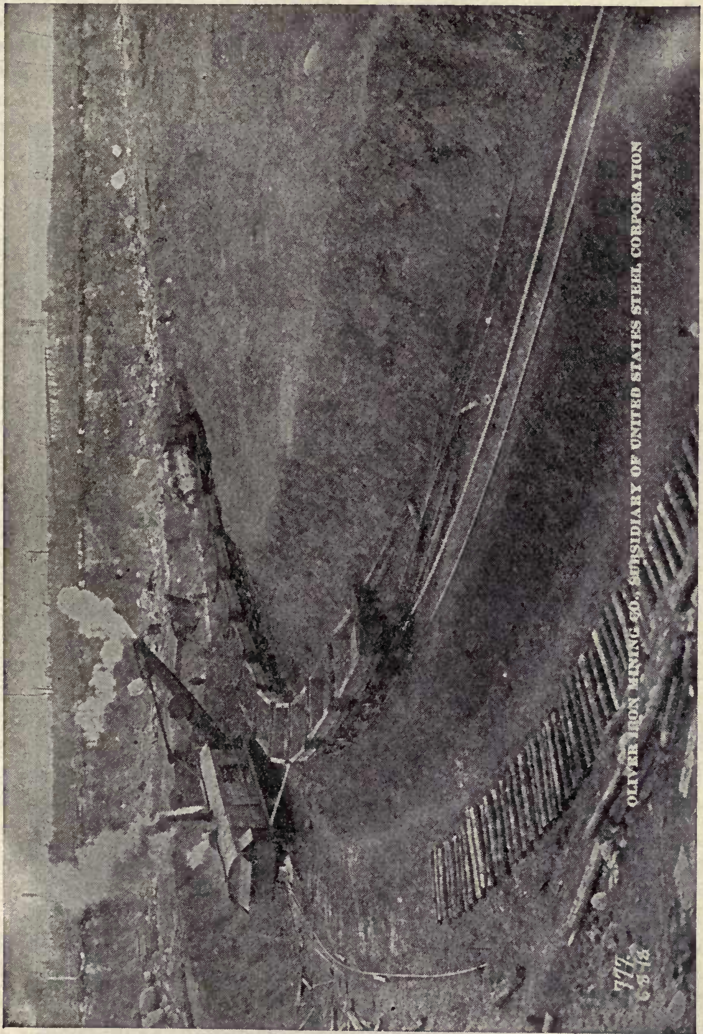

FIG. 5. Open Pit Mining. Steam Shovel with Four Yard Dipper Loading Stripping.

**Milling** is a term applied to a thoroughly well worked out system of open pit mining, extensively prosecuted in the early days and still applied under suitable conditions. It consists of the following operations: first, the removal of the overburden from the ore body to be mined, this being done by steamshovel; second, the sinking of a hoisting shaft or incline to the bottom of the ore and the development of a system of underground

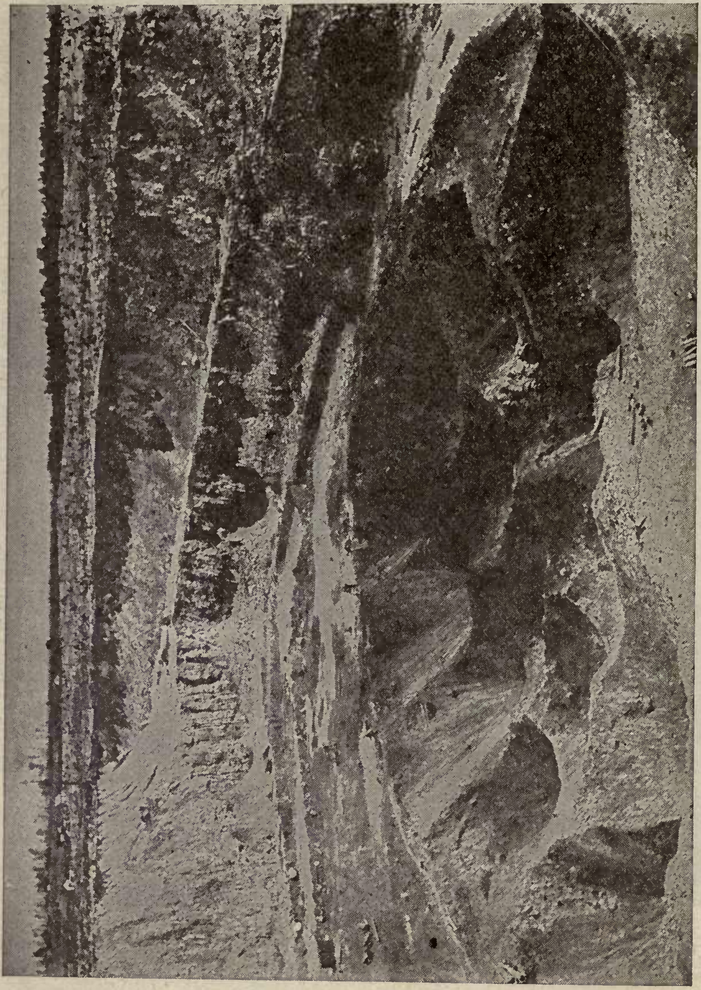

Fig. 6. Milling Pit.

tramming drifts tributary to the shaft and underneath the ore to be mined; third, the putting up of a number of raises (vertical openings) extending from the underground drifts through the ore; fourth, "milling" or shoveling the ore into the raises, through which it is drawn into tram cars operating in haulage drifts that lead to the shaft or incline, where it is hoisted to the surface. The milling system of mining can well be applied to small ore bodies which can be successfully stripped, but where the resultant open pit areas are too small to permit of steamshovel operation; also, as a sequel to steamshovel mining in larger pits where considerable depths of ore remain after the limits of steamshovel work have been reached.

**Scramming** is a term applied colloquially on the Missabe Range to the operation of recovering shallow pockets and hummocks of ore left unmined in and around the open pits following the period of steamshovel mining. It is a general term inclusive of hand work, scraper work, mining with dragline excavators, etc., and is applicable generally to the operation of "cleaning up" a pit after its period of real production has passed.

**Advantages of Open Pit Mining:** It is very apparent that open pit mining, when feasible, offers decided advantages as compared with underground methods. Probably the most evident of these is the possibility of big production; in 1916 the Hull Rust Mine alone shipped 7,665,611 tons of ore,—more than 10% of the total mined in the United States during that year, which, according to the U. S. Geological Survey, amounted to 75,167,672 tons. Where the overburden is light in comparison with the depth of ore, and stripping charges are not heavy, open pit mining produces low cost ore. It accomplishes a great saving in labor; the output per man per day from the open pit mine is many times that from the average underground mine. Aside from the skilled operators of the steamshovels and locomotives, common labor only is required in open pit mining, while in underground work the miner is a rather high class workman, and he receives a relatively high wage. Owing to this latter condition, strikes have never been able to interfere seriously, so far, with the output of Missabe Range open pit mines.

**Underground Mining—Slicing:** The system of underground mining most generally in use in the mines of the Missabe Range, and in the soft-ore mines of the old ranges, as well, is known as **top-slicing and caving.** The development of a mine under this method is as follows: First, a shaft is sunk to the bottom of the ore body, or to such depth in the ore as has been determined as desirable. Second, after cutting a "station," pumproom and pocket at the bottom of the shaft, a main haulage drift, or system of haulage drifts, is driven out underneath the ore body. Third, raises are put up from the haulage drifts at intervals of about 50 feet along the drifts through the ore body to the top of the ore. Fourth, cross cuts are driven from the tops of the raises to the limits of the ore body or the property lines, the cross cuts being parallel and the same distance apart as the raises. Fifth, beginning at the ends of the cross cuts farthest from the raises, the ore is "sliced" out between cross cuts, trammed to the raises, dumped into the latter, drawn off thru chutes into cars operating on the main haulage level, hauled to the shaft, dumped into the shaft pocket and hoisted to the surface, where it is either loaded direct into railroad ore

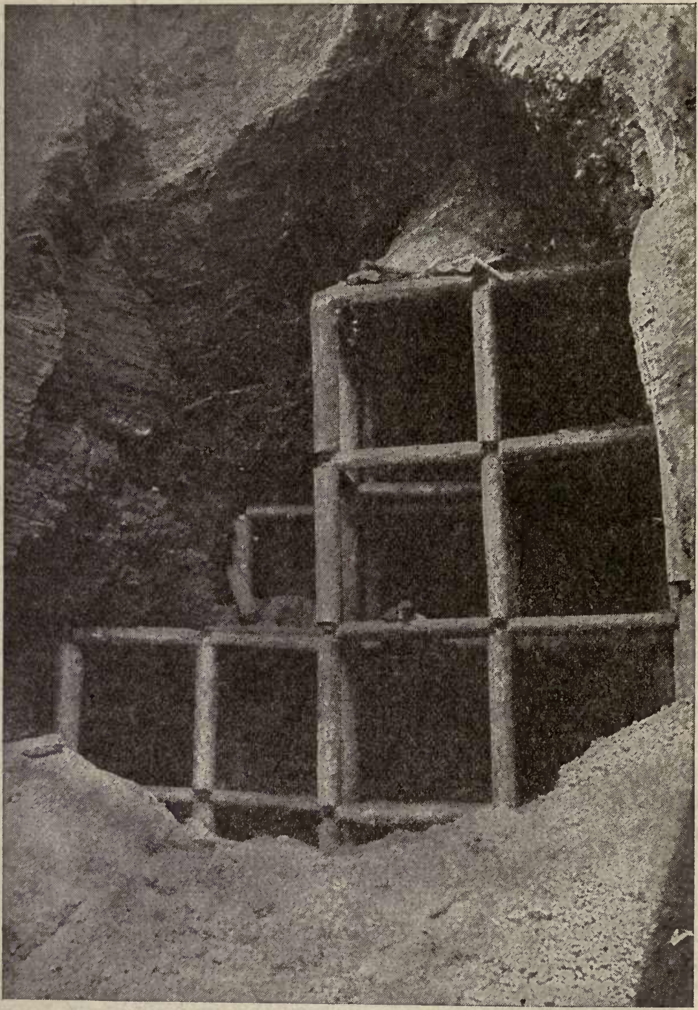

Fig. 7. Underground Ore Mining—Square Set Timber.

cars, or (if in the Winter time) stockpiled for later shipment. A "slice" consists of a room opened up between crosscuts, and may be one, two or more sets wide depending on the tendency of the overburden to crush the temporary timber supports. When the ore has been removed from the room or slice, the supporting timbers are blasted out and the overburden allowed to cave and fill it. Before blasting the timbers, however, boards are laid over the floor of the room to prevent admixture of the caved material with the ore below. While slicing and caving operations are proceeding on the top level, the cross cuts to develop the next level immediately below are being driven, and as soon as considerable areas of cave have been developed on the first level, slicing under these areas is started on the second level. Thus, the entire ore body is mined, slice by slice, and level by level. Levels are generally about eleven feet apart, floor to floor. Haulage of ore on main levels from chutes to shaft may be by hand, mule or electric motor, depending on the size of the mine. On the sub-levels the ore is hand-trammed in small dump cars, or for short hauls, in wheelbarrows, from the slices to the raises.

**Advantages of the Slicing System of Mining:** The top-slicing-and-caving system has many advantages. It gives a high percentage of ore extraction. If desired, the ore from different working places can be separated, and two or more grades can be produced from the same mine. Development and mining operations are simple and safe, and can be carried out along well defined plans worked out in advance. While the consumption of mining timber is high, cheap inferior grades are used, and under ordinary conditions this item of cost is not excessive. In common with most other systems of mining, it possesses the disadvantage of a limited number of working places; considerable handling of the ore is also necessary.

**The depth of mine shafts** on the Missabe Range rarely exceeds 350 feet. The average is probably between 250 and 300 feet. On the old ranges, where the rock formations have been folded and tilted, mining operations extend much deeper. Here mine shafts 500 to 1500 feet deep are common, while in some cases mining operations are still in ore at depths well in excess of 2,000 feet.

**Grading the Ores:** In the early days of iron ore mining, no grading of the ore from analysis, such as prevails today, was made, and the ore was known by the name of the mine that produced it. Then, the number of mines was small, and the ore from any one mine was fairly uniform. As the production increased, however, and the field of available ore was broadened to include deposits previously regarded as unprofitable, it became necessary, in order to simplify shipping, to grade ores according to their composition, and, further, to mix ores differing in composition to produce certain grades. Finally, it became quite common for one mine to ship several different grades, and for the ore from several mines to be grouped under one name. These conditions brought about a necessity for knowing the exact composition of the various ores, and whether or not, in the case of mixed ore, each cargo was of the grade guaranteed. This grading is done by sampling the ore in the cars as fast as they are loaded at the mine, in lots not exceeding ten, and making a rapid but accurate analysis for the determining elements. From this analysis the class or grade of the ore is fixed, and its allotment into a certain group can be made. This is the work of the grader, who, from the analysis of the cars as submitted to him, makes a theoretical shipment in which the contents in silica, iron, phosphorus and possibly manganese, the determining factors in the value of an ore for its particular purpose, must fall within certain predetermined limits.

**Transporting the Ores:** The Lake ores now supply all the furnaces in Western New York, Western Pennsylvania, Ohio, Illinois, and Indiana, as well as those in the ore producing states of Michigan, Wisconsin, and Minnesota. In order to reach these markets, the ores must be transported for distances varying from 300 to more than 1000 miles, depending upon the locations of both the mine and the furnaces. The cost of transporting this ore by rail alone would be a serious handicap to some furnaces, but fortunately the chain of Great Lakes affords a cheap mode of transportation for the greater part of the long as well as the short distances. Nearly all the ore mined in the ranges, then, goes first by rail to a harbor on Lake Michigan or Lake Superior, where it is loaded on ore carrying boats that carry it either down Lake Michigan to Chicago or Gary or through Lake Huron and Lake Erie to ports further south. For most of the ore, even these lower lake ports are not ultimate destinations, and another haul by rail is required to place it at the furnaces. Now, to return to the grading of the ore, what was there referred to as a theoretical shipment might better have been called a theoretical cargo or boat load. When the cars containing this theoretical cargo, which may weigh from 3000 to 13,600 tons, depending upon the size of the boat, reach the dock at the shipping port, they are unloaded into the dock pockets, one on top of the other, three to six cars to a pocket, in such order as to mix the ore as much as possible. The ore is then allowed to flow from these pockets into the hatches of the steamer, thus, again mixing the ore. Then the boat proceeds to her destination, where the ore is unloaded by electrical, or otherwise operated, grabs, which process of unloading still further tends to mix the ore and make it uniform. All this mixing of the ore is not to be thought of as merely incidental to the operations, but as a necessary course of procedure, for uniformity in the ore is a very important requirement in the successful operation of the blast furnaces. If the ore is unloaded at the works located on the lakes, it is sampled for analysis during the unloading by an elaborate system and is dumped upon its appropriate stock pile; if for inland works, such as Pittsburgh, it is placed in cars and ultimately reaches the works, where each car is sampled, according to printed instructions common to all the works of the Steel Corporation. The cars are then unloaded upon a stock pile from which the ore can be used as needed, or directly into the furnace bins, if the ore is needed for immediate use.

**Mining and Grading in Winter:** In winter the procedure as outlined above has to be changed somewhat. During a part of November, and all of the winter months of December, January, February and March, the ore cannot be transported over the lakes because of the ice. On this account, operations in the open pit mines of the Missabe District are suspended in winter; but in all the underground works, both of the old ranges and the Missabe, mining is continuous throughout the year, and the ore mined during the non-shipping season must be stock piled. As this ore is removed it is carefully sampled, and average samples are analyzed daily. These analyses, supplemented by those made in the work of exploration that is constantly carried on in advance of the mining, make it possible to calculate the average composition of each stock pile at the beginning of the shipping season in the spring. This stock, therefore, may be combined, if necessary, with the ore direct from the mines to make up cargoes of definite and known composition.

# CHAPTER IV.

# FUELS.

## SECTION I.

### SOME PRE-REQUISITES TO THE STUDY OF FUELS.

**Introductory:** There are five basic materials upon which the metallurgical arts depend; namely, ore, fuel, flux, air and water. Of these one is as important as the other, for all metallurgical industry would cease with the failure of any one. At one time all these were thought to be inexhaustible, but recently it has been generally recognized that the supply of the higher grades of ore are limited, and that the more suitable fuels, at the present rate of consumption, must be exhausted in a comparatively short time. Representing the only source of energy under man's absolute control, fuels are the foundation upon which a nation's progress and prosperity depends. The subject is also a very large one. Hence, in this chapter it is desirable to discuss briefly a few fundamental topics of general interest, and more in detail, a few matters especially important in the iron and steel industry.

**Sensible and Specific Heat:** Provided no change of state is involved, the effect produced by imparting heat to a body is a rise in temperature of the body, and if the body is made to give up heat, its temperature falls. This heat, which is easily detected, is often spoken of as **sensible heat.** The quantity of heat required to raise the temperature of a body 1°C. is called its **thermal capacity.** The amount of heat required to raise the temperature of equal masses of different substances 1°C. varies greatly, and the thermal capacity of one gram of any substance, in other words, the number of calories required to raise the temperature of one gram 1°C., is called its **specific heat.** Specific heats are determined by the method of mixtures, which is based on the law of **heat exchange.** This law states that when bodies at different temperatures are brought into contact, exchange of heat takes place until a uniform temperature for all is reached, and that the heat lost by the hotter bodies equals in quantity that gained by the colder ones. The specific heats of a few common metals follow: Iron=.109 cal. Copper=.092 cal. Zinc=.093 cal. Mercury=.033 cal.

**Latent Heat and Change of State:** Changes of state are governed by the following laws:[1]

Laws of Fusion:

I. "Every crystalline substance begins to melt at a definite temperture, which is invariable for each substance if the pressure is constant."

II. "The temperature of a body, when slowly melting, remains constant till the whole mass is melted."

III. "Substances that expand on solidifying have their melting points lowered by pressure, and vice versa."

Laws of Evaporation:

I. "The rate of evaporation increases with rise of temperature."

II. "The rate of evaporation increases with the surface of the liquid exposed."

III. "The rate of evaporation is increased by a continual change of air in contact with the liquid."

IV. "The rate of evaporation is increased by diminishing the vapor pressure, that is, by applying suction to the vessel inclosing the liquid"

Laws of Ebullition:

I. "A pure liquid has a definite boiling point, which is invariable for that liquid under the same conditions."

II. The temperature of the vapor given off by a pure liquid near its surface remains constant till all the liquid is vaporized if the pressure remains constant.

III. "The boiling point of a liquid is raised by salts and lowered by gases dissolved in it."

IV. "The boiling point of a liquid rises with increase of pressure and falls with decrease of pressure."

It will be noted from these laws that when change of state takes place, there is no change in temperature of the body, notwithstanding the constant application or withdrawal of heat. The heat thus involved is sometimes spoken of as **latent** heat, though **heat of fusion** and **heat of vaporization** would appear to be the better terms to employ. The heat of fusion for water is about 80 calories per gram, while its heat of vaporization is 535.9 calories per gram under standard pressure.

**Transmission of Heat:** Heat is transmitted in three ways; namely, by conduction, by convection and by radiation. **Conduction** is the transmission of heat through a body without visible motion of the body, as through an iron bar. When the heat is transmitted by mechanical motion of the particles of matter, through air or water currents for example, it is called **convection.** The distribution of heat through a blast furnace makes use of these principles. **Radiation** refers to the transmission of heat, independently of matter, by means of waves in the ether. This is the means by which the heat of the sun reaches the earth. These factors are important considerations in the action of furnaces, stacks, ventilators and heating plants.

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[1] See High School Physics and University Physics by Henry S. Carhart and Horatio N. Chute, published by Allyn and Bacon, Boston and Chicago.

**.Fuels and Combustion:** Any chemical reaction by which light and heat are evolved is called combustion. In the ordinary cases of combustion, one of the reacting substances is the oxygen of the air. Therefore, fuels are sometimes defined as substances which will burn in air and liberate heat with sufficient rapidity to be applied to practical purposes. The chief elements constituting fuels are carbon and hydrogen, though in certain processes silicon, phosphorus, sulphur, manganese and the metals may serve as fuel. In metallurgy the fuel is often required to act as a reducing agent, in which cases the total heat produced will be derived from two sources, namely, by combustion with oxygen of the air and by combination with oxygen of the ore.

**Fuels and Chemical Energy:** Fuels represent potential energy, which is given off as heat by chemical action. Therefore, the relations of the weights of fuel, weights of air, and the amounts of heat evolved are fixed quantities. The following reaction furnishes a simple illustration:

$$C+O_2=CO_2+\text{Heat},$$

that is, 12 gm. $C+32$ gm. $O_2=44$ gm. $CO_2+97200$ cal. (Heat of formation of $CO_2$) or 1 gm. $C+2.666$ gm. $O_2$ (11.51 gm. air) $=3.666$ gm. $CO_2+8100$ cal. (Calorific power of carbon).

The heat liberate is referred to in two ways. The chemist bases his calculations on the total heat evolved to form a molecular weight in grams of a given substance, in this case, 44 gms. $CO_2$, which is called the **heat of formation** for that compound. But the metallurgist and engineer employ the heat evolved from a unit weight of fuel, in this case, one gram of carbon, and refer to it as the **calorific power** of the fuel. It should be observed that these terms take into consideration only the total amount of heat evolved, irrespective of the time or speed of the reaction, the duration of which may vary through wide limits. This point is important in the attainment of high temperatures and is connected with the second important factor affecting the combustion of fuels, namely, the temperature to which the products of combustion may be raised by the heat evolved. This is referred to as the **calorific intensity** of the fuels. Both the calorific power and the intensity enter into the valuation of fuels.

**Measurement of Calorific Power:** As has already been noted, the two practical heat units are the large calorie and the B. t. u. Metallurgists express the calorific power in large calories per kilogram, which is numerically the same as small calories per gram employed by chemists, while engineers use B. t. u. per pound of fuel as the basis of their calculations. The units are readily converted from one to the other; the relation with respect to the quantity of heat they contain is expressed thus:

B. t. u. per lb.: Cal. per kilo=1 : 1.8

Hence, to reduce Cal. per kilo. to B. t. u. per pound, it is only necessary to multiply by 1.8. The factor for changing B. t. u. per lb. to Cal. per kilo is .5555.

**The Calorific Power** of some common elements in simple oxidation reactions is as follows:[1]

**Table 6. Calorific Power of Some Elements.**

| Element | Reaction. | Calorific Power in Calories per Kilo. |
|---|---|---|
| H | $2H_2+O_2=2H_2O$ Liquid | 34500 |
| H | $2H_2+O_2=2H_2O$ Vapor | 29030 |
| C | $C+O_2=CO_2$ | 8100 |
| C | $2C+O_2=2CO$ | 2430 |
| Si | $Si+O_2=SiO_2$ | 7000 |
| Al | $4Al+3O_2=2Al_2O_3$ | 7270 |
| P | $4P+5O_2=2P_2O_5$ | 5895 |
| S | $S+O_2=SO_2$ | 2196 |
| Fe | $3Fe+2O_2=Fe_3O_4$ | 1612 |
| N | $N_2+O_2=2NO$ | —1541 |

**Calculating Calorific Power:** Given the heats of formation of the reacting substances and of the products of combustion, it is possible to calculate the calorific power of some fuels from their analyses. The calorific power of a well made coke can be estimated approximately from the fixed carbon, if the moisture and volatile matter are low.

By analysis, Fixed Carbon=87.0%
Calorific Power of Carbon=8100 Cal. per Kilo
.87

7047 Cal. per kilo.=calorific power of coke

This calculation for gases becomes more complicated, because the calorific power is usually expressed in Calories per cubic meter or B. t. u. per cu. ft. This fact requires a conversion from weight to volume, since the calorific powers in the table are based on weight. This conversion, however, is a simple matter, since a gram molecular weight of any gas has a volume of 22.32 liters under standard conditions. To find the heat evolved from a gas in calories per liter, it is only necessary to divide the heat of formation by 22.32. In the case of a blast furnace gas composed of $CH_4$, .2%; CO, 25%; $H_2$, 3%; $CO_2$, 12%; $N_2$, 59.8%; the calorific power may be found as follows: The reactions that may occur in complete combustion are

Reaction (1) $CH_4+2O_2=2H_2O+CO_2$
Heats of formation, 21700 cal.+0=2x58060 cal. +97200 cal.

Reaction (2) $2CO+O_2=2\ CO_2$
Heats of formation, 2x29160 cal.+0=2x97200 cal.

Reaction (3) $2H_2+O_2=2H_2O$
Heats of formation, 2x58060 cal.

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[1] See Metallurgical Calculations by Joseph W. Richards, One Volume Edition published by McGraw-Hill Book Company, New York.

From reaction (1) the total heat available from $CH_4$=

$$\frac{2x58060+97200-21700}{22.32}=8585.+\text{calories per liter.}$$

From (2) available heat from CO=

$$\frac{97200-29160}{22.32}=3048+\text{calories per liter.}$$

From (3) available heat from $H_2$=

$$\frac{116310}{2x22.32}=2605.+\text{calories per liter.}$$

Total heat of gas available is,

for $CH_4$ .2% of 8585= 17.17
CO 25% of 3048=762.00
$H_2$ 3% of 2605= 78.16

857.33 calories per liter at 0°C. and 760 m. m. pressure=(857.33 x .11236)=96.33—B. t. u. per cu. ft.

**Practical Tests:** All calculated results, however, are usually higher than can be obtained in actual practice. Furthermore, with complex fuels, like coals, the composition of which can only be guessed at, it is impossible to make accurate calculations from the analysis, because no account is taken of the heat required to decompose the fuel and gasify the products. Many fuel chemists, however, have evolved formulas by which they are able to determine very closely from the analysis the calorific value of a coal as obtained by laboratory experiment. Nevertheless, experimental methods are relied upon almost wholly to determine the heating power of fuels. These tests may be practical, in which large quantities of the fuel are consumed under conditions approximating closely those of the process for which the fuel is to be used; or they may be laboratory tests, in which small quantities of fuel are burned, and the heat evolved is measured. Practical tests may be made in specially constructed apparatus or under boilers in actual service. These specially constructed apparatus are in the form of large heaters through which water circulates and in which the fuel may be completely consumed. From the amount of fuel consumed, the weight of water heated, the rise in temperature of the water, the difference in temperature between the in-going air and the products of combustion, the calorific power may be accurately determined.

**Laboratory Tests:** For determining the maximum amount of heat a given fuel is capable of generating, laboratory tests are more exact than practical tests. Such tests are carried out in specially designed apparatus called calorimeters. There are several makes of these instruments, but the fundamental principles of all are the same. The process consists in completely oxidizing the fuel in a space enclosed by a metal jacket (the bomb) so submerged that the heat evolved is absorbed by a weighed portion of water contained in a perfectly insulated vessel. From the rise in temperature of the water, the heat liberated by one gram of the fuel is calculated. The best types of calorimeters are those called oxygen bomb calorimeters, in which the fuel is burned in the presence of compressed oxygen.

**Calorific Intensity:** The calorific intensity is more precisely defined as the degree of heat evolved by a given weight of fuel in perfect combustion in air at 0°C. and 760 m. m. pressure. The theoretical maximum temperature depends on the calorific power, and the density and specific heats of the products of combustion, and is inversely proportional to the time required in producing it. In practice the temperature is also affected by the initial temperature of the fuel and air, the amount of air used, amount of water in fuel and air, and by radiation, conduction and convection of materials of the furnace. As the attainment of high temperatures is necessary to many metallurgical processes, all these factors are important, and special devices have been invented to prevent waste, preheat air and gas, and eliminate moisture.

**Methods of Conserving Heat:** Owing to the high temperature at which the products of combustion escape from furnaces and the large volume of air necessary for the combustion of the great quantities of fuel used, much of the heat generated in the furnace is carried away by the outgoing gases and wasted, unless special methods are employed to recover this waste. This can be done in several ways. The hot gases may be passed through boilers and made to generate steam, conducted into other furnaces requiring lower temperatures, or used to preheat the air and fuel and thus increase the intensity of the heat in the furnace. Since high temperatures are required in most metallurgical processes, the third option is generally selected. The methods by which this preheating is accomplished depends upon two principles, called the **regenerative** and the **recuperative.** In the regenerative method the hot gases from the furnace are conducted through expanded portions of the horizontal flues, almost filled with open brick work, called the "checkers" from the manner of laying the bricks. When the checkers have absorbed heat sufficient to raise their temperature to nearly that of the gases, their connection with the stack is closed, and the air, or air and fuel, if the latter can be preheated, is made to pass through the checkers on its way into the furnace, thus taking on the stored up heat in the checkers. With two such sets of checkers to a furnace this process is made practically continuous by reversing the direction of the gases at short intervals. In the recuperative method the checkers are replaced by a system of pipes through which the out-going gases must pass. The in-going air, being at the same time drawn in through the space around the pipes, is heated in proportion as the waste gas is cooled.

**Pyrometers:** The measurement of high temperatures requires special instruments called pyrometers, many of which are made self recording so as to measure continuously the temperature of a furnace through long periods of time. There are many types of these instruments, and only the principles upon which some of the more important types are based will be briefly described.

**Specific Heat, or Water, Pyrometer:** This is an old type of instrument, and one that is still extensively used. The operation of the instrument is carried out as follows: A weighed amount of metal of known specific heat is placed in a furnace, and when it has attained the temperature of the furnace, it is withdrawn and quickly dropped into an insulated vessel, containing a definite amount of water and provided with a thermometer for reading the temperature of the water. The rise in temperature of the water is proportional to the weight of the ball, its specific heat, and the temperature of the furnace. The first two factors being known, the temperature of the furnace can be readily calculated.

**Electric Resistance Pyrometers:** Instruments of this type depend on the fact that the electrical resistance of metals increases with rise in their temperatures. In practice the metal will be platinum in the form of wire, which will be inserted in one arm of a wheatstone bridge for measuring resistance. A battery and a galvanometer for detecting difference in potential, both being attached to the bridge, completes the apparatus. In operating the instrument, the slide on the bridge is adjusted so that the resistance of the two arms of the bridge are the same and the galvanometer reading is zero. The "bulb" of platinum wire is now inserted in the furnace, when, the resistance of the platinum wire being increased by the rise in temperature, it is necessary to insert resistance in the other arm of the bridge to keep the galvanometer reading at zero. The amount of the resistance inserted measures the increase in resistance of the wire, which can be interpreted in degrees of temperature.

**Thermo-Electric Pyrometers:** These instruments are both convenient and accurate, being very simple in construction. They depend upon the fact that if two metals are in contact at a given point, any change in temperature at that point causes an electric current, the intensity of which is proportional to the change in temperature, to flow around a circuit connecting their free ends. This current can be measured by inserting a millevolt meter in the circuit. In practice the metals employed for high temperatures are platinum in conjunction with an alloy of platinum and 10%

rhodium or iridium in the form of wires, which are insulated from each other by means of hollow tubes of refractory materials. For low temperatures the baser metals may be used, such as iron and nickel-copper alloys.

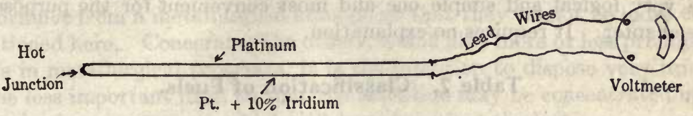


FIG. 8. Diagram of Wiring for Thermo-Electric Pyrometer.

**Radiation Pyrometers** are based on the law of heat radiation which is briefly stated thus: The energy emitted by a highly heated black body is proportional to the fourth power of its absolute temperature. Such instruments consist of a millevoltmeter and a telescope which contains a concave mirror reflector and a delicate thermo electric couple. By pointing the telescope, from a certain distance, toward a highly heated surface, a portion of the radiant heat is made to fall upon the mirror, which concentrates the rays upon the couple, causing it to generate a current that can be measured by the millevolt meter.

**Optical Pyrometers** depend upon the relation of the intensity of light emitted by an incandescent body and its temperature. In them the intensity of the light from the hot body is compared with that of an incandescent lamp. The simplest form consists of a telescope containing the lamp and a battery to supply the current. In making a determination, the telescope is pointed at the heated body, and the current is adjusted so that the intensity of light from the filament of the lamp matches that from the body. From the adjustment necessary the temperature of the body is determined. In improved forms of this instrument, a circular plate of colored glass is inserted in the telescope between the lamp and the eye in such a manner that the light from the lamp falls on one-half of this plate and light from the body falls on the other. The two lights are matched by varying the intensity of the light from the body with a diaphragm. A second improvement is made by providing a special rotating prism by means of which the lights from both the body and the lamp are varied in intensity. The amount and direction of rotation necessary to match the lights measures the temperature.

All modern pyrometers are constructed with graduated scales to read in degrees, so that no calculations for converting the various relations into temperatures are required.

## SECTION II.

### CLASSIFICATION OF FUELS.

Of the many ways of classifying fuels, that shown below in Table 7 is a very logical and simple one and most convenient for the purposes of this chapter. It requires no explanation.

**Table 7. Classification of Fuels.**

- Carbon-Hydrogen Fuels
  - Solid
    - Natural
      - Wood
        - Hard.
        - Soft.
      - Peat
        - New.
        - Old.
      - Lignite
        - New.
        - Old.
      - Coal
        - Bituminous
          - Coking.
          - Non-coking.
        - Anthracite.
    - Prepared
      - Briquettes.
      - Pulverized Coal.
      - Carbonized Fuel
        - Charcoal.
        - Coke
          - Beehive.
          - By-product.
  - Liquid
    - Natural—Petroleum.
    - Prepared
      - Distilled Oils.
      - Coal Tar.
  - Gaseous
    - Natural—Natural Gas.
    - Prepared
      - Producer Gas.
      - Blast Furnace Gas.
      - Coke Oven Gas.
      - Coal Gas.
- Incidental Fuels
  - Bessemer Converter
    - Iron.
    - Manganese.
    - Carbon.
    - Silicon.
    - Phosphorus.
  - Sulphur Works
    - Roasting.
    - Smelting.

**Plan of Study:** In discussing the different fuels it does not seem desirable to follow the order of the outline above. Some, like blast furnace and coke oven gases, are best taken up in connection with the processes that produce them, while others, like the distilled oils, are of so little importance from a metallurgical standpoint that they cannot be more than mentioned here. Concerning the others, which play more or less prominent parts in metallurgical processes, it is the intention to dispose very briefly of the less important first, so that the attention may be concentrated upon the more important ones, which will be taken up at the last.

## SECTION III.

### INCIDENTAL AND LIQUID FUELS.

**Incidental Fuels:** Under this heading is included all substances which incidentally act as fuels in certain processes. In the acid Bessemer converter, for example, the oxidation of the impurities, silicon, manganese and carbon, to which is added phosphorus and sulphur in the basic converter, furnish heat necessary to keep the metal in a molten state during the blow, and so perform the function of fuels. In the roasting and smelting of pyritic ores the burning of a portion of the sulphur furnishes a great part of the heat necessary for those processes.

**Tar:** The use of tar as a fuel is of recent origin, and offers a means for the disposal of the excess quantities produced above that required by the tar refiners. Having a low ash and sulphur content, it is well suited chemically for use as open hearth and heating-furnace fuel. It is a viscous fluid at ordinary temperatures. Hence, it must be kept at a relatively high temperature both in the storage tanks and feed lines. This heating is accomplished by means of steam pipes immersed in the tar. Special burners, one type of which is shown in the accompanying figure, of the steam or air injector type are required to burn tar properly. Tar carries in suspension a great many small carbonaceous bodies, and on standing, especially at the lower temperatures prevailing in storage tanks, these grow into pitch-like bodies of considerable size, which clog up the burners and the small pipe lines of the system. Its calorific power is between that of coal and oil, 16000—18000 B. t. u. per pound. This fact, coupled with its low cost due to the increased production, tends to stimulate efforts to use it wherever possible.

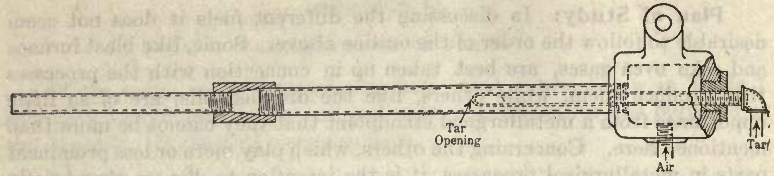


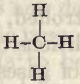
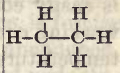
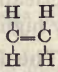
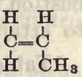
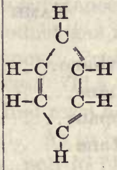
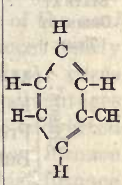
Fig. 9. One Type of Tar Burner.

**Petroleum:** The only natural liquid fuel, and a material of the highest commercial importance, is petroleum, a product obtained from reservoirs deep in the earth. Its heating power is much greater than that of coal, (The calorific power of crude petroleum=21000 B. t. u. per pound, Coal= 9000 to 15000 B. t. u. per pound) and it is obtained in immense quantities. On distilling, it yields a high percentage of very valuable oils. On this account it is used as a metallurgical fuel only where coal is scarce and high in price. In using the oil special burners are required, as it must be vaporized or atomized and properly mixed with air to insure complete combustion.

**Composition of Petroleum:** Petroleum is a very complex mixture of organic compounds. In small amounts it contains compounds of oxygen, sulphur, and nitrogen, but principally it is composed of compounds of carbon and hydrogen. Its content of the former element varies from 84 to 87%, and of the latter, from 11 to 13%, depending upon the locality from which it is obtained.

**Hydrocarbons—Generalized, Empirical and Structural Formulas:** These compounds of carbon and hydrogen found in petroleum are called hydrocarbons. They are numbered by the hundred, and a study of their composition has shown that they fall into a number of homologous series which may be represented by generalized formulas as shown in Table 8. In representing these compounds, the empirical, or simplest, formulas are often found inadequate, because it frequently happens that two different compounds will have the same empirical formula, and that in many compounds the valence of carbon is apparently not a whole number. To overcome this defect, the structural formula, which aims to show how the molecules are built up, was invented. In these formulas the valence of carbon, which is represented by —'s, called valence bonds, is assumed to be four in all cases, and it is also assumed that the atoms of carbon have the power of uniting with each other to form nuclei to which other elements may attach themselves. These formulas are also illustrated in the following table:

**Table 8. The Different Homologous Series of Hydrocarbons.**

| Generalized Formula of Series | Names Applied To Series | Names of First Compound of Series | Empirical Formula | Structural Formula | Formula of Second Member |
|---|---|---|---|---|---|
| $C_nH_{2n+2}$ ... | Methane, Paraffin, or Chain Series. | Methane<br>Marsh Gas<br>Fire Damp | $CH_4$ |  $\mathrm{H-\overset{H}{\underset{H}{C}}-H}$ |  $\mathrm{H-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-H}$ |
| $C_nH_{2n}$ ...... | Olefine, Ethylene, Unsaturated Open Chain Series. | Ethylene. | $C_2H_4$ |  $\mathrm{\overset{H}{\underset{H}{C}}=\overset{H}{\underset{H}{C}}}$ |  $\mathrm{\overset{H}{\underset{H}{C}}=\overset{H}{\underset{CH_3}{C}}}$ |
| $C_nH_{2n-2}$ .... | Acetylene Series. | Acetylene. | $C_2H_2$ | $\mathrm{H-C\equiv C-H}$ | $\mathrm{H-C\equiv C-CH_3}$ |
| $C_nH_{2n-4}$ .... | First member unknown. | | | | |
| $C_nH_{2n-6}$ ..... | Benzene,– Aromatic or Closed Ring Series. | Benzene. | $C_6H_6$ |  |  |
| $C_nH_{2n-8}$ ..... | Not many members discovered. | | | | |
| $C_nH_{2n-10}$ ... | Not many members discovered. | | | | |
| So on to.... | | | | | |
| $C_nH_{2n-32}$ ... | Not many members discovered. | | | | |

Hydrocarbons of the series $C_nH_{2n+2}$ make up the greater portion of the paraffine base of petroleums, as is indicated in Table 9. Members of the series $C_nH_{2n}$ are also constituents of many petroleums, while only a few of the higher members of the series $C_nH_{2n-2}$ and $C_nH_{2n-4}$, have been found in oils west of Pennsylvania. The aromatic series, $C_nH_{2n-6}$, occur in small amounts in nearly all petroleums. Occurrence of members of the other series is somewhat rare in petroleums, and are in small amounts when found at all.

**Fuel Oil and Other Products of Petroleum:** The increasing demand for gasoline and other petroleum products makes it very undesirable that crude petroleum as obtained from the wells be used for fuel. Besides, gasoline in a fuel oil is dangerous on account of the increased danger of explosions its presence entails. Fuel oil, then, is a very indefinite term that is applied to any product of petroleum used for the production of heat or power. There are no fixed specifications for it, and consumers order it to suit their requirements. The usual grades have a calorific value of about 135000 B. t. u. per gallon. The products from many of the oil refineries west of the Mississippi River are gasoline, naphtha, kerosene and fuel oil, while Eastern refineries usually carry the fractionation of the oil much farther, their output being such products as gasoline, benzine, naphtha, kerosene, light machine oil, automobile oils, cylinder oils, paraffin wax and tar, pitch, or coke.

## SECTION IV.

### GASEOUS FUELS.

**Advantages of Gaseous Fuels:** The many advantages possessed by gaseous fuels make them ideal for many purposes. Owing to their gaseous state, they require no labor in handling, and their freedom from foreign matter eliminates ash and danger of contamination. As the temperature is easily controlled, and the flame can be directed wherever desired, the working conditions of a furnace may be kept very uniform. The kindling temperature of gases is between 650°C and 700°C, and the speed of combustion is practically instantaneous at that point, which fact makes it easy to attain very high temperatures.

**Table 9. The Paraffin Series of Hydrocarbons, the Members of which are found in Natural Gas and Petroleum of the Western Pennsylvania District.**

| State at Ordinary Temp. | Name | Empirical Formula | Melting* Point Deg. C. | Boiling* Point Deg. C. |
|---|---|---|---|---|
| Gases: | Methane | $CH_4$ | —184.0 | —165.0 |
| | Ethane | $C_2H_6$ | —171.4 | — 93.0 |
| | Propane | $C_3H_8$ | —195 | — 45.0 |
| | Butane | $C_4H_{10}$ | —135 | + .1 |
| Liquids: | Pentane | $C_5H_{12}$ | —130.8 | 36.3 |
| | Hexane | $C_6H_{14}$ | — 94.0 | 69.0 |
| | Heptane | $C_7H_{16}$ | — 97.1 | 98.4 |
| | Octane | $C_8H_{18}$ | — 56.5 | 125.5 |
| | Nonane | $C_9H_{20}$ | — 51.0 | 150.0 |
| | Decane | $C_{10}H_{22}$ | — 31.0 | 173.0 |
| | Undecane | $C_{11}H_{24}$ | — 26.0 | 195.0 |
| | Dodecane | $C_{12}H_{26}$ | — 12.0 | 214.0 |
| | Tridecane | $C_{13}H_{28}$ | — 6.0 | 234.0 |
| | Tetradecane | $C_{14}H_{30}$ | + 5.0 | 252.0 |
| | Pentadecane | $C_{15}H_{32}$ | 10 | 270.0 |
| | Hexadecane | $C_{16}H_{34}$ | 18.0 | 287.0 |
| Solids: | Octadecane | $C_{18}H_{38}$ | 28.0 | 317.0 |
| | Eicosane | $C_{20}H_{42}$ | 37.0 | ....... |
| | Tricosane | $C_{23}H_{48}$ | 48.0 | ....... |
| | Tetracosane | $C_{24}H_{50}$ | 51.0 | ....... |
| | Pentacosane | $C_{25}H_{52}$ | 53–54.0 | ....... |
| | Hexacosane | $C_{26}H_{54}$ | 55–56.0 | ....... |
| | Octocosane | $C_{28}H_{58}$ | 60.0 | ....... |
| | Nonocosane | $C_{29}H_{60}$ | 62–63.0 | ....... |
| | Hentriacontane | $C_{31}H_{64}$ | 68.0 | ....... |
| | Dotriacontane | $C_{32}H_{66}$ | 70.0 | ....... |
| | Tetratriacontane | $C_{34}H_{70}$ | 71–72.0 | ....... |
| | Pentatriacontane | $C_{35}H_{72}$ | 75.0 | ....... |

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See American Petroleum Industry by Raymond F. Bacon and William A. Hamor, Published by McGraw-Hill Book Company, New York. Also Organic Chemistry by A. F. Holleman, Fourth English Edition, published by John Wiley & Sons, Inc., N.Y.

**Natural Gas** is the most remarkable fuel of all. Found in the earth under high pressure and free from non-combustible gases, it represents a perfect fuel. Upon being regenerated it undergoes partial decomposition and is, therefore, never preheated, but with it the highest temperatures that are practical are easily obtained by proper manipulation. The supply of this gas, formerly thought to be inexhaustible, is now declining rapidly, and this fact, combined with its demand for domestic purposes, is forcing its use in the metallurgical and other industrial arts to be abandoned. Geologically, natural gas is closely associated with petroleum and undoubtedly is of similar origin. It is composed of the lower gaseous hydrocarbons of the paraffin series, mainly methane.

**Artificial Gases** are manufactured from coal. The method of manufacture depends on the end sought. Thus in retort gases—coal gas and coke oven gas—only the volatile products of the coal are utilized for gas, while in the gas producer the whole combustible substance of the coal is converted into gas. Of these, coal gas and by-product gas most nearly approach natural gas in calorific power and efficiency. Producer gases always contain a high percentage of non-combustibles. The advantages in favor of the producer are that an otherwise poor fuel may be converted into a desirable one, and that all of the fuel is gasified. As to blast furnace gases, their utilization under boilers, in gas engines, and in blast furnace stoves represents a saving that amounts to millions in a single year. A detailed account of this fuel will be taken up later. Table 10 below shows useful data in comparing the various gaseous fuels.

### Table 10. Composition of Gaseous Fuels.

**Representative Analyses**
**Percent by Volume**

| | Natural Gas | | Coke Oven Gas | Bench or Coal Gas | Carburetted Water Gas | Water or Blue Gas | Producer Gas | | Blast Furnace Gas |
|---|---|---|---|---|---|---|---|---|---|
| | #1 | #2 | | | | | #1 | #2 | |
| Carbon Dioxide, $CO_2$ | .2 | .2 | 1.7 | 2.0 | 3.0 | 3.8 | 5.0 | 10.6 | 12.9 |
| Illuminants (as $C_2H_4$) | .4 | .5 | 3.0 | 3.7 | 10.0 | 0 | .2 | .4 | 0 |
| Oxygen, $O_2$ .......... | 0 | .3 | .1 | .8 | .5 | .5 | 0 | 0 | 0 |
| Carbon Monoxide, CO | 0 | .5 | 3.5 | 7.5 | 34.0 | 43.1 | 25.6 | 17.6 | 26.3 |
| Hydrogen, $H_2$ ........ | 0 | 0 | 53.9 | 48.5 | 35.5 | 47.5 | 10.2 | 11.8 | 3.7 |
| Methane, $CH_4$ ....... | 77.7 | 94.5 | 34.6 | 33.0 | 12.0 | .8 | 3.8 | 4.4 | 0 |
| Ethane, $C_2H_6$ ........ | 19.4 | 0 | not det'd | not det'd | not det'd | 0 | 0 | 0 | 0 |
| Nitrogen, $N_2$ ......... | 2.3 | 4.0 | 3.2 | 4.5 | 5.0 | 4.3 | 55.2 | 55.2 | 57.1 |
| *Net B.t.u. per cu.ft. | 1027 | 868 | 518 | 512 | 465 | 277 | 148 | 135 | 94.8 |
| Gross " " " " | 1134 | 963 | 583 | 573 | 505 | 301 | 157 | 146 | 96.7 |
| Sulphur per 1000 cu.ft | 0 | 0 | .8 lbs. | not det'd | not det'd | 0 | .1 lbs. | .15 lbs. | 0 |

*Does not include the latent heat of the water formed in combustion.

**Principle of the Gas Producer:** While there are many different types of gas producer, the apparatus is essentially a vertical cylindrical shaft, lined with fire brick, partially filled with coal when in use, through which air, or steam and air, are forced at the bottom where combustion of the non volatile part of the coal is continuous. In its upward passage the carbonic acid gas formed by the combustion of the carbon of the coal is reduced, in part, by the incandescent fuel, forming carbon monoxide. Part of the water, if steam is used, is also acted upon by the hot coke, forming carbon monoxide and free hydrogen, and some methane is obtained from the distillation which the coal undergoes at first. In case steam is used with the air the producer gives a gas which may vary in composition about as follows:

| | | |
|---|---|---|
| Carbonic Acid | $CO_2$ | 5 to 9% |
| Carbon Monoxide | $CO$ | 18 to 27% |
| Methane | $CH_4$ | 2 to 4% |
| Hydrogen | $H_2$ | 10 to 18% |
| Nitrogen | $N_2$ | 48 to 55% |

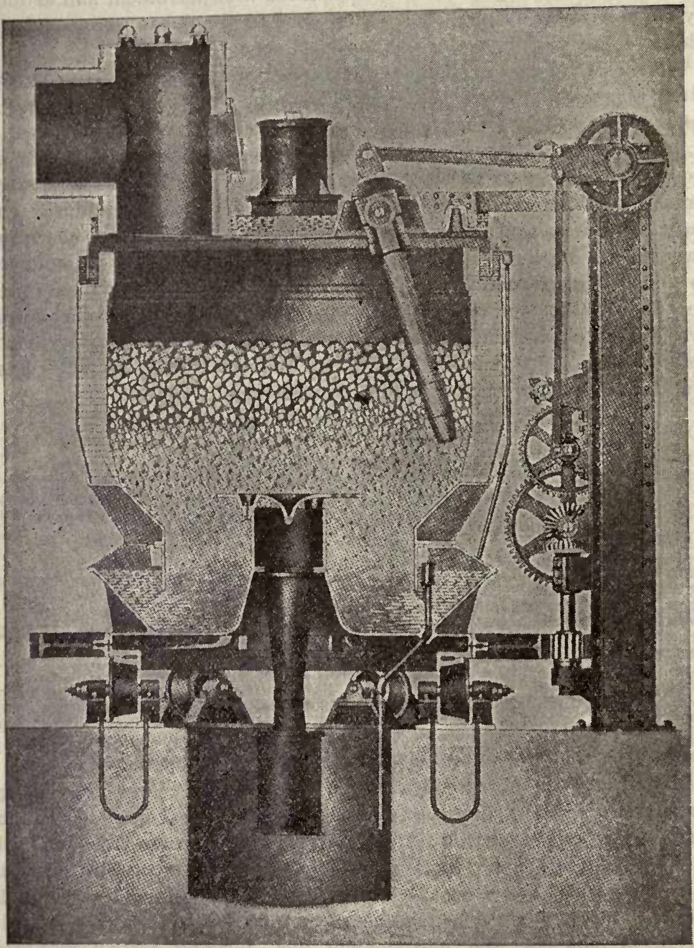


**Fig. 10. Sketch. Section Through Gas Producer.**

**Factors Affecting the Efficiency of the Producer:** The greatest efficiency of the gas producer is attained when all the oxygen of the injected air is caused to combine with carbon to form only carbon monoxide, provided the excess heat thus generated is also made available. In practice these results are never accomplished entirely, but efforts to attain them have revealed the fact that they can be most nearly approached by carefully regulating the temperature, by maintaining perfect uniformity of the working conditions, and by injecting steam with the air. All these objects are accomplished in fairly efficient degree in the Hughes mechanically poked producer, a brief description of which follows:

**The Hughes Producer as an Example of Mechanically Poked Producer:** This producer, a vertical section of which is illustrated in the accompanying sketch, is a cylindrical steel shell, 5/16″ thick, lined with 9 inches of first quality fire brick, and closed at the ends with water sealed tops and bottoms. When ready for use it sets with its base resting on five wheels which are mounted on a frame carried on a concrete foundation. By means of gears connected to a driving mechanism, it is rotated over these wheels, the speed of rotation when in use being 1/10 r. p. m. The top plate is a steel casting riveted to the charging floor, under which the producer itself revolves. It contains the openings for the gas outlet, the hoppers, the poker and the observation holes. There are two hoppers, through which coal is fed to the producer, one on each side of the outlet, but they are at different distances from the center of the producer to help provide even distribution of the coal. A bell valve closes the base of the hopper, and when this bell is dropped to dump the coal into the producer, the hopper may be closed by sliding a circular plate over its top. There are several holes three inches in diameter at various points in the top seal for observing the condition of the fire, and for poking out clinkers; these holes are closed with water sealed caps. The poker is a round hollow steel casting with a forged steel tip. It is six feet in length and tapers from eight inches in diameter at the top to five inches at the tip. The poker and its trunnions are water cooled, the water being admitted through the trunnions, then passing through the poker to the top plate which is covered with the water to a depth of five inches. From the top plate the water flows to the top seal, or trough, around the top plate, then through a drain pipe to the water seal in the ash pan. The top of the poker is enclosed in a gas tight mounting, and is so mounted that the poker is swung back and forth through an arc of about 35° by means of eccentric connections from the producer rotating mechanism. A full stroke of the poker carries its tip from the center to the side wall of the producer, and is timed to occupy 3.21 minutes, thus allowing 3.1 strokes in one revolution of the producer. The result of the rotating motion of the producer and the backward and forward action of the poker is to produce a series of semi-ellipses, so that the poker covers, in a period of 70.72 minutes, or 22 strokes, practically the entire area of the shell. The bottom of the vessel serves as an ash pan, which must also be water sealed. To form this seal the bottom is made in the form of a circular trough, which is attached to the main shell of the vessel so that its outer rim, or lip, extends several inches beyond this circumference of the shell. Into this trough the sealing shell of the producer projects to within five inches of the bottom. Since this construction leaves the central portion of the bottom within the producer somewhat cone shaped, the ashes are deflected toward this five-inch opening at the bottom of the trough, where they may be removed through the water which flows from the top and fills the trough to prevent the escape of gases. The steam blower is inserted through the center of the bottom and extends some twenty inches into the producer, where it is capped by a conical hood to prevent it from becoming choked with the ashes. The mixture of steam and air is admitted just beneath this hood through three rows of small openings to provide for equal distribution of the blast. The ratio of steam and air is controlled by the openings at the bottom of the blower, but the quantity of the mixture admitted to the producer is regulated by the steam pressure, which may be changed at will by the operator from the charging floor.

**Conditions and Reactions:** An understanding of the principle and the operation of the producer is much clarified by a study of the reactions and conditions prevailing in it while it is in use. A study of the conditions show that there are three zones or belts of action in the producer, known as the distillation or top zone, the reaction, or middle, zone, and the combustion, or bottom, zone. Then, below these zones is the inactive, or ash, zone. Thus, upon being charged into the producer, the raw coal is first subjected to a distillation very much as in the process of coking. In this top zone the volatile products are driven off, and the coal is converted into a kind of coke, which will have then reached the reaction zone. Some of this coke, passing through the reaction zone unchanged, reaches the region just over and around the hood of the blower. Here it meets the incoming air, and having been heated to above the kindling temperature, combustion takes place, whereby all the remaining carbon is consumed according to this simple reaction, $C+O_2=CO_2+\text{heat}$. The carbon dioxide gas thus generated, together with the undecomposed steam and other gases, rises at once into the reaction zone. Here the coke, having been heated to a high temperature from the heat liberated by the above reaction, acts as a reducing agent toward both carbon dioxide and water, thus, $CO_2+C+\text{heat}=2\ CO$ and $H_2O+C+\text{heat}=H_2+CO$. It will be noted that both these reactions absorb heat, but that only the second is under control and, hence, available for lowering the temperature in the producer. The reduction of all the $CO_2$ formed in the combustion zone has never been brought about, so that a small quantity is always present in producer gas. The relative amounts of $CO$, $H_2$ and $CO_2$ in the final gas depends to a great extent upon the manipulation of the producer. As to the other components of this gas, the nitrogen, being introduced with the oxygen as air, cannot be controlled, while the hydrocarbons such as $CH_4$ and $C_2H_4$ represent products of the distillation.

**Operation of the Hughes Producer:** The ideal conditions in a Hughes producer are realized when the combustion zone extends to about a foot above the top of the blower hood; when the reaction zone is from one and one-half to two feet thick; when the distillation zone is from one-half to one foot thick; when the conditions are such that the ash, the coke and the coal occur in level zones; and when the amount of air and steam are so adjusted that the fuel is properly burned without excess of any of the undesirable components in the final gas. The necessary air is injected into the producer by a steam jet. Thus the steam serves the two-fold purpose of injecting the air and of controlling the temperature in the producer by absorbing heat, during its decomposition, which later appears as potential energy in the gas. This lowering of the temperature, combined with the disintegrating effect of the steam upon the ash, tends to prevent clinkering. If too much steam be used, the temperature in the reaction zone will drop below normal, the CO will be low and the percentage of hydrogen will be high. This condition causes the gas to burn with a short, intense non-luminous flame that has a detrimental effect upon the brick work of the furnace in which it is used, especially upon the ports and roof of the open hearth furnace. But the judicious use of steam may increase the efficiency of the producer to 80 or 85% of the heating power of the fuel. The experienced operator judges the quality of the gas by its appearance, striving for a dense yellowish blue gas. The greatest trouble in operating arises from the accumulation of unburned carbon and fine ash in the mains, which must be cleaned out at regular intervals. The mains are brick lined and are fitted with numerous dust catchers, or man holes, to afford access for cleaning.

## SECTION V.

### THE SOLID NATURAL FUELS.

**Analysis of Solid Natural Fuels:** Upon examination all the solid natural fuels are found to consist of combustible and non-combustible materials. The combustible portion is composed mainly of carbon and hydrogen, and the constituents of the non-combustibles are water and a mixture of mineral substances called ash. By the gradual application of heat without access of air, the water is first expelled, which is followed closely by the combustible volatile matter, and there remains a non-volatile mass composed of carbon, called fixed carbon, and ash. Upon admitting air, the fixed carbon burns readily, leaving only the ash. A similar process carried out so as to determine the amounts of these four classes of materials is called a **proximate analysis.** There are two general methods for making a proximate analysis, depending upon whether or not it is desired to separate the volatile matter into its constituents. These are often referred to as the American and the European methods, the latter being also called the **progressive distillation method.** The determination of the percentages of the various elements present in the fuel constitutes an **ultimate analysis.** The following analysis of a coal by each of these three methods will illustrate all the points mentioned, and help to show the importance of the chemical analysis.

**Table 11. Analysis of a Solid Fuel, Coal, by the Three Different Methods.**

| | | |
|---|---|---|
| Proximate Analysis, American Method | Ash | 7.16% |
| | Fixed Carbon | 59.98 |
| | Volatile Matter | 32.86 |
| | Total | 100.00% |
| | Total Sulphur | 1.02% |
| | Phosphorus | .005% |

| | | | |
|---|---|---|---|
| Proximate Analysis, Progressive Distillation Method | Coke | Ash | 7.160% |
| | | Carbon | 59.980 |
| | Tar | | 5.420 |
| | Free $NH_3$ | | .285 |
| | Comb. $NH_3$ | | .041 |
| | Moist | | 4.765 |
| | Oxygen | | 1.046 |
| | Volatile Sulphur | | .313 |
| | Crude Benzol | | 1.353 |
| | Gas | | 19.640 |
| | Total | | 100.003% |

| | | |
|---|---|---|
| Ultimate Analysis | Ash | 7.16% |
| | C | 79.41 |
| | H | 5.14 |
| | N | 1.46 |
| | O | 6.03 |
| | S | 1.02 |
| | | 100.22% |

**Wood:** This very interesting substance is composed mainly of cellulose, $C_6H_{10}O_5$, a compound formed in the tree or plant from water taken up from the soil and carbon dioxide from the air. The change is wrought mainly in the leaves of plants through the agency of sunlight. Wood, then, represents potential energy, the original source of which is the heat from the sun, and it, in turn, is the source of all the natural solid fuels. It was the first fuel used by man, and for centuries was the principal one. In metallurgy it has been supplanted by coal, though for some purposes it is still used, mainly in the form of charcoal obtained by the destructive distillation of wood. The calorific power of dry wood is about half that of good coal.

**Peat** is of little value as a metallurgical fuel. It finds extensive use in Europe as a domestic fuel, and the better grades may be successfully employed in gas producers. Its chief interest lies in the fact that it is the first step in the formation of coal. Peat results from the decomposition of wood substance out of contact with air. It is formed in swamps and marshes from water plants of all kinds such as algae, mosses, sedges, rushes, reeds, shrubs, like willows, and even trees. A species of moss called sphagnum is especially important in the formation of peat. It grows on the surface of still and shallow waters with only a small portion in air, and as it grows the submerged portion extends farther and farther beneath the surface until the bottom is reached. Starting growth near the shore of shallow lakes, it gradually extends into a lake until the whole basin is filled with soft carbonaceous matter, and a bog results. This growth is followed by larger growths, until the former lake is packed with carbonaceous matter. The accumulation being submerged, the carbon compounds of the plants are slowly decomposed, by which process the carbon is isolated, though a part escapes with hydrogen and oxygen as marsh gas and carbon dioxide. The reaction is represented thus:

$$6C_6H_{10}O_5 = 7\,CO_2 + 3\,CH_4 + 14\,H_2O + C_{26}H_{20}O_2$$

| | | | | |
|---|---|---|---|---|
| Cellulose or Wood Substance | Carbon Dioxide | Marsh Gas | Water | Peat Substance |

In certain geological periods, particularly the carboniferous, the conditions being more favorable for plant growth of this kind, the processes described proceeded more rapidly than at present, with the result that marshes of great depth and area were filled with vegetable growths. These carbonaceous deposits were subsequently submerged through vertical movements of the earth's crust, in which position they became covered by deposits of sedimentary rocks. Later movements of the earth's crust raised many of these deposits up out of the sea. In the meantime the peat had been changed into coal.

**Lignite and Brown Coal,** geologically and chemically, occupy positions intermediate between peat and coal. They were formed between the Quaternary and Jurassic periods and are widely distributed. They have low calorific power, and some kinds contain as much as 15% of water. They are sharply distinguishable from peat, but grade into coal so gradually that no one has attempted to distinguish between the oldest lignite and the youngest coal. The relation between vegetable and mineral fuels are more clearly shown by the accompanying table (12) and diagram (Fig. 11).

**Table 12. Approximate Analyses of the Different Solid Fuels.**

| | Air Dried Wood | Air Dried Peat | Lignite | Bituminous Coal | Anthracite Coal |
|---|---|---|---|---|---|
| | % | % | % | % | % |
| Vol. M.... | 42–40 | 30–60 | 30–45 | 20–45 | .5–6 |
| Fixed C.... | 39–41 | 11–40 | 45–50 | 40–85 | 85–92 |
| Ash........ | .15–2 | 3–75 | 4–15 | 4–20 | 2–15 |
| Moisture or Water.... | 20–25 | 6–20 | 10–15 | 1–6 | .5–4 |
| C. P. (Cals. per Kilo). | 4600–5000 | 2000–5000 | 3000–6000 | 7000–9000 | 9000–9500 |

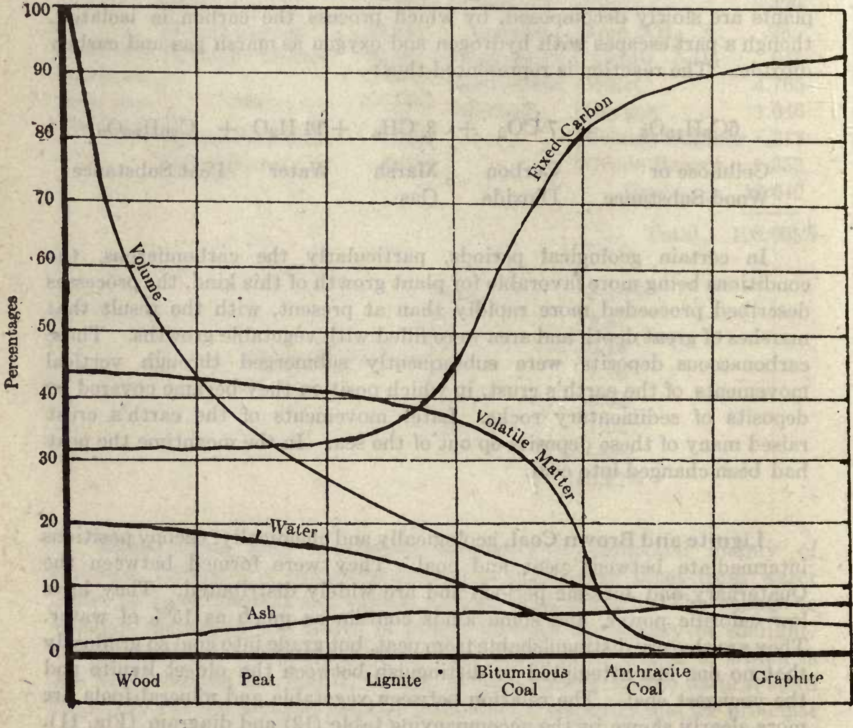
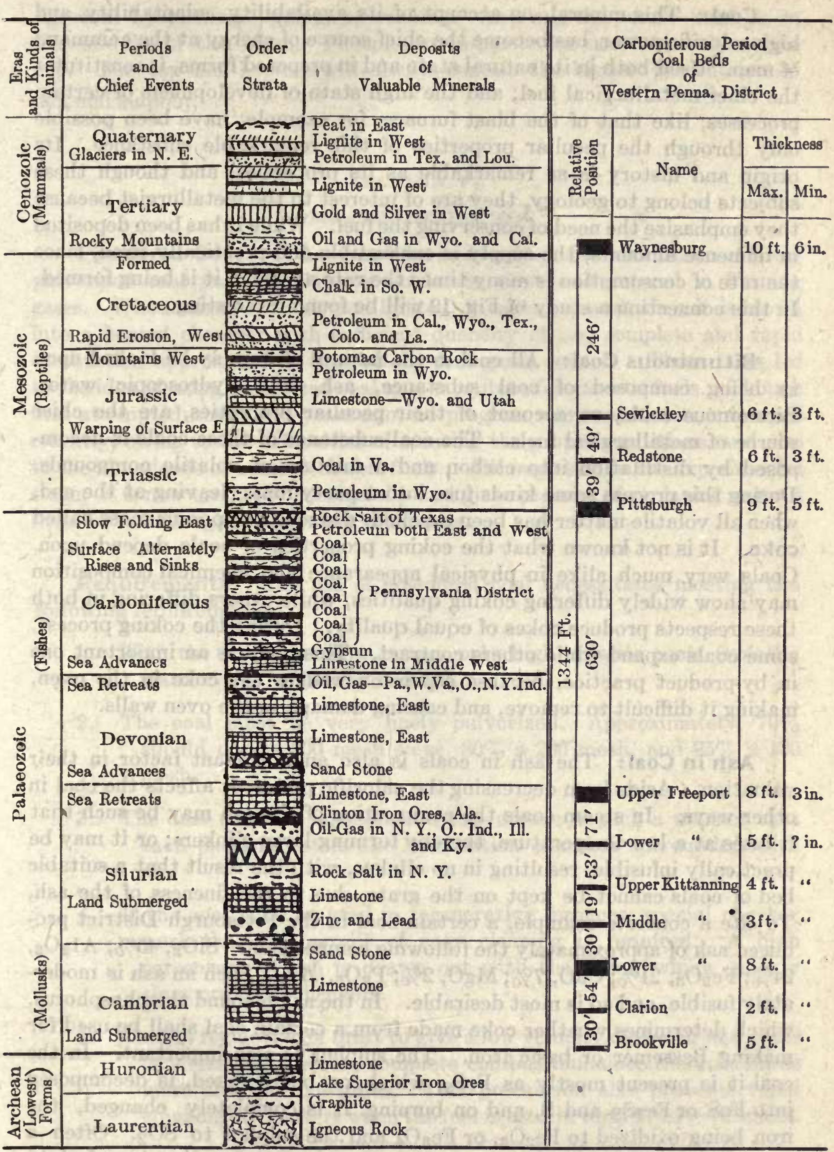


Fig. 11. Graphic Representation of Transformation of Fuels.



| Eras and Kinds of Animals | Periods and Chief Events | Deposits of Valuable Minerals |
|---|---|---|
| Cenozoic (Mammals) | Quaternary<br>Glaciers in N. E. | Peat in East<br>Lignite in West<br>Petroleum in Tex. and Lou. |
| | Tertiary<br>Rocky Mountains | Lignite in West<br>Gold and Silver in West<br>Oil and Gas in Wyo. and Cal. |
| Mesozoic (Reptiles) | Formed<br>Cretaceous<br>Rapid Erosion, West | Lignite in West<br>Chalk in So. W.<br>Petroleum in Cal., Wyo., Tex., Colo. and La. |
| | Mountains West<br>Jurassic<br>Warping of Surface E | Potomac Carbon Rock<br>Petroleum in Wyo.<br>Limestone—Wyo. and Utah |
| | Triassic | Coal in Va.<br>Petroleum in Wyo. |
| Palaeozoic (Fishes) | Slow Folding East<br>Surface Alternately Rises and Sinks<br>Carboniferous<br>Sea Advances | Rock Salt of Texas<br>Petroleum both East and West<br>Coal<br>Coal<br>Coal<br>Coal<br>Coal } Pennsylvania District<br>Coal<br>Coal<br>Coal<br>Gypsum<br>Limestone in Middle West |
| | Sea Retreats<br>Devonian<br>Sea Advances | Oil, Gas—Pa., W.Va., O., N.Y. Ind.<br>Limestone, East<br>Limestone, East<br>Sand Stone |
| | Sea Retreats<br>Silurian<br>Land Submerged | Limestone, East<br>Clinton Iron Ores, Ala.<br>Oil-Gas in N. Y., O.. Ind., Ill. and Ky.<br>Rock Salt in N. Y.<br>Limestone<br>Zinc and Lead |
| (Mollusks) | Cambrian<br>Land Submerged | Sand Stone<br>Limestone |
| Archean (Lowest Forms) | Huronian | Limestone<br>Lake Superior Iron Ores |
| | Laurentian | Graphite<br>Igneous Rock |

Carboniferous Period Coal Beds of Western Penna. District

| Relative Position | Name | Thickness Max. | Thickness Min. |
|---|---|---|---|
| | Waynesburg | 10 ft. | 6 in. |
| 246′ | | | |
| | Sewickley | 6 ft. | 3 ft. |
| 49′ | | | |
| | Redstone | 6 ft. | 3 ft. |
| 39′ | | | |
| | Pittsburgh | 9 ft. | 5 ft. |
| 630′ | | | |
| | Upper Freeport | 8 ft. | 3 in. |
| 71′ | | | |
| | Lower " | 5 ft. | ? in. |
| 53′ | | | |
| | Upper Kittanning | 4 ft. | " |
| 19′ | | | |
| | Middle " | 3 ft. | " |
| 30′ | | | |
| | Lower " | 8 ft. | " |
| 54′ | | | |
| | Clarion | 2 ft. | " |
| 30′ | | | |
| | Brookville | 5 ft. | " |
| 1344 Ft. | | | |

Fig. 12. Diagram Depicting Geologic Periods in which Gas, Oil and the Valuable Minerals are Found in the United States.

**Coal:** This mineral, on account of its availability, adaptability, and high calorific power, has become the chief source of energy at the command of man. Used both in its natural state and in prepared forms, it constitutes the chief metallurgical fuel; and the high state of development of certain processes, like that of the blast furnace, for example, have been possible only through the peculiar properties of this remarkable substance. Its origin and history is as remarkable as its properties, and though these subjects belong to geology, they are of interest to the metallurgist because they emphasize the need of conserving the fuel. While it has been deposited in immense amounts, the supply is exhaustible and practically fixed, since the rate of consumption is many times the rate at which it is being formed. In this connection a study of Fig. 12 will be found interesting.

**Bituminous Coal:** All coal in the natural state may be looked upon as being composed of coal substance, ash, and hydroscopic water. Bituminous coals, on account of their peculiar properties, are the chief source of metallurgical fuels. The coal substance of these coals is decomposed by distillation into carbon and a mixture of volatile compounds. During this process some kinds fuse into a pasty mass, leaving at the end, when all volatile matter has been expelled, a strong but porous mass called **coke.** It is not known what the coking properties of coals depend upon. Coals very much alike in physical appearance and chemical composition may show widely differing coking qualities, while others differing in both these respects produce cokes of equal quality. During the coking process, some coals expand while others contract. This point is an important one in by-product practice, because expansion wedges the coke in the oven, making it difficult to remove, and causing damage to the oven walls.

**Ash in Coal:** The ash in coals is also an important factor in their valuation. Aside from decreasing the calorific power, it affects the coal in other ways. In steam coals the composition of the ash may be such that it fuses at a low temperature, thereby forming large clinkers; or it may be practically infusible, resulting in no clinker, with the result that a suitable bed of coals cannot be kept on the grate, due to the fineness of the ash. To cite a concrete example, a certain coal in the Pittsburgh District produced ash of approximately the following composition: $SiO_2$, 45%; $Al_2O_3$, 24%; $Fe_2O_3$, 21%; CaO, 7%; MgO, 2%; $P_2O_5$, .6%. Such an ash is moderately fusible, and so is most desirable. In the ash is found the phosphorus, which determines whether coke made from a certain coal shall be used for making Bessemer or basic iron. The sulphur is also important. In the coal it is present mostly as $FeS_2$, which, on being coked, is decomposed into FeS or $Fe_7S_8$ and S, and on burning, it is completely changed, the iron being oxidized to $Fe_2O_3$, or $Fe_3O_4$ and the sulphur to $SO_2$. Often a seam of good quality coal is divided or cut horizontally by deposits of slaty material known as bone coal, binder, horse back, etc., all of which must be mined with the coal. Where these conditions exist, it is necessary to clean the coal by picking, jigging, or washing. As a rule the purest coal is in the middle of the seam. Phosphorus in particular occurs mainly at the top. The top and bottom will always contain the highest percentages of ash and sulphur.

## SECTION VI.

### PREPARED SOLID FUELS.

**Powdered Coal:** It has long been known that the combustion of finely pulverized coal presents features similar to those encountered in burning gases. When mixed with air and ignited, it explodes; and when it is blown into a heated chamber with sufficient quantity of air, complete and rapid combustion approximating that of the fuel gases ensues. These facts led to the idea of using pulverized coal as a substitute for gaseous fuels. Though first attempted about 100 years ago, no progress was made in its use until recently, owing to the difficulties of securing the proper conditions, and also to the abundance of other desirable fuels. Although still in the experimental stage, it is now used very successfully and gives promise of replacing gaseous fuels for metallurgical and many other uses.

**Requirements:** The use of powdered coal necessitates meeting the following requirements:

1. With the apparatus now in use, only high volatile coals (volatile matter over 30%) may be used.
2. The coal must be very finely pulverized. Approximately, 70% should pass a 300 mesh sieve, 80% a 200 mesh, and 95% a 100 mesh.
3. The dust must be injected into the furnace in such a manner that each particle enters the combustion chamber surrounded with air.
4. If the coal is to be used in regenerative furnaces, special checker work that will permit of easy cleaning is required. A high percentage of ash is drawn out with the gases, which quickly clogs ordinary checkers.
5. Careful regulation of draft to give a low velocity of the air and gases is necessary to secure complete combustion, since the dust burns more slowly than gases. This precaution also prevents rapid clogging of checkers when the fuel is used in regenerative furnaces.

The pulverizing of coal makes it necessary to dry it thoroughly, and necessitates the installation of special appliances for handling the dust, which can be done only through pipes and tightly closed bins. Two general methods of handling are available, namely, the worm screw and the pneumatic. The third requirement calls for special burners, so constructed as to permit of the regulation of the amounts of both air and dust and the adjustment of the direction of the flame. The equipment will consist, then, of a dryer, a pulverizer, separator, conveyors, bins, burners, and air compressors, with the necessary motors or engines. Added to these, in many cases, will be the special regenerators previously mentioned.

**Advantages of Powdered Coal:** It is adaptable for use wherever large amounts of fuel are consumed, and many claims as to its advantages are made. As compared with producer gas to fire open hearth furnaces, for example, it is said to be as efficient and convenient as the gas and to give a more regular supply of heat. It is cheaper to prepare than producer gas, increases the production of steel 10% or more, and reduces the loss by oxidation—all without contamination of the steel from impurities in the ash, if proper conditions prevail.

**The Sharon Plant:** The appliances for preparing and burning the coal vary in form and method. A brief description of the installation at the Sharon Works of the Carnegie Steel Company, which is equipped to supply three 40-ton basic open hearth furnaces, may serve as an example of one of the methods employed in its use. This plant was the first of the Carnegie Company's to use this fuel in the open hearth. The installation is that of the Raymond Bros. of Chicago, who employ an impact pulverizer with an air-separating system.

**Description of Pulverizing Plant:** The building in which the pulverizing is done is separated from the open hearth building by about 75 yards. Outside this building, is a small trestle storage bin to which the coal, crushed to pass a one inch ring, is delivered from the cars. From this bin the coal is delivered by a motor driven belt conveyor to the elevated end of a revolving cylindrical dryer, about 30 ft. long and 5 ft. in diameter, inclined at an angle of about 10°. By revolving this dryer, the coal is caused to pass slowly toward the lower end, and in so doing it is stirred and scattered in the cylinder, so as to be thoroughly dried by a forced circulation of an atmosphere of hot gases from a small brick furnace located at the elevated end of the furnace. These gases are conducted from the furnace to the lower end of the dryer by a stationary flue, about 18 inches in diameter and concentric with the external cylinder. Upon reaching the lower end of the dryer, the coal is discharged into a hopper bin from which it is elevated vertically a distance of about 20 ft., by means of belt buckets, to a 25-ton storage bin. From this bin it is fed by gravity to the pulverizer, through the opening of which it is mechanically fed at a rate adjusted to the speed of the pulverizer, which has a capacity of 5 tons per hour. Through a pipe, about 16 inches in diameter, leading from the top of the pulverizer, the finest dust is pneumatically elevated to a cone shaped cyclone separator, about 6 ft. in diameter and some 70 ft. above the pulverizer. The mixture of air and dust enters at the top of the separator on a tangent, and is, therefore, given a swirling motion at the same time that its velocity is reduced. The air, carrying very little dust, is forced out through a pipe, about 24 inches in diameter, inserted in the center of the top of the separator. Through this pipe the air is returned to the pulverizer, completing the circuit. By this arrangement the dust in the air, on entering the separator, is subject to the double effect produced by the whirling motion and the reduction in speed—namely, centrifugal force and gravity—with the result that it is precipitated upon the inclined wall of the separator and falls out at the bottom through a rectangular chute (about 6″x8″) leading vertically down to a 12-inch screw conveyor, which carries the dust to the distributing conveyor located above the open hearth furnaces. This conveyor, extending at right angles to the 12-inch one, distributes the dust to six 9-ton bins, one of which is located above and at each end of each furnace. The bottoms of these bins are connected to small 4-inch screw conveyors, driven by variable speed motors, which feed the dust to the burners at any speed desired. Falling vertically through a 4-inch pipe, the dust passes through a 1-inch opening into a 2-inch horizontal pipe where it is met at right angles by a jet of compressed air. This jet blows the dust through the 2-inch pipe a distance of about 8 inches into a 5-inch nozzle, some 16 inches long, where it is mixed with a larger volume of air under the low pressure of 16 inches of water. The velocity of this air is sufficient to carry the dust into the furnace through a water cooled opening, where it comes in contact with regenerated air and is completely burned. The air blown in through the burner is about 25% of the total required for combustion.

**Clairton and Homestead Plants:** More recent and much larger installations for powdered coal have been made at Clairton and Homestead. The plant at Clairton is equipped to supply 5 of the 16 sixty-ton open hearth furnaces, while the one at Homestead is designed to furnish fuel for the whole of the No. 3 open hearth plant, which consists of twenty-four 60-ton furnaces. At both these plants the drying, pulverizing and conveying equipment is practically the same in kind as that used at Sharon, but a different type of burner is used. While the burners at Sharon are mechanically fed, at Clairton and Homestead they are wholly pneumatic. The principle of the pneumatically fed burners is easily understood from a description of the apparatus. The arrangement of the burner is shown in the accompanying drawing, Fig. 14. It consists of a delivery pipe, 1¼ inches in diameter by 2 feet 3 inches long, a compressed air nozzle, and a "cross," which is a small casting containing a 3-inch cubical cavity. The nozzle, ⅜ inches in diameter inside, passes through one side of the cross, then across the cavity and enters the delivery pipe inserted in the opposite side, so as to give an injector effect that draws the dust through the one inch opening shown by the dotted lines of the drawing. This opening is connected by a suitable pipe to a cast iron feeder box attached to the bottom of the storage bin, located some ten feet away. This box, about twelve by fourteen inches in cross section, is in the form of an elbow. One end is bolted to the bottom opening of the bin, while the other is closed with a steel plate. The pipe leading to the burner is inserted in an opening on the top of the horizontal portion of the box. With all connections between burner and feeder box tight, the operation of the burner is very simple. By means of a valve, not shown in the drawing, compressed air delivered under a pressure of about eighty pounds may be admitted through the nozzle, when the suction draws the

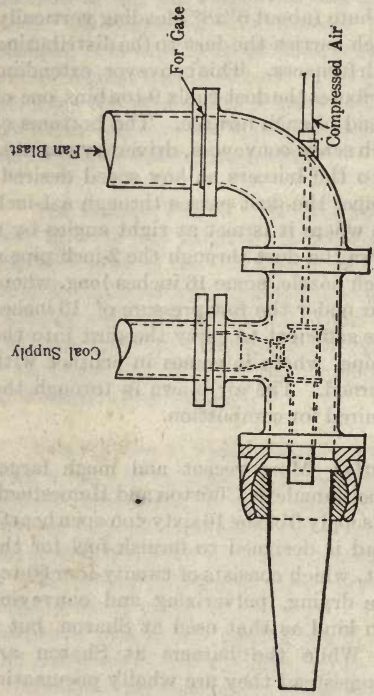


FIG. 13. Coal Burner Used with Mechanical Feed.

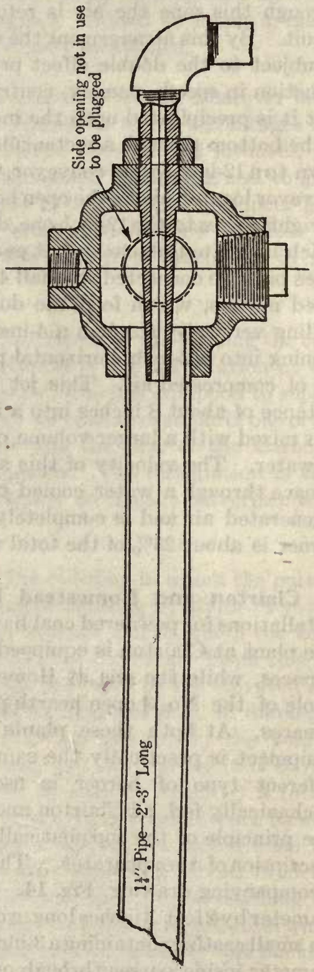


FIG. 14. Coal Burner Used with Pneumatic Feed.

coal dust from the feeder box and blows it through the delivery pipe into the furnace. It will be observed that the design of this burner is based upon the principle that the quantity of fuel dust injected into the furnace is controlled by the quantity of air passing through the injector. The threaded hole in the top of the cross provides a means of attaching the burner to its supports.

**Coke.** Coke is the residue that remains after certain bituminous coals have been subjected to destructive distillation. Owing to its peculiar structure and physical, or mechanical, properties, it has become the chief metallurgical fuel. All coke possesses a cellular structure, but there is a wide variation in the degree of porosity for different cokes. Likewise the hardness, brittleness and strength of coke is subject to wide variations. Coke for blast furnace consumption should be of a porous character to admit of ready combustion, and it must at all times be sufficiently strong to resist pressure due to the heavy burden without crushing. In chemical composition, the different cokes show a similar wide variation, though for metallurgical purposes the fixed carbon, which is the only constituent sought, will constitute 85 to 90% of the coke. The other constituents, roughly stated as ash, sulphur and phosphorus, are impurities. The per cent. of phosphorus in the coke determines whether the coke is suitable for making Bessemer or basic iron. For the former grade, modern practice requires that the phosphorus content of the coke must not exceed .018%. The sulphur content ranges from .60% to 1.50%, though it is evident that both the sulphur and ash should be kept as low as possible.

**Methods of Manufacturing Coke:** There are two methods for the manufacture of coke, known as the beehive and the by-product, or retort, process. In the beehive process, air is admitted to the coking chamber for the purpose of burning therein all of the volatile products of the coal to generate heat for further distillation. Incidentally, some of the fixed carbon of the coal is also consumed. In the other method, the coking chambers are air tight, and the necessary heat for distillation is supplied from external combustion of the volatile products of the coal; and with modern ovens, properly operated, only about half of the gaseous matter from the coal is used in carrying on the coking process. While the beehive process was, until recently, the leading method for the manufacture of coke, it is fast being replaced by the by-product process. The processes of manufacture have very little effect on the quality of the coke, but if there is any difference, the latter process has the advantage. There is, however, a difference in appearance, due mainly to the difference in the coking temperature of the two processes, that of the by-product being much lower than the beehive. In general, beehive coke is silvery gray in appearance, while by-product coke is of a much darker color. As examples of these two methods of coking, the following brief descriptions of plants are to be taken as typical of the best modern practice for each process.

## SECTION VII.

### THE BEEHIVE PROCESS FOR THE MANUFACTURE OF COKE.

**The Continental No. 1 Plant of the H. C. Frick Coke Company** may be cited as an example of beehive coke practice. It is located near Uniontown, Pa., in the southeastern part of the famous Connellsville coke region. It consists of a coal mine and a coking plant of 400 beehive ovens.

**The Mine:** Since the coal bed here lies about 330 feet below the surface, the coal is mined through a shaft. Although some gas is given off as the coal is mined, it is prevented from collecting and thus becoming dangerous by a very efficient system of ventilation, which permits the installation of electrical appliances for lighting and the use of both pick and machine methods of mining. The coal seam in this mine varies from seven to nine feet in thickness, but in mining the coal, about four inches at the bottom and from four to eight inches at the top, being high in ash, sulphur and phosphorus, is allowed to remain in order to improve the quality of the coke. Incidentally, this top discard also helps to support the gob, an easily dislodged and treacherous slate-like formation lying between the coal and the hard overlying rock deposit and forming the roof of the mine. The average output of the mine is twelve hundred net tons per day. For transporting this coal through the mine underground, a combination system of electric and rope haulage is employed from certain points, while horses are used to distribute empty cars to and assemble loaded cars from the various working places. From these assembling points the loaded cars are moved by electric locomotives in trains of thirty cars each to a sub-station, where they are attached to the rope haulage which pulls them to the foot of the shaft. Here they are hoisted, one at a time, to the tipple and automatically dumped into bins. From these bins the coal is loaded by chutes into electric larries which convey it to the ovens some hundred yards away. Each larry holds sufficient coal to charge one oven, and it will be noted that run-of-mine coal is used for coking, no crushing nor preparation of any kind being necessary.

**Construction and Arrangement of the Ovens:** As to the essential features of construction, the name beehive is literally descriptive of the form of the beehive oven. The dome-like chamber, built on a suitable foundation, is constructed of highly refractory brick, has a flat but slightly sloping bottom, an opening in the top, the "trunnel head," through which the coal is charged and the products of distillation and combustion escape, and an arched opening at the bottom, called the door, through which air is admitted for combustion and the coke is watered and drawn. In general, the dimensions of different ovens vary a great deal. The ovens at this plant are each 12 feet 3 inches in diameter and 8 feet high from the bottom to the top of the dome, inside dimensions. Of this height, the side wall, built of fire brick, rises vertically a distance of 27 inches, and is capped by the crown which is built of silica brick. Except in the case of the special brick used about the openings, the brick in these walls are of standard size and are laid ends in and out, thus making both the side wall and the crown wall approximately 9 inches thick. Finally, this brick structure is covered on the outside and up to the level of the "trunnel head," which is 14 inches in diameter, with loam or rough clay which acts as an insulator of and a store house for heat. For retaining this loam covering, there are in general three different arrangements of ovens as follows: (1) the bank system, in which the ovens are built in single rows against a bank of earth, natural or artificial, thus making it necessary to build but one retaining wall along the front of the ovens; (2) the single block system, which consists of a single row of ovens with retaining walls at both the front and back; and (3) the double block system, in which the ovens, in a double row, are built back to back or staggered with a retaining wall extending along the front of each row. At this plant there are four double block batteries and two batteries of banked ovens.

**Waste Heat System:** One battery of the banked ovens, forty in number, is arranged for utilizing the waste heat from the products of combustion to generate steam. For this purpose a large tunnel is constructed in the bank some 10 feet back of the ovens and parallel to the battery. This tunnel is connected to each oven by means of a small flue, which conducts the hot gases out of the oven from an opening sufficiently above the side wall to prevent its being closed by the largest charge of coal used. Each flue is provided with a damper for closing off the draft during the period the oven is being watered, drawn and charged. From the battery, the tunnel passes to the boiler house, where branches conduct the hot gases through the fire boxes and flues of the boilers which are connected to a common stack, about 100 feet in height to cause the proper draft. During the coking period, the "trunnel head" is necessarily kept tightly closed. Owing to the increased draft, these ovens are inclined to run up a little higher temperature than the ordinary oven, so that the temperature in the tunnel is high, sometimes reaching 1500°C. A maximum of about 800 horsepower is generated from the waste heat from this battery of forty ovens.

**Charging the Ovens:** The ovens are charged as soon as practicable after drawing, so that the stored up heat from the previous charge will be sufficient to start the coking process. In the case of new work, the ovens must be heated up gradually to a coking temperature by means of wood and coal fires, after which period small charges of coal for coking are used until the ovens reach normal working conditions. With the oven in readiness for charging, the door is bricked up to within about one and one half inches of the top; and the charge, which consists of six and one half tons of coal for 48-hour coke and eight tons for 72-hour coke, the latter being made over the week-ends, is dropped through the "trunnel head" from the larry above, leaving the coal in a cone shaped pile in the oven. In order to secure uniformity in the coking of the coal, this pile must be levelled so that the coal will lie in a bed of uniform depth over the entire bottom of the oven. This result is attained by means of an electrically operated leveling machine, which is moved from oven to oven on the same tracks that the charging larry uses. The essential part of this machine consists of a vertical rod and sleeve, on the lower end, or head, of which is mounted two collapsible leveling arms. By means of suitable gear connections with an electric motor, this apparatus, with the head closed, may be mechanically lowered through the "trunnel head" upon the apex of the pile of coal, when the rod and sleeve are made to revolve and the leveling arms are at the same time slowly extended. These motions, combined with the continued lowering of the head, distribute the coal to a uniform depth in a very few minutes. In works not equipped with this machine, the leveling is accomplished by means of a large long-handled scraper, operated, by a laborer, through the door of the oven, which is purposely bricked up to about only two-thirds of its height at the time of charging.

**The Coking Process** begins very soon after the levelling is completed, as the ovens retain enough heat in the brick of the walls and the loam backing to start the distillation of the volatile matter of the coal. As more and more heat is conducted through the walls from the hot loam backing, the temperature of the interior of the oven soon reaches the kindling point for these volatile gases, which, in the presence of the air admitted to the oven, ignite with a slight explosion at first, then continue to burn quietly in the crown of the oven, or, as small candle-like flames at the surface of the coking mass, thus supplying heat to continue the process. The coking proceeds from the top of the coal downward, so that the coking time depends mainly upon the depth of the coal. The volume of volatile matter thus rapidly approaches a maximum, which is maintained for a period, then declines to practically nothing, hence the burning of this volatile matter must be regulated by gradually closing up the opening at the top of the door for the admission of air. This regulation is very necessary to maintain the temperature at a maximum, and conserve coke, as an excess of air at the beginning of the coking period tends to cool the oven, and later consumes the carbon of the coke. The yield is also reduced by improper leveling. If the coal is not of uniform depth to begin with, the thin portions coke through before the thick, and some of the coke in the thin sections is consumed while the coking of the thick portions is being completed. On the other hand, if the process be stopped when the thin areas have coked through, there will be a loss due to green butts on the thick areas. It will be recalled that the coal assumes a semifused, or pasty, state during the coking process. The result to be expected from such behavior is that the coke would be found in a continuous mass, or cake, at the end of the process; but, due to expansions and contractions of the mass in coking and on cooling, the cake is ramified by a great number of irregular vertical fissures, thus giving it a long columnar structure, in which the very irregular columns extend from the top to the bottom of the cake. This structure affords a second means by which beehive coke can be distinguished from by-product.

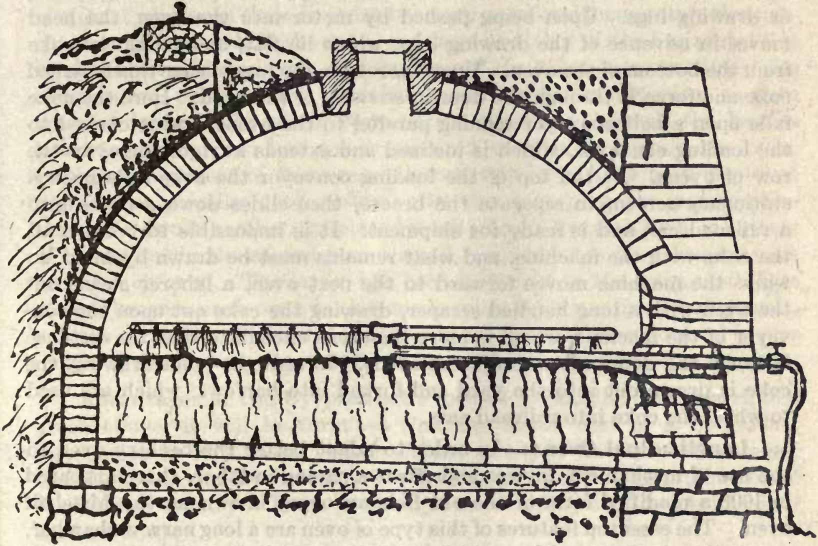


FIG. 15. **Ideal Section of Beehive Coke Oven Showing Watering Machine in Use and Structure of Coke.**

**Watering and Drawing the Coke:** As soon as the volatile matter has ceased to be evolved, as indicated by a subsidence of the smoke at the "trunnel head" and a decided shortening of the candle flames on the surface of the coke, the coke should be drawn. In good practice, the charge will be so regulated that this point is reached near the coking time assigned, and the ovens will be drawn on a schedule. If any circumstances delay the drawing, the doors of the ovens are sealed tight with clay, and the draft at the "trunnel head" is reduced. However, it is very important that the ovens be drawn on schedule, as a delay results in burning some coke and in cooling the oven, so that it will not coke the next charge in the period assigned. At the end of the coking time, then, the brick work closing the door is torn out, and the coke is watered out. At Continental this watering is accomplished by a self propelled spraying device. It consists of a tube or pipe a few inches shorter than the diameter of the oven, pivoted at the center to a feed pipe and perforated by two rows of holes on opposite sides, starting from the center. The holes are arranged to throw jets of water horizontally, which causes the pipe to revolve. Where this device is not provided, the ovens are watered by spraying with a pipe on the end of a hose in the hands of a laborer, who directs a stream of water through the door of the oven. For drawing the coke, a Covington coke drawing machine is employed at this plant. It is provided with a long arm fitted with a head, flat on the bottom, but inclined on the top, and a pair of hinged ears, or drawing lugs. Upon being pushed by motor into the oven, the head moves in advance of the drawing lugs, which lie flat, and raises the coke from the bottom of the oven. Upon the return, the lugs engage this loosened coke and force it through the door in advance of the head. Here the coke falls upon a belt conveyor running parallel to the ovens, and is carried to the loading conveyor, which is inclined and extends at right angles to the row of ovens. At the top of the loading conveyor the coke falls upon a stationary screen, to separate the breeze, then slides down a chute into a railroad car, and is ready for shipment. It is impossible to remove all the coke with the machine, and what remains must be drawn by hand, so while the machine moves forward to the next oven, a laborer cleans out the oven with a long handled scraper, drawing the coke out upon the conveyor of the machine, which is more than long enough to span the distance between the doors of two adjacent ovens. In straight hand drawing, the coke is drawn out into the yard and forked into barrows, which are used to wheel the coke into railroad cars.

**Longitudinal Ovens:** In order to adapt better the beehive oven to the use of mechanical devices and effect a saving in labor, there appeared in 1906 a modified form of the old Belgian oven, known as the Mitchell oven. The essential features of this type of oven are a long narrow chamber, rectangular in shape, with a flat tile bottom, an arched roof sloping towards the ends, a "trunnel head" in the center of the roof, and two doors, one at each end, which extend over the entire width and height of the oven ends. These ovens are built side by side in blocks or batteries, and are charged, controlled and watered like beehive ovens. The coke is pushed out of the oven by a mechanical pusher upon a loading conveyor which is made to screen the coke and drop it directly into railroad cars.

## SECTION VIII.

### THE BY-PRODUCT PROCESS FOR MANUFACTURING COKE.

**General Features of the Process:** The by-product process, being a true distillation process, involves the use of retort ovens. While there are many modifications, these ovens may be said to consist essentially of three main parts, namely, the coking chambers, the heating chambers, and the regenerative chambers—all constructed of brick. The retorts are rectangular in shape, varying in general from 30 to 42 feet in length, from 6 to 10 feet in height, and from 17 to 22 inches in width, and are built in batteries, of from 40 to 90 ovens, in which the coking chambers alternate with the heating chambers. The coal is charged through openings in the top of the oven, and the coke is pushed out one end by means of a power driven pusher acting through the other end. All watering is done outside of the oven. During the coking period, the ends of the oven are closed by brick lined doors, while an opening in the top, connected with suitable pipes, provides a means for the escape of the volatile products of the coal, which must undergo several different treatments in order to separate the many valuable products. As to the combustion chambers, these consist of a great number of flues, in order to secure a uniform temperature throughout the entire length of the oven, and may be either of the horizontal flue or of the vertical flue type. While some of the older ovens employed the recuperative principle for pre-heating the air for combustion, modern practice demands the use of regenerative chambers, because the heat is better conserved and less gas is required thereby to operate the oven. In the arrangement of these regenerators, two plans have been employed with about equally good results. By the first plan the regenerative chambers, two in number, are placed longitudinally beneath a whole battery of ovens, but in the second plan a small regenerator is placed under each end of each oven. The latter has been employed in the most up-to-date plants, because each oven is thus made more nearly an independent unit, and the operation of the whole battery is not liable to be influenced by one or two ovens that may be shut down for repairs or other reasons.

**Advantages of the By-product Process:** From the brief description given above, it will be surmised that the initial cost of a by-product installation is very great. Nevertheless, owing to its many advantages, the method is rapidly becoming the leading process for the production of coke in this country. These advantages as stated by Mr. Carl A. Meissner are as follows:

1. "The by-product coke plant can be constructed at or near the blast furnaces which are to consume its coke, and thus be under the same management.
2. It is practicable to ship to it coking coals from any section within a radius of a favorable freight rate.
3. Many coals not suitable for coking in beehive ovens become available for by-product ovens by mixing with other coals and are so used to make a first-class blast furnace coke.
4. Coking coals in by-product ovens permit of the full recovery and use of the very valuable by-products and the gas.
5. The cost of making by-product coke at the iron and steel works is considerably less than the cost of making beehive coke at the coal mines and transporting the coke to blast furnaces, especially when located some distance away from the beehive district.
6. The profits thus obtained give a substantial return on the investment in by-product coke plants, large though such investment may at first appear."

**The Plant of the Clairton By-product Coke Company** is located at Clairton, Pa., in close proximity to the Clairton Steel Works and Furnaces. This plant is the largest of its kind in the world. It consists

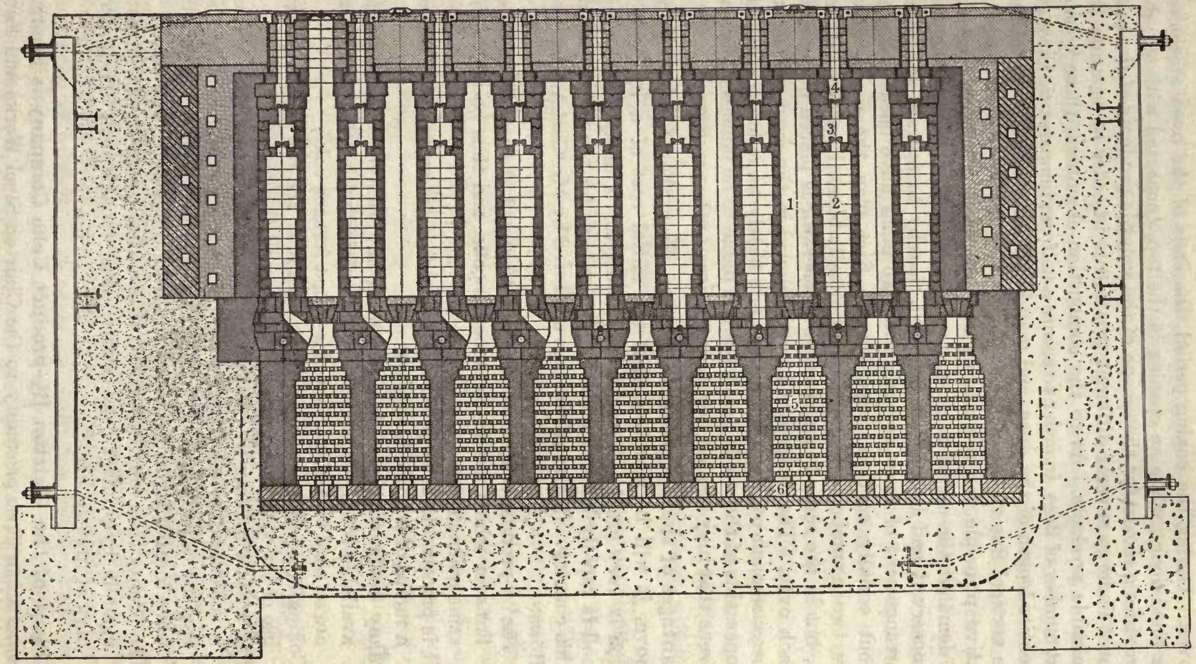


FIG. 16. Koppers By-Product Coke Ovens.
Illustrating Cross Section of Battery.
1. Coking Chamber. 2. Heating Chamber. 3. Horizontal Flue. 4. Opening to Top. 5. Regenerative Chambers.

of two units, the first of which was completed in the Spring of 1918. Each unit consists of 768 ovens. The ovens are constructed in groups, or batteries, of 64 ovens each, and in each unit they are arranged in two parallel rows of six batteries each. As each oven has a capacity of 13.3 net tons of coal, more than 25000 tons of coal per day are required to supply these two units when coking on a 19-hour schedule. From this coal there are produced in the neighborhood of 16,700 net tons of furnace coke; 500 net tons of domestic coke; 1,500 net tons of breeze and dust, which is used to generate steam for the plant; 275,000,000 cubic feet of gas (average thermal value 565 B. t. u.), 57 per cent. of which is surplus not needed for heating the coke ovens at the plant and therefore available as fuel gas for the mills; 285,000 gallons of tar; 650,000 pounds of ammonium sulphate; 68,000 gallons of motor benzol, or 50,000 gallons C. P. benzol, 11,500 gallons C. P. toluol and 10,500 gallons refined solvent naphthas; and 10,000 pounds of crude naphthalene. The coal for the works is obtained from the mines of the H. C. Frick Coke Company in the lower Connellsville Field, and is known commercially as Klondike coal. These mines are located near the Monongahela River, and the coal is transported from the mines to the coke works by water, for which purpose more than 180 barges of 1,000 tons capacity each and ten steamers are employed.

**Construction of the Ovens:** The ovens of this plant are known as the Koppers 500 cubic feet by-product oven. All parts of these ovens are constructed almost entirely of the best grade of silica brick. To give the coking chamber a volume of 500 cubic feet, each oven inside has a length of 37 feet from face to face of the doors, a height of 9 feet 10 inches from floor to roof, and a width that tapers from 17 inches at the pusher end to 19½ inches at the discharge end. Four "trunnel heads" in the top provide means for admitting the charge, while a separate opening at one end provides an outlet for volatile matter. The oven is of the vertical flue type with individual regenerative chambers. The heating chamber is composed of a total of thirty vertical flues, which rise from the bottom of the chamber, where they are provided with openings to the regenerative chambers and to the gas mains, to a large horizontal cross-over flue on a level a little below the top of the coking chamber. A dividing wall near the middle of the oven separates this chamber, except the cross-over flue, into two parts with sixteen vertical flues on the narrower end of the oven and fourteen on the wider end. Each end, approximately each half, of the oven may thus be heated alternately, and in practice the reversals are made, automatically every half hour for each battery of sixty-four ovens, by means of a reversing motor controlled by an electrical clock attachment. Two large underground flues, one on each side, extending along in front of and parallel to the battery and connected to the checker chambers by means of cast iron goose necks, furnish means for the escape of the products of combustion. These flues lead to a stack, which is located at one end of the battery and is 200 feet high in order to furnish the draft necessary to draw the gases through their tortuous course. An idea of the magnitude of the structure may be gained from the fact that a single battery of these ovens contains the equivalent of about 2,500,000 nine inch brick.

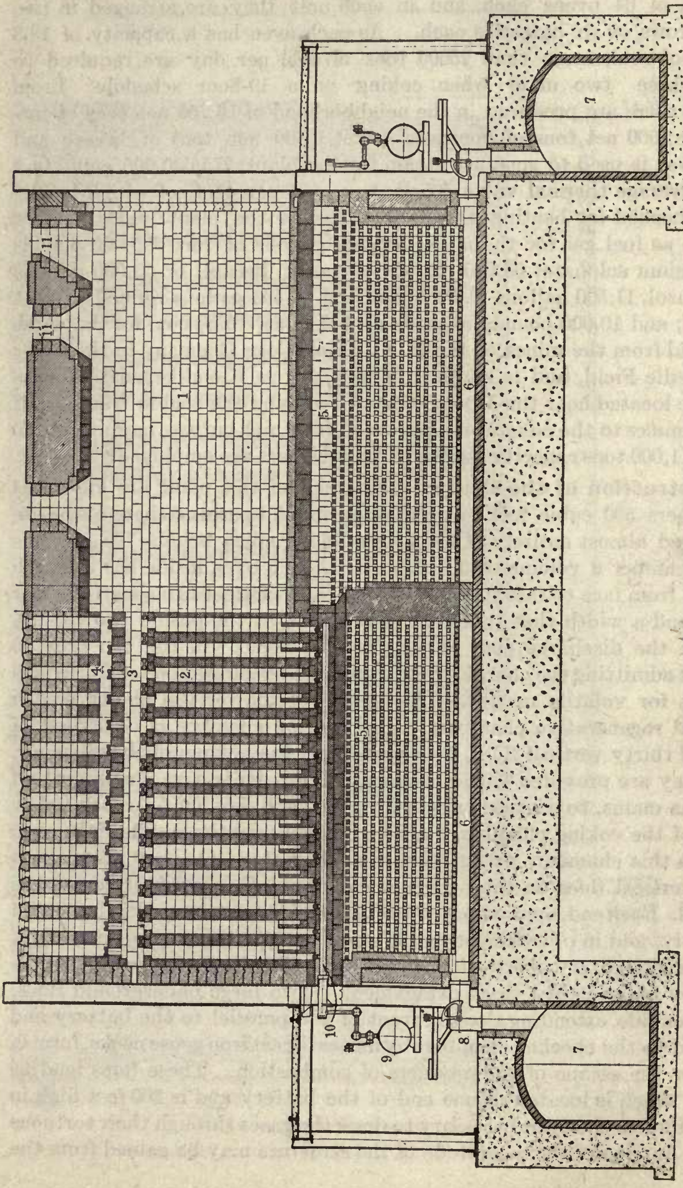


Fig. 17. Koppers Standard Coke Oven. Cross Section of Coking and Combustion Chambers. 1. Coking Chamber. 2. Combustion Flue with gas nozzle at bottom. 3. Horizontal Flue. 4. Opening through top. 5. Checker Chamber and Flue. 6. Flues under checkers. 7. Flue to stack. 8. Cast iron connection from checkers to stack flue. 9. Gas main. 10. Gun brick. 11. "Trunnel Head", and Outlet for Volatile Matter on the right.

**Heating the Ovens:** This construction may be further explained by tracing the course of the gases when the ovens are in operation. The air

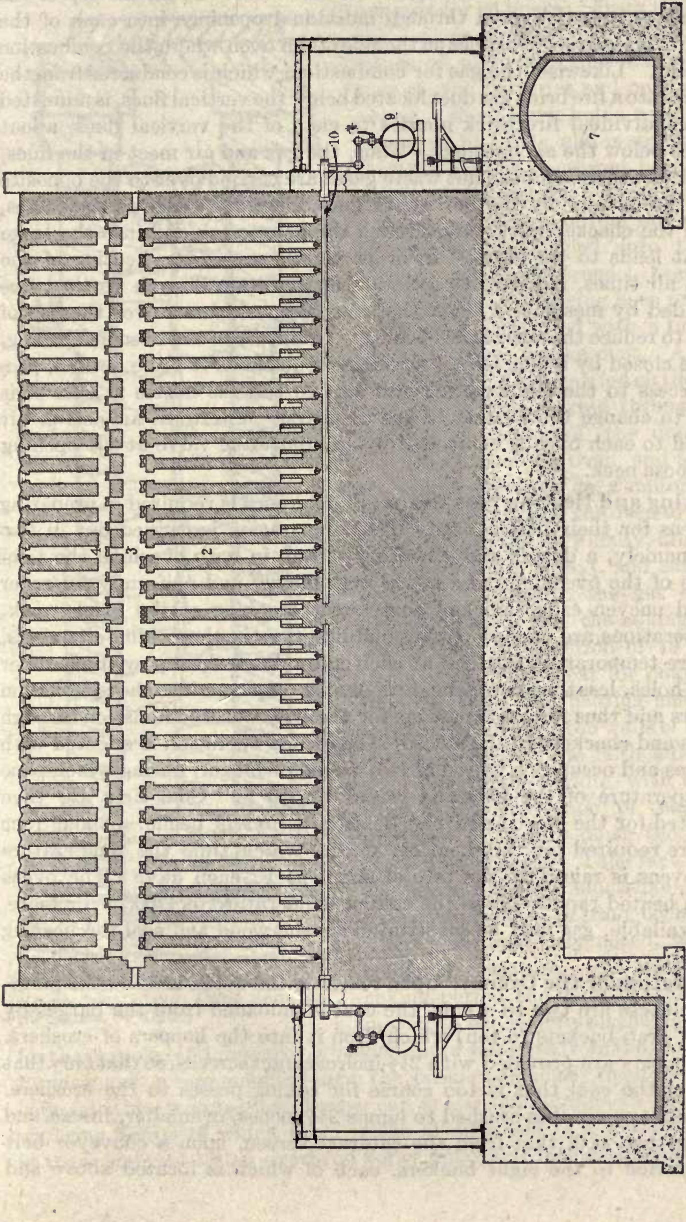


FIG. 18. Koppers Standard Coke Oven, Longitudinal Section through heating flues. 2. Combustion flue showing intake for air and gas at bottom. 3. Horizontal flue. 4. Sliding Brick. 7. Flue leading to stack. 9. Gas Main. 10. Gun Brick and Gas Nozzle.

for combustion is admitted to the checker chamber through a capped opening on the goose neck leading to the stack flue. From the top of the regenerators it is delivered through individual openings into each of the fourteen or sixteen vertical flues on the side of the oven where the combustion is to occur. Likewise, the gas for combustion, which is conducted from the gas main into a fire brick gas duct located below the vertical flues, is admitted through individual fire brick nozzles to each of the vertical flues, about 10 inches below the air openings. Thus, the gas and air meet in the flues, combustion occurs, and the hot waste gases are carried over to the opposite side of the battery by the horizontal flues, then down the vertical flues, through the checker work, out through the goose neck and into the large flue that leads to the stack. In order to secure uniform heating of the oven at all times, individual regulation of the draft in each vertical flue is provided by means of a brick that may be pushed out over the top of the flue to reduce the size of the opening. In the top of the oven an opening, which is closed by a plug except as occasion demands it to be opened, provides access to the sliding brick and also to the gas nozzle in case it is desired to change the amount of gas admitted. The total amount of air admitted to each oven is controlled by an adjustable valve at an opening in the goose neck.

**Drying and Heating New Ovens:** Great care is required in preparing new ovens for their first charge. This preparation is carried out in two stages, namely, a drying and a heating period, in both of which the temperature of the ovens must be raised very slowly and uniformly, in order to avoid uneven expansion and consequent cracking of the brick work. Both operations are carried out by building fires in the coking chambers, which are temporarily provided at each end and near the tops with a number of small holes, less than two inches in diameter, that open into the combustion chambers and thus furnish a passage for the products of combustion through the flues and checkers to the stack. The drying operation is effected with wood fires and occupies a period of two weeks or longer, during which time the temperature of the ovens is raised to 250°F. Coal fires are then substituted for the wood, and the heating period is begun. About four weeks are required for this heating, during which time the temperature of the ovens is raised at the rate of about 25°F. each day. The ovens are then heated rapidly up to the coking temperature of 1700° F or more. When available, gas may be substituted for the wood and coal for heating the ovens.

**Operation of the Ovens:** Upon reaching the docks at the coke plant, of which there are two to a unit, the coal is unloaded from the barges by means of grab buckets (5 ton) which drop it into the hoppers of crushers. These hoppers are provided with 2½-inch cataract screens, so that only that portion of the coal that is too coarse for coking passes to the crushers. Here this coarse coal is crushed to lumps 2½ inches, or smaller, in size, and falls, together with that from the cataract screen, upon a conveyor belt and is carried to the eight bunkers, each of which is located above and between two batteries of ovens. These bunkers have a capacity of 4,000 tons each, so that four bunkers contain, when filled, enough coal to supply one unit for 24 hours. From the bunkers the coal is charged into the ovens by means of larry cars that travel lengthwise of the batteries and on top of the ovens. Each larry holds a single oven charge of 13.3 tons, and is so constructed that the coal is measured both by volume and by weight. From the larry, which has the form of four large funnels, the charge is dropped into the oven through the four "trunnel heads," the doors of the oven having been previously set in place and luted with a mixture of loam or clay and coke dust. A reciprocating levelling bar, carried on the pushing machine, is then inserted through a small opening at the top of the door on the narrower end of the oven, and the peaks of coal are levelled to a uniform depth of 9 feet, thus filling the oven to within 10 inches of the top. Finally, all openings to the oven are closed and sealed, the valve or damper to the gas collecting main is opened, and the coking process, which lasts for a period of 19 hours or less, begins. The heat for coking being supplied from the heating chamber by conduction through the walls of the oven, coking proceeds from both sides of the oven toward the middle, with the result that a marked plane of cleavage is produced vertically down the center of the whole charge. This fact gives to the coke a short, block-like structure that distinguishes it from beehive coke, which, as previously noted, has a long columnar structure. At the end of the coking period the doors of the oven are moved to one side by mechanical devices for the purpose, and the coke is pushed out of the oven from the narrower end by means of a ram mounted upon the pusher previously mentioned. The coke falls into a side-dump hopper car, is carried therein to a quenching, or watering house, of which there is one at each end of a row of batteries, is there watered by an overhead spray until well blackened, but still hot

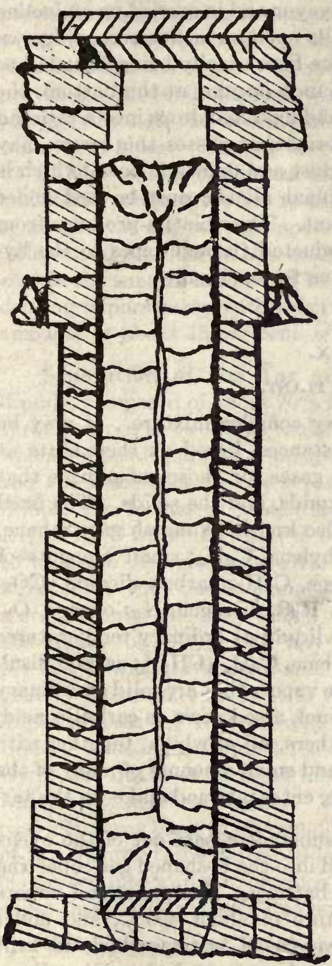


FIG. 19. Ideal Section of the By-product Coke Oven Showing Structure of Coke.

enough to dry itself, and is then discharged into an inclined dock or bin. Here it is allowed to become dry and to cool somewhat, after which period it is permitted to fall upon a large belt conveyor and is carried up an incline to the screening house. The coke then falls upon an incline screen, known as the adjustable Grizzley bar screen. The bars usually being adjusted to give a ½ inch opening at the top and a ¾ inch opening at the bottom, the furnace coke is separated from the breeze and dust and drops into a railroad car placed ready to receive it. The material that passes this screen may be further divided by rotary screens into dust and domestic coke, which is also loaded directly into cars. At this plant all the dust is used under boilers to generate steam for use at the plant. The volatile products from the coal pass out of the oven and are conducted through pipes to the by-product plants, of which there are two, one for each unit.

## SECTION IX.

### THE BY-PRODUCT PLANT.

**The Volatile Matter of Coal** is a very complex mixture. It may be roughly divided into three classes of substances, based on their state at ordinary temperatures; namely, the fixed gases, or those substances that are gases at ordinary temperatures, the liquids, and the solids. The fixed gases are hydrogen, $H_2$; methane, $CH_4$, also known as marsh gas; ethane, $C_2H_6$; propane, $C_3H_8$; butane, $C_4H_{10}$; ethylene, $C_2H_4$; small amounts of propylene, $C_3H_6$; butylene, $C_4H_8$; acetylene, $C_2H_2$; carbon dioxide, $CO_2$; carbon monoxide, CO; hydrogen sulphide, $H_2S$; nitrogen, $N_2$; oxygen, $O_2$; and ammonia, $NH_3$. The vapors that are liquid at ordinary temperatures are benzene, $C_6H_6$; toluene, $C_6H_5CH_3$; xylene, $C_6H_4(CH_3)_2$; carbon disulphide $CS_2$; and aqueous vapors. Among the vapors that are solid at ordinary temperatures, are naphthalene, $C_{10}H_8$; phenol, also known as carbolic acid, $C_6H_5OH$; anthracene, $C_{14}H_{10}$; and many others, all of which, together with heavy pitch-like substances, soot carbon, and small amounts of many of the more volatile liquid compounds cited above, enter into and make up the tar.

**Gas Mains and Coolers:** All these substances pass out of the ovens through up-takes at their narrower ends and into the U-shaped gas collecting main that extends above and parallel to a battery. The gases and vapors enter this collecting main at a temperature of about 400°C, and under a uniform suction of about .078 inch (2 mm.) of water, which is kept constant by means of a Northwestern gage governor and valve. From the collecting main the gas is conducted by two pipes to a large main, known as the suction main, which serves as a common main for one half of a row of six batteries. This suction main leads to the primary coolers. In passing through these mains, the temperature of the gases drops to about 75°C, at the inlet to the primary coolers. This reduction in temperature causes much of the heavy tar vapors to condense in the mains, and it is found necessary to maintain a heavy stream of new flushing tar (composed of tar, 50%, and ammonia liquor, 50%), flowing through the collecting mains to keep them clear of pitch and carbon stoppages. The requirements for this flushing tar amount to approximately 450 gallons of tar and weak liquor to be circulated through the gas mains for each ton of coal carbonized in the ovens. The primary coolers are large rectangular tanks provided with tubes through which water circulates, while the gas, in its passage through the cooling chamber, is brought into intimate contact with these pipes. The gas leaves these coolers at a temperature of about 32°C. The cooling of the gas in its travel from the ovens through the gas mains and primary coolers results in the condensation of about 95 per cent of all the tar and water vapor. The condensation takes place about as follows: 50 per cent in the collecting mains and cross-over mains, 35 per cent in the suction main, and 10 per cent in the primary coolers. The condensing vapors carry with them all of the fixed ammonia in the gas which amounts to about 15 per cent. of the total ammonia.

**Separation of the Tar and Ammonia Liquor:** These condensed liquids, composed of about 70% tar and 30% ammonia liquor, are conducted through pipes to two large tanks known as the hot drain tanks, or tar wells, whence a small portion is pumped back into the gas mains as flushing tar and the remainder to two separating tanks. In these tanks the tar and liquor, the former of which has a specific gravity varying from 1.15 to 1.17 at 15°C while the latter is little, if any, heavier than water, are allowed to separate by gravity, when the liquor is drained off into storage tanks and the tar is pumped also into storage tanks. From these storage tanks the tar, which is composed of water, 2%, pitch, 65%, and heavy oil, 33%, and has a heating value of about 16,500 B. t. u. per lb., is withdrawn to a small loading tank from which it is loaded by gravity into tank cars as it is required for shipment; but since the semi-direct process for the recovery of ammonia is employed, the ammonia liquor, containing about 1.1% of ammonia, is pumped to ammonia stills. Here, the liquor is brought into contact with steam heated lime water, which liberates the ammonia. This ammonia gas is then conducted through cast iron pipes back to certain points in the gas mains, where it is disposed of in a manner to be described later. If desired, this ammonia gas may be conducted into water to produce concentrated ammonia liquor. For operating these stills exhaust steam from various engines in the plant is used.

**Compressors and Tar Extractors:** After the gas leaves the primary coolers, it enters a number of positive exhausters (Connersville Exhausters) which produce a suction of 15 inches of water on the entering side and compress the gas to a pressure equivalent to 50 inches of water on the discharge side. This pressure is required in order to force the gas through the apparatus succeeding, the first of which are the P. and A. (Pelouze and Audouin) tar extractors. In each of these extractors the gas stream, by means of a perforated plate, is broken up into innumerable small jets which impinge upon the cold surface of a plate immediately behind the perforated plate. The impact causes the very fine particles of tar to collect on the impact plate, and the tar, thus accumulating, runs off the plate and out of the apparatus through a sealed overflow at the bottom. In these apparatus it is necessary to maintain a constant differential pressure of about 8 inches of water, and since the holes in the perforated plate tend to become closed by the more viscous of the tarry substances, thus causing an increase of the pressure, special means must be employed to overcome this tendency. At this plant the desired result is accomplished by lowering the tar level in the bottom of the apparatus, thus exposing more holes as those in use become clogged. The tar level is controlled by means of a pressure gauge and automatic regulator attached to the gate valve through which the tar passes in flowing out of the apparatus. The tar extracted by this machine amounts to about 5% of the total tar originally carried by the gas.

**Recovery of Ammonia:** The temperature of the gas, now about 38°C., having been raised about 6°C. by compression in the exhausters, is brought to about 66°C. by being forced through preheaters, which are cylindrical steel tanks containing steam coils. This preheating is necessary to prevent the accumulation of water in the saturators and to accelerate the reaction, between the ammonia and the dilute sulphuric acid, that occurs in them. These saturators, of which there are ten to a unit, are large lead lined steel pots containing a 5% solution of sulphuric acid, through which the gas is forced in tiny bubbles. This gas, it is to be noted, contains all the ammonia recovered from the coal, for that which was liberated in the ammonia liquor stills, previously described, has been introduced into the gas mains just after the latter leaves the preheaters. In this way all the ammonia given off by the coal in coking is brought into direct contact with the dilute acid, with which it immediately reacts to form ammonium sulphate, $(NH_4)_2 SO_4$. This salt dissolves in the water with which the acid was diluted, but, when the baths become saturated, it is precipitated and settles to the bottom, where it is forced through syphon ejectors by means of compressed air to elevated draining tables, also lead lined. From the draining tables, the salt is periodically removed, placed in centrifugal dryers, and whizzed for fifteen minutes, which process removes nearly all the water, the salt retaining about 2.0% of its own weight of moisture. The mother liquor derived from the drying operations, as well as the wash water used to free the crystals of the slightly acid mother liquor, flows back into the saturators, while the salt is scraped off the copper screen plates of the centrifugal machines with wooden paddles and delivered through a chute to a belt conveyor, which carries it to a final dryer, where the moisture content, by means of hot gases, may be reduced to .25% or less. The final drying prevents caking, so that the salt will remain in a finely divided state for indefinite periods. From the final dryer the salt falls into a pit, from which it is removed with grab buckets to a storage pile, to be shipped later as required.

**Debenzolating the Gas:** In bubbling through the liquid in the saturator, the gas tends to carry a little of the acid along with it. Hence, from the saturator the gas passes into an acid separator. Its temperature here is about 54°C. which is much too high for the complete separation of the benzene and its homologues. Therefore, the gas is put through final coolers where its temperature is lowered to 30°C. These coolers are tall steel towers, about 100 feet in height. In them the gas is brought into direct contact with cold water, which is introduced at the top, while the gas enters at the bottom and leaves at the top. From these coolers the gas is forced through three benzol, or oil, scrubbers in series. Like the coolers, these scrubbers are large steel towers, in which the principle of counter currents is employed throughout. They are filled with a kind of checker work of wooden slats. A product from the refining of petroleum, (or of tar), known as straw oil or wash oil, with a distilling temperature ranging from 270 to 370°C., is sprayed into the top of the washers, where it trickles down over the wooden checker work and is thus brought into intimate contact with the ascending current of gases. The oil absorbs the benzene, toluene, xylene, naphtha and naphthalene, becoming saturated to the extent of about 3%, and removing 92% or more of the total amount of these products in the gas. The entire removal of the naphthalene at this point is of great importance, because, if any remains in the gas, it crystallizes out and clogs the gas lines. From the scrubbers, the oil carrying the benzene, toluene, etc., is pumped to the benzol plant, which serves both units of the plant, while the gas, now freed from all except its fixed gases, is divided, half being sent to the fuel lines to heat up the ovens and half to the booster station, where it is compressed by steam turbo-blowers and delivered to the mills as surplus gas. The loss in heating power of the gas from a given quantity of coal, due to the removal of the by-products, amounts to about 5.8%.

## SECTION X.

### THE BENZOL PLANT.

**Light Oil:** At the benzol plant the wash oil, carrying in solution the benzene, naphthalene, and their homologues, is first delivered to the wash oil, or separating, stills. In order to conserve as much heat as possible, the inflowing wash oil is made to serve as a condensing liquid for the vapors from the still. After leaving the condensers, or heat exchangers, the oil passes to preheaters, or superheaters, in which its temperature is raised to about 145°C. and much of the benzol is vaporized. The oil then passes to the stills, where it comes into direct contact with steam which drives off the higher boiling oils and naphthalene. Since the wash oil has a much higher boiling point than the hydrocarbons it is desired to recover, only a small portion of it escapes from the stills. The vapors from the stills, passing into the condensers, or heat exchangers, are cooled and condense to form a liquid, known as "light oil," which flows from the bottom of the condensers into storage tanks. The wash oil, which is not vaporized, flows from the bottom of the stills and is conducted to heat exchangers, and then to water coolers where its temperature is lowered to 30°C. From these coolers it is pumped back to the oil scrubbers, and can be used repeatedly. However, there is a daily loss of approximately 2%.

**Composition of the Light Oil:** The light oil is pumped from the storage tank to the crude still. The composition of a light oil is approximately as follows:

| | |
|---|---|
| Light Runnings (benzol and carbon bisulphide) | 1.00% |
| Pure Benzol | 57.00% |
| Pure Toluol | 14.50% |
| No. 1 Refined Solvent Naphtha | 4.50% |
| No. 2 Crude Heavy Solvent Naphtha | 1.50% |
| Crude Naphthalene | .40% by weight. |
| Wash Oil | 12.00% |

**Construction and Principles of the Still:** The crude still consists of three sections. The lowest section is a horizontal cylinder provided with steam coils, and has a capacity of 20,000 gallons; the second part, called the fractionating column, is a vertical column mounted upon this cylinder and composed of thirty-one bell sections for scrubbing the vapors as they pass upward; the third part, mounted on top of the column and called the dephlegmator, is a short horizontal cylinder, that contains a number of water cooled pipes and acts as a partial condenser. The separation of light oil into its component oils is effected by taking advantage of their different boiling points. As the temperature of the light oil is raised and approaches the boiling point of the first runnings, this liquid is vaporized and passes up through the columns; a portion of the other oils with higher boiling points is also vaporized, but is condensed before reaching the top of the column. There are thus two movements in the fractionating column and dephlegmator, the vapors going upward and the condensed oils flowing downward into the still. The vapors are thus forced to pass through the return oils which aid in condensing the vaporized oils of higher boiling points and permit only the lighter vaporized oils to reach the top of the dephlegmator, where they are condensed and flow from the still through a manifold into the storage tanks. As the temperature of the still is further raised, the benzol, toluol, etc., is successively vaporized and condensed, and flows from the still. However, it is impossible to separate absolutely, the benzol from the toluol, since, before the benzol is completely driven over, some toluol will be carried along with it. It is likewise impossible to separate absolutely one from another the other constituent oils. Hence, it is only aimed to separate roughly the light oil into what are termed fractions. These fractions, designated in the order in which they are made, are as follows: Light Runnings, Crude 90% Benzol, Crude 90% Toluol, Crude Light Solvent Naphtha, Crude Heavy Solvent Naphtha and Still Residue. Each fraction is stored in a separate tank.

**Operation of the Crude Still:** The details of the operation of the crude still are as follows: 20,000 gallons of light oil are charged. The temperature is gradually raised, and approximately 1,600 gallons of oil are vaporized and condensed. This product, known as the light runnings and consisting of benzol containing approximately 3% carbon bisulphide, is conducted into the light runnings storage tank. The next product is the 90% benzol. The still is continued on this fraction until a test shows 30% by volume will distill over at 100°C. Ninety per cent. toluol is then collected until a test shows that 10% will distill over at 130°C. The next product is the light solvent naphtha which is collected until the flow of oil is very small, at which point, and continuing throughout the operation, the still is maintained under partial vacuum. The oil in this fraction is collected until 10% will distill over at 160°C., when heavy solvent naphtha is produced until a test shows that 90% will distill over at 205°C. The residue in the still, consisting of wash oil and naphthalene, is drained into the naphthalene pans, where, upon cooling, the naphthalene separates as a solid. The wash oil is removed by a centrifugal machine, and the naphthalene is washed with hot water. It is sold as crude naphthalene, or refined and sold as C. P. naphthalene.

**Washing the Products of the Crude Stills:** Before the products of the crude still are further treated for the separation of their component oils, they are pumped to the washer and there agitated with sulphuric acid. The object of this treatment is to free the oils from unsaturated hydrocarbon compounds, paraffins and other impurities. These substances are acted upon and polymerized by the acid, to form substances that have very high boiling points. Some of these are insoluble in the oils and will settle out with the acid, forming a sludge. Several thousand gallons of oil are transferred to the washer and 66° Baumé sulphuric acid is added, the proportions being about 920 pounds of acid to 5,000 gallons oil. The contents of the washer are agitated for twenty minutes and allowed to stand for fifteen minutes, when the sludge settles to the bottom and is drawn off. This acid sludge is then heated in special pots with live steam, and the acid thus separated from the carbonaceous matter, when it is used in the saturators to produce ammonium sulphate. For the purest product the oil is then washed an additional number of times in the same manner. After the use of the acid, the oil is washed with 10% caustic soda solution until the last trace of acid is neutralized. The oil is then transferred to the pure still.

**The Pure Stills:** The construction and operation of the pure still is practically identical to that of the crude still. However, while the fractions of the latter consist of a mixture of oils, the pure still is operated so that one or more fractions may be pure compounds, as is shown by the following data:

Still Charge—17,676 Gals. Washed 90% Benzol.

| Fraction. | Time | Gals. | Product. |
|---|---|---|---|
| 1 | 12¾ hrs. | 1440 | R. R. (Rerun) Benzol—Benzol containing Carbon Bi-sulphide. |
| 2 | 31 " | 10950 | C. P. Benzol. |

| Fraction. | Time | Gals. | Product. |
|---|---|---|---|
| 3 | 2½ hrs. | 790 | R. R. (Rerun) Benzol—Greater portion Benzol, part Toluol. |
| Residue | | 4496 | Principally Toluol. |

Fraction 2, being pure benzol, is not further treated, and is ready for the market. The rerun (R. R.) benzol fraction, 1 and 3, and the residue are stored in separate tanks. When a sufficient quantity of a R. R. fraction has accumulated, the pure still can be charged with it and a C. P. (chemically pure) product obtained, as is shown by the following data:

Still Charge—18,200 Gals.
R. R. Benzol.

| Fraction. | Time | Gals. | Product. |
|---|---|---|---|
| 1 | 16¾ hrs. | 2550 | R. R. Benzol—containing Carbon Bisulphide. |
| 2 | 39 “ | 10900 | C. P. Benzol. |
| 3 | 10 “ | 1750 | R. R. Benzol—Greater portion Benzol, part Toluol. |
| 4 | 5 “ | 650 | R. R. Toluol—Part Benzol, greater portion Toluol. |
| 5 | 6½ “ | 1300 | C. P. Toluol. |
| Residue | | 1050 | Toluol and Solvent Naphtha. |

Fraction 2 and 5 being C. P., are ready for the market, the other fractions are stored and, when a sufficient amount is collected, are distilled like the R. R. Benzol charge just described. It is not essential that the pure still be charged with a straight R. R., or 90% product, as a mixture of the two is often distilled as follows:

Still Charge—6800 Gals. 90% Washed Toluol.
10150 “ R. R. Toluol.

| Fraction. | Time. | Gals. | Product. |
|---|---|---|---|
| 1 | 15¾ hrs. | 1610 | R. R. Benzol—greater portion Benzol, part Toluol. |
| 2 | 29 “ | 5130 | R. R. Toluol—greater portion Toluol, part Benzol. |
| 3 | 24 “ | 6950 | C. P. Toluol. |
| 4 | 6¼ “ | 400 | R. R. Toluol—greater portion Toluol, part Naphtha. |
| | | 2860 | Residue—Toluol and Naphtha. |

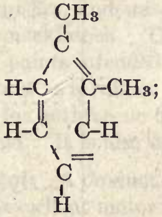
It is thus apparent that the light oil will eventually be completely worked up into its pure product. There is one exception, however, in that the light runnings containing the carbon bisulphide cannot be separated by fractional distillation. The crude carbon bisulphide benzol is the first 1600 gallons that come over in the crude still. This is placed in a separate tank, into which the forerunnings, or carbon bisulphide benzol, from the pure still is also collected. When 20,000 gallons of this product, containing approximately 3% carbon bisulphide, is collected, it is placed in the 90% crude still. The first 4000 gallons condensed is benzol containing 10% carbon bisulphide, the remaining portion is 90% benzol, which is transferred to the crude 90% benzol tank. Only a restricted market has so far been found for the 10% carbon bisulphide benzol.

## SECTION XI.

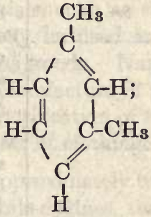
### SOME PROPERTIES AND USES OF THE RAW BY-PRODUCTS FROM THE COKE WORKS.

**Characteristics of Benzol, Toluol and Naphtha:** While the names benzol, toluol, xylol and naphtha are those commonly applied in commerce, chemical names used to designate corresponding pure compounds are benzene, toluene, xylene, cumene, etc. Naphtha is a mixture of several compounds, including xylene, cumene and others, so it has no chemical name. As previously indicated, these compounds are members of the aromatic, or benzene, series of hydrocarbons represented by the general formula $C_nH_{2n-6}$. The empirical formulas for benzene, $C_6H_6$, and toluene, $C_7H_8$, represent individual compounds, but these formulas for xylene, $C_8H_{10}$, and cumene, $C_9H_{12}$, represent series of isomeric compounds, which, though they are members of the same series and may have the same formula, differ widely in properties. Thus the formula $C_8H_{10}$, may represent

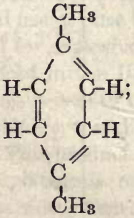
orthoxylene



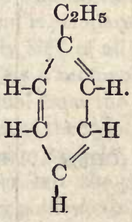
metaxylene



paraxylene,



or ethylbenzene,



The chief physical properties of the first and more important members of the series are given in the following table, which will also give some idea of the method of naming the compounds:

### Table 13. Some Members of the Benzene Series and Their Physical Properties.

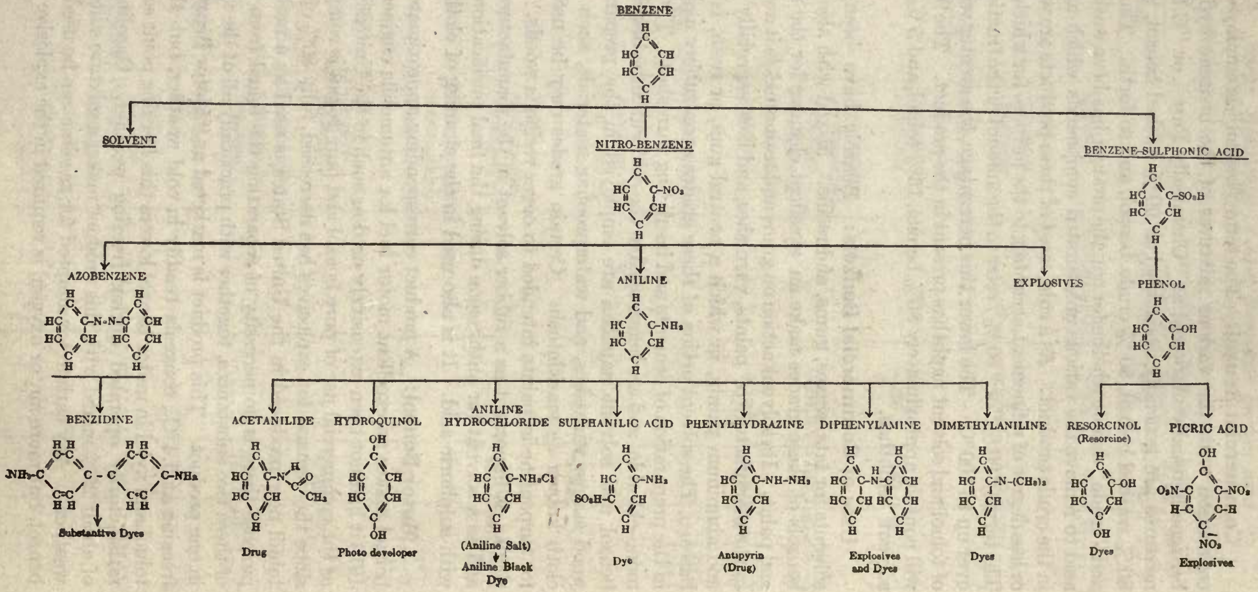
| FORMULAS | | NAME | State at Ordinary Temperature | Melting or Freezing Point °C. | Boiling Point °C. | Specific Gravity |
|---|---|---|---|---|---|---|
| Empirical | Rational | | | | | |
| $C_6H_6$ | $C_6H_6$ | Benzene | Clear Liquid | +5.4 | 80.4 | .884 $\left\{\frac{15^\circ}{4^\circ}\right\}$ |
| $C_7H_8$ | $C_6H_5 \cdot CH_3$ | Toluene or Methylbenzene | " " | —92.4 | 110.3 | .871 $\left\{\frac{15^\circ}{4^\circ}\right\}$ |
| $C_8H_{10}$ | $C_6H_4 \cdot (CH_3)_2$ | Ortho xylene or Ortho-dimethylbenzene | " " | —28 | 142.0 | .893 $\left\{\frac{0^\circ}{4^\circ}\right\}$ |
| | ................ | Meta-xylene or dimethylbenzene | " " | —54.8 | 139.1 | .87- $\left\{\frac{15^\circ}{4^\circ}\right\}$ |
| | ................ | Para-xylene or dimethylbenzene | " " | +13° | 138.0 | .880 $\left\{\frac{0^\circ}{4^\circ}\right\}$ |
| | $C_6H_5 \cdot (C_2H_5)$ | Ethylbenzene | " " | ...... | 136.0 | .883 $\left\{\frac{0^\circ}{4^\circ}\right\}$ |
| $C_9H_{12}$ | $C_6H_3 \cdot (CH_3)_3$ | Hemimellithene or v—Tri methylbenzene | " " | ...... | 175.0 | .... |
| | ................ | Pseudocumene or as-Trimethylbenzene | " " | ...... | 169.5 | .895 $\left\{\frac{0^\circ}{4^\circ}\right\}$ |
| | ................ | Mesitylene or s-trimethylbenzene | " " | ...... | 165.0 | .865 $\left\{\frac{15^\circ}{4^\circ}\right\}$ |
| | $C_6H_5 \cdot C_3H_7$ | Normal Propylbenzene | " " | ...... | 159.0 | .867 $\left\{\frac{15^\circ}{4^\circ}\right\}$ |
| | ................ | Cumene or Isopropylbenzene | " " | ...... | 153.0 | .866 $\left\{\frac{15^\circ}{4^\circ}\right\}$ |
| $C_{10}H_{14}$ | $C_6H_2 \cdot (CH_3)_4$ | Prehitene or Tetramethylbenzene | ........ | ........ | ........ | ........ |
| | $C_6H_4 \cdot CH_3 . C_3H_7$ | Cymene or Methylisopropylbenzene | ........ | ........ | ........ | ........ |
| and so on to $C_{25}H_{44}$ | | ........ | ........ | ........ | ........ | ........ |

**Commercial Benzol:** The term "benzol" is employed commercially in connection with the various mixtures of the benzene hydrocarbons. Pure benzene is usually marketed as "Chemically Pure", or "C.P.," benzol. The mixtures are generally designated as 90 % washed benzol, 90% crude benzol, 80 % washed benzol, 80 % crude benzol, and so forth. The terms "washed" and "crude" denote whether or not the product has been washed with sulphuric acid to remove the various unsaturated compounds which are always present in the crude product. As a rule, most of these products are washed to a greater or less degree of refinement, according to the purpose for which they are required. The terms "90 %" or "80 %" refer to the amount of the fraction which will distil over up to 100°C. The lower this percentage, the greater will be the amounts of toluol and solvent naphthas present in the product. The 90% washed benzol will contain approximately 80% benzol, 15% toluol, and 5 % of xylols and light solvent naphthas.

**Uses of Commercial Benzols:** Benzols have been largely used as solvents for fats, waxes, gums, and resins. Mixed with alcohol and ammonia, benzols of these grades make an excellent cleanser for the removal of grease and paint. Its solvent action on gums and resins makes it a valuable substance in the manufacture of paints, varnishes, and lacs, especially of enamel, bronze and aluminum paints, in which a neutral gum, or resin, is used to form the bases. The solvent action of these grades upon rubber makes them valuable in the preparation of cements and insulating varnishes. They dissolve sulphur mono-chloride, and are hence used in the cold vulcanization of rubber. Heavy benzol and solvent naphtha are employed in the preparation of enamels, wood stains, varnishes, and waterproofing materials, such as the rubberized cloth known as mackintosh. Certain grades may be used as a substitute for turpentine in paints intended to cover resinous woods. Naphtha, in particular, is important as a rubber solvent in the manufacture of rubber goods, and as a solvent for anthracene during the final purification of this substance with sulphuric acid. It is also used in the cleaning of clothing.

**Motor Benzol:** A product corresponding approximately to 80% washed benzol makes an excellent motor fuel for automobile engines, though up until 1919 it had not been extensively used as such in the United States. Inasmuch as the commercial use of pure benzol and pure toluol is comparatively limited, since the demand for explosives has decreased, fully 80% of all the benzol and toluol now produced in the United States is used as a motor fuel. For this purpose there is no necessity of separating the toluol from the benzol, and all of these two substances, together with practically all of the xylol, are combined in one product. This product is marketed as "Motor Benzol". Pure benzol, freezing at 5.4°C., congeals readily in cold weather, but the presence of the toluol and xylol in motor benzol lowers this freezing point so that cars may be satisfactorily operated during freezing weather. Gasoline to the amount of about 25% mixed with this product makes a mixture suitable for the coldest weather. Any carburetor adapted for gasoline can be used as well for motor benzol, but more air, or oxygen, is required in the explosive mixture with this

Table 14. Diagram Showing Some of the Products Derived from Benzene, Their Formulas and Their Uses.



fuel than with gasoline. When properly handled, motor benzol gives from 20% to 30% greater mileage than does gasoline. At the present time motor benzol is made under the following specifications:

| | |
|---|---|
| Color | Water-white. |
| Distillation | Start 78° to 82°C.<br>Dry not higher than 135°C. |
| Wash Test | No 9, or better. |

Sulphur content not to exceed 0.25%.

The wash test is made by agitating equal quantities, usually 20 cc., of the oil and pure sulphuric acid in a glass tube and comparing the color with that of numbered standards, the first of which, No. 1, is perfectly clear.

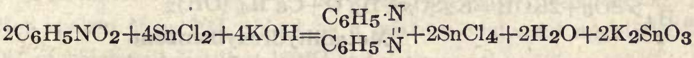
**Properties and Uses of Pure Benzol, or Benzene:** The chief physical properties of this very interesting substance have already been given. Concerning its chemical properties and uses, it may be said that it is one of the most interesting and useful compounds known to the chemical profession. This fact is more fully appreciated when it is known that it is the base from which such drugs as phenol, hydroquinon, antipyrin and acetanilid; such dye stuffs as resorcinol, benzidine, aniline, and indigo; and such explosives as nitrobenzol and picric acid are prepared. The relations of benzene to these compounds is best shown briefly by means of some such diagram as that on the opposite page.

To illustrate the reactions by means of which some of the more important compounds are derived from benzene, the following tables have been prepared:

### Table 15. Reactions Showing How Aniline and Benzidine Are Derived from Benzene.

$$C_6H_6+HNO_3\ (H_2SO_4)=C_6H_5NO_2+H_2O\ (H_2SO_4)$$

**Nitro Benzene.**

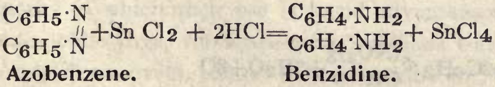


$$2C_6H_5NO_2+4SnCl_2+4KOH=\begin{matrix}C_6H_5\cdot N\\ C_6H_5\cdot \overset{\|}{N}\end{matrix}+2SnCl_4+2H_2O+2K_2SnO_3$$

**Nitro Benzene.** **Azobenzene.**

$$C_6H_5\cdot NO_2+6HCl+3Fe=C_6H_5\cdot NH_2+3FeCl_2+2H_2O$$

**Nitro Benzene.** **Aniline.**

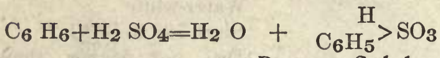


$$\begin{matrix}C_6H_5\cdot N\\ C_6H_5\cdot \overset{\|}{N}\end{matrix}+SnCl_2+2HCl=\begin{matrix}C_6H_4\cdot NH_2\\ C_6H_4\cdot NH_2\end{matrix}+SnCl_4$$

**Azobenzene.** **Benzidine.**

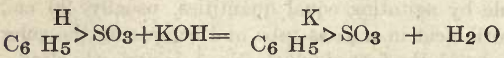
Substantive Cotton Dyes.

## Table 16. Reactions Showing How Phenol, Picric Acid and Resorcinol May Be Derived from Benzene.



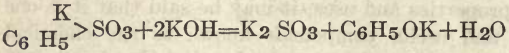
$$C_6H_6+H_2SO_4=H_2O+\overset{H}{C_6H_5}>SO_3$$

**Benzene Sulphonic Acid.**



$$\overset{H}{C_6H_5}>SO_3+KOH=\overset{K}{C_6H_5}>SO_3+H_2O$$

**Potassium Benzene Sulphonate.**

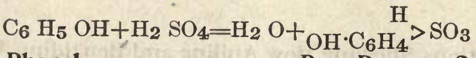


$$\overset{K}{C_6H_5}>SO_3+2KOH=K_2SO_3+C_6H_5OK+H_2O$$

(Heated to fusion) **Potassium Phenate.**

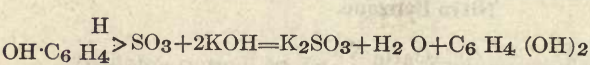
$$2C_6H_5OK+H_2SO_4=2C_6H_5OH+K_2SO_4$$

**Phenol.**



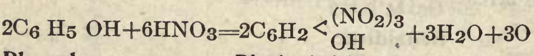
$$C_6H_5OH+H_2SO_4=H_2O+\overset{H}{OH\cdot C_6H_4}>SO_3$$

**Phenol.** **Para Benzene Sulphonic Acid.**



$$\overset{H}{OH\cdot C_6H_4}>SO_3+2KOH=K_2SO_3+H_2O+C_6H_4(OH)_2$$

**Metadihydroxylbenzene**
**or Resorcinol**
**(Resorcine)**
**Base of many colors.**

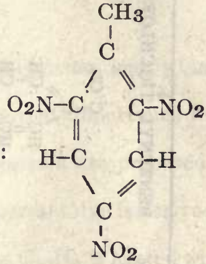


$$2C_6H_5OH+6HNO_3=2C_6H_2<\begin{matrix}(NO_2)_3\\OH\end{matrix}+3H_2O+3O$$

**Phenol.** **Picric Acid.**

**Uses of Toluene:** One of the chief uses of toluene is found in the manufacture of high explosives. These are prepared by nitrating toluene. Both the di-nitro-toluene and the tri-nitro-toluene are used, but of these the latter, often referred to as T. N. T., is more important. In intensity of explosion it ranks below picric acid, derived from phenol, but is much safer to handle, because the acid has the property of reacting direct with metals to form picrates, which are very sensitive to shock, whereas T. N. T. does not form dangerous salts with metals and is not sensitive to mechanical shock. It is also replacing gun cotton, or nitrocellulose, in torpedoes, mines, etc.

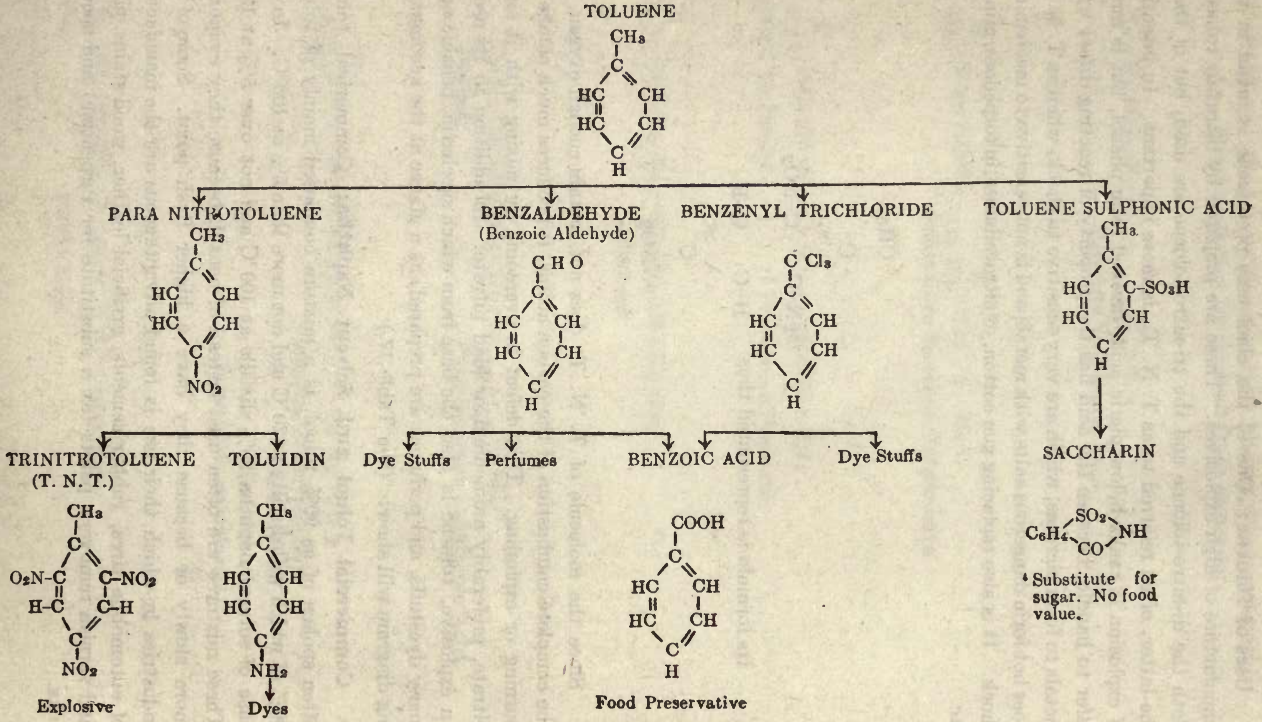
Its formula is represented thus:



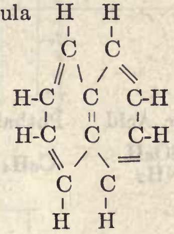
Since the molecule of T. N. T. does not contain enough oxygen for the complete combustion of the carbon atoms, it produces much smoke on burning or exploding. This defect is overcome by mixing with it some nitrate, preferably ammonium or lead nitrate. In addition to its use as an explosive, toluene is also the base from which saccharin, benzoic acid, many dyestuffs, and perfumes are prepared, as a glance at the accompanying diagram will show: (See Table 17.)

**Commercial Toluol and Solvent Naphtha:** Commerical toluol, often spoken of as 90% toluol, is a mixture composed mainly of toluol, 90% of which will distill at 120°C and not more than 5% at 100°C. In the case of solvent naphtha, 90% distills at 160°C and not over 5% at 130°. These mixtures are often used instead of benzol, because they evaporate more slowly or because they have a higher flash point. Some of the industries in which their use is found advantageous are the manufacture of automobile tires, rubber cements, artificial leather, wood stains, paint and varnish removers, paints (as a substitute for turpentine) and special inks.

Table 17. Some Products Derived from Toluene, Their Formulas and Uses.

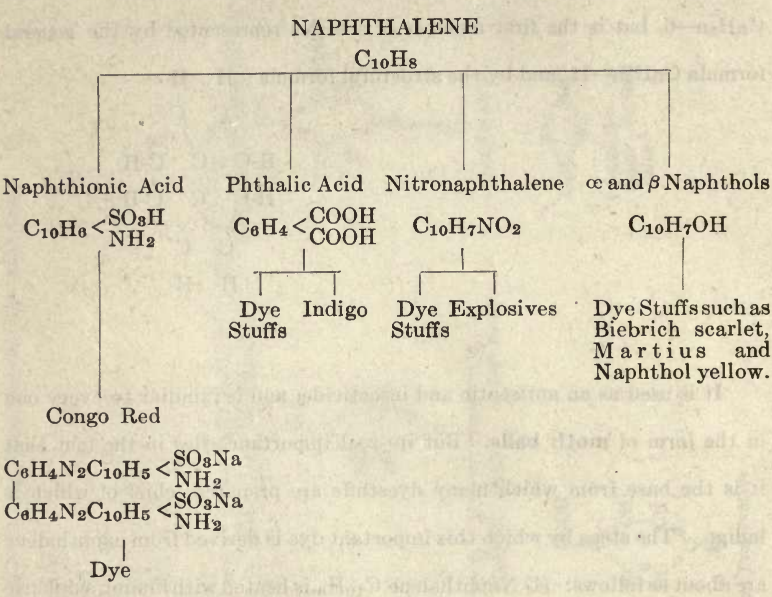


**Uses of Naphthalene:** $C_{10}H_8$ does not belong to the benzene series, $C_nH_{2n}-6$, but is the first member of a series represented by the general formula $C_nH_{2n}-12$, and by the structural formula



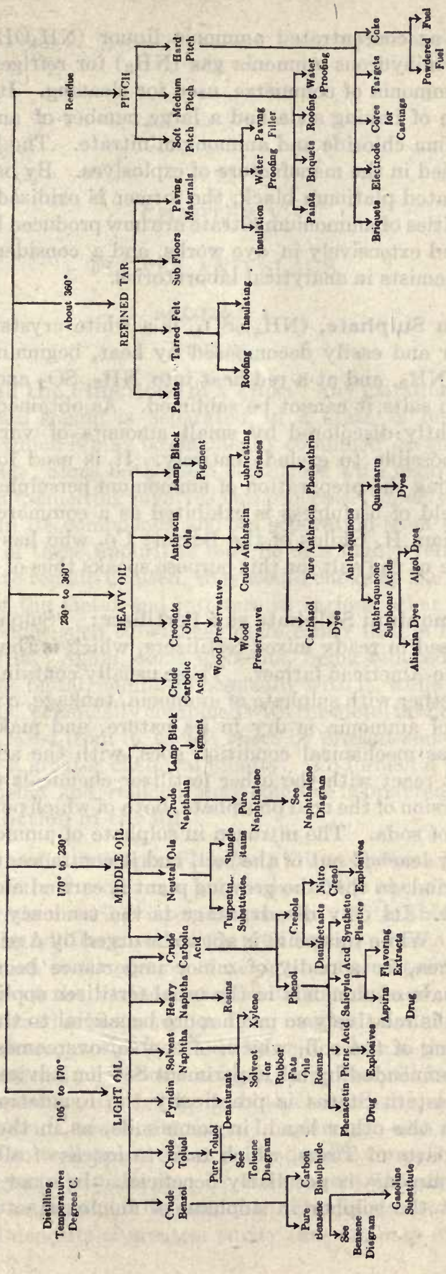
It is used as an antiseptic and insecticide, and is familiar to every one in the form of **moth balls.** But its real importance lies in the fact that it is the base from which many dyestuffs are prepared, chief of which is indigo. The steps by which this important dye is derived from naphthalene are about as follows: (1) Naphthalene, $C_{10}H_8$, is heated with fuming sulphuric acid and mercury, which acts as a catalytic agent, whereupon there is formed phthalic acid, $C_6H_4(COOH)_2$, (2) which, on being heated, passes into phthalic anhydride, $C_6H_4<\substack{CO\\CO}>O$ (3) from which phthalimide, $C_6H_4<\substack{CO\\CO}>NH$, is obtained with the aid of ammonia and heat (4). By oxidizing phthalimide with bleaching powder, anthranilic acid, $C_6H_4\cdot NH_2\cdot COOH$ is formed, (5) which is changed by treatment with monochloacetic acid to phenyl-glycine-ortho-carboxylic acid, $C_6H_4\cdot COOH\cdot NH\cdot CH_2\cdot COOH$, (6) By fusing this compound with caustic soda, indoxyl, $C_2H_4NH\cdot CO\cdot CH_2$, is formed and is readily oxidized by the oxygen of the air to indigotin, $C_6H_4\cdot NH\cdot CO\cdot C{=}C\cdot CO\cdot NH\cdot C_6H_4$, or indigo-blue. The following table will serve to show the many other dyestuffs that may be obtained from naphthalene:

**Table 18. Showing Some Products Derived from Naphthalene.**



**Tar:** As obtained from gas works as well as from by-product coke plants, tar is a black, viscous, oily liquid, with a specific gravity that varies from 1.15 to 1.20, that from coke works having a gravity of about 1.16. It also varies a great deal in other respects, especially in composition. It is a very complex substance; the number of its compounds have been estimated at about 300, only some of which have been isolated in the laboratory and but a very few in the commercial working up of the liquid. In the crude state it may be used as a fuel and for road dressing, but, by refining, it is made to yield a great number of products of great economic and hygienic importance. The refining of tar forms an industry by itself, which requires volumes to describe in all its details. Suffice it to say, that the refining of tar is essentially a process of fractional distillation, in which it is first separated roughly into several parts, which may then be further rectified into purer substances as shown in the following diagram, which is also made to indicate the uses to which the products are applied.

Table 19. Diagram Illustrative of the Refining of Tar.



**Ammonia,** as concentrated ammonia liquor ($NH_4OH$ and $H_2O$), is used in making anhydrous ammonia gas ($NH_3$) for refrigeration purposes and the aqua ammonia of commerce, used for cleaning. It is also used in the manufacture of baking soda and a large number of ammonium salts, such as ammonium chloride and ammonium nitrate. The last named salt is extensively used in the manufacture of explosives. By passing ammonia and air over heated platinum black, the former is oxidized to nitric acid, and large quantities of ammonium nitrate are now produced by this method. Ammonia is used extensively in dye works, and a considerable amount is consumed by chemists in analytical laboratories.

**Ammonium Sulphate,** $(NH_4)_2SO_4$, is a white crystalline salt, very soluble in water and easily decomposed by heat, beginning at 140°, into $NH_4HSO_4$ and $NH_3$, and at a red heat into $NH_3$, $SO_2$ and $H_2O$. Unlike most ammonium salts, it cannot be sublimed. As obtained from the coke works, it is slightly discolored by small amounts of various impurities which it is impossible to exclude entirely. It is used for a number of purposes, including the preparation of ammonium persulphate and nitrate, but its great field of usefulness is exhibited as a commercial agricultural fertilizer. William H. Childs of the Barrett Co. who has made a careful study of the use of the salt for this purpose speaks thus of it:

**Use of Ammonium Sulphate as a Fertilizer:** "Sulphate of ammonia is extensively used in ready mixed fertilizers, which is the form generally purchased by the American farmer. These usually contain acid phosphate and potash, together with sulphate of ammonia, tankage, cotton-seed meal, etc. Sulphate of ammonia is dry in its nature, and makes an excellent mixture as far as mechanical condition goes, with the added advantage that it does not react with the other fertilizer chemicals to cause loss of nitrogen or reversion of the acid phosphate, both of which points are claimed against nitrate of soda. The nitrogen in sulphate of ammonia is quick to act, is not easily leached out of the soil, and it continues its action over a considerable period, so that the growing plant is carried along to maturity without setback. Its only disadvantage is the tendency to exhaust the lime in the soil. While this point is apt to be urged by Agricultural Experiment Station men, it is really of minor importance because the actual amount of sulphate of ammonia in the usual fertilizer application is small, and its nitrogen is relatively so much more beneficial to the growth of the crop. The liming of the soil, which, of course, overcomes all objections, is urgently recommended by all Experiment Station advisers, and in large areas of the Eastern States is practically the foundation of profitable agriculture. On the other hand, in some soils, as in those of Southern California and parts of Texas, which tend to excess of alkali, the action of sulphate of ammonia is peculiarly beneficial. In some soils sulphur is lacking, so that the sulphur in sulphate of ammonia actually acts as a plant food."

# CHAPTER V.

## FLUXES AND SLAGS.

### SECTION I.

### FLUXES.

**Smelting and the Functions of a Flux:** Any metallurgical operation in which the metal sought is separated, in a state of fusion, from the impurities with which it may be chemically combined or physically mixed is called **smelting.** Since both these conditions with regard to impurities are usually present, smelting involves two processes; namely, the reduction of the metal from its compounds and its separation from the mechanical mixture. Many of these impurities may be of a highly refractory nature, and if they were to remain unfused, they would choke up the furnace, retard the separation of the metal and interfere in various other ways with the smelting. To render such substances more easily fusible is the **primary function of a flux.** Again, some elements, being reduced almost simultaneously with the metal, combine chemically with it, while other elements and some radicals, chemically combined with the metal in the raw materials, refuse to be separated from it, except there be present some substance for which they have a greater chemical affinity. To furnish a substance with which these elements and radicals may combine in preference to the metal is **the second function of the flux.**

**The Selection of the Proper Flux for a Given Process** is, then, chiefly a chemical problem and requires a knowledge of the chemical composition of all the materials entering into the process. With this knowledge in hand, the selection will be governed by well known physical and chemical laws, chief of which is the action of acids and bases toward each other and the fusibility of the various compounds thus formed. In general, if the matter to be fluxed is basic, such as lime, magnesia and other compounds of base forming elements, the flux must be acid, while if the impurities be acid, such as silica and phosphoric acid, a basic flux will be required. In most ores the impurities will belong to both classes with one or the other class, usually the acids, predominating. In a few iron ores the two classes of impurities are so well balanced as to render the ores self-fluxing, or by proper mixing they can be made so. In order to control fusibility, a neutral flux is sometimes required. The cost of the flux is also to be considered, hence the natural deposits of greatest purity that are easy of access and in close proximity to the works are made use of. A brief discussion of the fluxes of greatest importance in the iron and steel industry follows:

**Acid Fluxes:** Silica is the only substance that may be classed as a strictly acid flux. For this purpose it is available as sand, gravel and quartz in large quantities and in a sufficiently pure state. In blast furnace practice, it is customary to employ acid open hearth or Bessemer slags or ores of high silica content when it is desired to increase the acids in the furnace,as,in this way,the metallic contents of these substances are recovered.

**Alumina:** Unlike silica, which is a strong acid under all conditions, alumina may perform either the function of an acid or a base, depending upon the conditions imposed. Thus, with silica, it forms aluminum silicate, and with a strong base, such as sodium, sodium aluminate. A marked peculiarity is its tendency to form, in conjunction with other bases, double salts with polybasic acids. As a rule, double silicates are more easily fused than those containing a single base. Alumina is seldom used intentionally as a flux, but it is present in nearly all raw material, hence unavoidable.

**Basic Fluxes:** The chief natural fluxes of this class are limestone and dolomite. In addition, iron and manganese oxides act as such in certain processes where their performing this function is uncontrollable, as is the case in the acid open hearth. Referring to limestone and dolomite as blast furnace materials, there is a difference of opinion among furnacemen as to their relative value as fluxes. Some hold that limestone is the better, while others maintain that dolomite gives as good, if not better results, their opinions usually being influenced by their training and by the extent of their experience with these materials. The presence of magnesium in limestone in small amounts has little effect, but as the content increases, it may lower the fusion point of the resultant slag by the formation of double salts. A high percentage (over 3%) of magnesia in blast furnace slag renders it undesirable for cement, but for concrete, ballast, etc., it is desirable, as it makes the slag harder. Aside from this objection, not one of much weight, the factor that governs the choice between limestone and dolomite is the cost per ton of available base.

**Available Base:** By available base is meant the amount of basic substance that remains in the raw flux after the acids of its own content are satisfied. Referring to the analysis of limestones on a succeeding page, it is at once noticed that the total is not 100%. The substance that is missing is carbon dioxide, which constitutes 44.0% of pure calcium carbonate, and, being evolved as a gas, is seldom determined in making an analysis. Using the Bessemer stone as an example and remembering that the iron and phosphorus are completely reduced in the furnace, we have remaining $SiO_2$, 3.43%; $Al_2O_3$, .86%; CaO, 51.45%; MgO, 1.66%. If now, it is desired to produce a slag in which the combined weight of the bases (CaO+MgO) equals the silica and alumina ($SiO_2+Al_2O_3$) the available base=(51.45+1.66)—(3.43+.86)=48.82% In a similar manner the basic stone will show 52.66% available base, if it be calculated on the same slag basis.

**Limestone,** which term also includes **dolomite** belongs to the sedimentary class of rock-formation and is widely distributed. Immense deposits underlie most of the area drained by the Ohio and Mississippi rivers. The best of these deposits are of more ancient origin than our coal beds, belonging to the Mississippi, or early carboniferous, period and previous geological periods. Some limestone is formed by chemical precipitation, but the greatest portion of these natural deposits in all probability originated by the accumulation of the remains of minute sea animals. During succeeding periods these deposits were covered to a great depth. They were later made accessible by processes of uplifting and erosion which have exposed the strata in places.

**Supply of Limestone:** The main supply of limestone for Carnegie Steel Company comes from the Altoona, New Castle, Martinsburg and Butler County districts. In the Altoona and Martinsburg districts the beds have been folded and broken in the uplifting and lie at various angles, while in the other fields their position is horizontal or nearly so. In all the districts mentioned the ledges representing the various deposits vary in their silica content, but by a process of combining the stone from the different ledges, the silica content of the different car loads is kept very constant, rarely exceeding 5%. Great care is exercised to keep the stone as free from clay as possible, as this is one of the disturbing elements in uniform blast furnace operation. At most of the quarries, suitable crushing and screening devices have been installed to size the stone and remove the more silicious fines.

**Action of Limestone in Furnaces:** In the blast furnace, limestone is not affected, excepting for the liberation of carbonic acid, until the lower levels and higher temperatures in the furnace are reached. In the smelting zone, or the regions just below, it combines with the gangue, forming slag, and also unites with varying amounts of sulphur depending upon the conditions of temperature and basicity of the slag. Ordinarily, about one-half ton of limestone is required in the production of one ton of pig iron. In the manufacture of steel, it plays the part of a purifying agent. Phosphorus, in particular, cannot be removed, commercially at least, without it. Stone with the lowest silica content is usually reserved for open hearth furnaces, that with the lowest phosphorus for furnaces making Bessemer pig iron, while stones with higher phosphorus content are used in furnaces making iron for basic open hearths. An analysis typical of each of these grades is shown in the following table:

**Table 20. Representative Analyses of the Three Different Grades of Limestone.**

| | Open Hearth | Bessemer Pig | Basic Pig |
|---|---|---|---|
| Silica.............. | .80 % | 3.43 % | 1.20 % |
| Iron............... | .10 % | .30 % | .60 % |
| Phosphorus........ | .005% | .006% | .033% |
| Moisture.......... | .10 % | .60 % | .60 % |
| Alumina........... | .16 % | .86 % | .70 % |
| Lime.............. | 54.90 % | 51.45 % | 53.88 % |
| Magnesia.......... | .47 % | 1.66 % | .68 % |

**Neutral Fluxes:** For the purpose of making slags more fusible without changing their acidity or basicity, neutral substances having very low fusion points may be used. This practice is common in basic open hearths. Fluorspar is the substance generally used, though calcium chloride can be substituted.

## SECTION II.

### SLAGS.

**Slag** is the name applied to the fused product formed by the action of the flux upon the gangue of an ore and fuel, or upon the oxidized impurities in a metal. As previously indicated, it results from the neutralization of bases and acids, hence corresponds to the salts of wet chemistry. The word cinder is used interchangeable with slag, but cinder is also applied to refuse in a solid form.

**Functions of Slags:** On account of their fusibility, chemical activity, dissolving power, and low density, slags furnish the means by which the impurities are separated from the metal and removed from the furnace. Incidentally, they perform other important functions. Lying upon the molten metal, they serve as a blanket to protect it from the injurious action of hot gases, and being poor conductors, they prevent over heating of the metal and at the same time conserve its heat by preventing radiation. Since they possess the power of dissolving oxides, they mark a sharp line between reduced and unreduced material, and on this account serve to keep the metal clean.

**Importance of Slags:** In the metallurgy of iron, the importance of slags cannot be over emphasized. In the blast furnace they furnish the only positive means of removing sulphur, and, as their fusion temperature varies with their composition, they are one of the means by which hearth temperature is regulated. On this account, the slag controls to the greatest extent the quality of the iron produced. In the open hearth, particularly in the basic process, the slag is the only means by which the impurities in pig iron, excepting carbon, are removed. To the metallurgist a knowledge of the properties of slags is essential. He understands their chemical behavior, knows their formation temperatures, fusibility and fluidity, and how to control these factors.

**The Chemical Composition of Slags** is within the control of the metallurgist, and by varying it, slags of almost any set of properties desired may be produced. Slags are mainly composed of two or more silicates in which other substances are dissolved or suspended. In the blast furnace, the slag will consist principally of calcium silicate, with a part of which the magnesium charged into the furnace will be found as a double salt. The same may also be the case with the small quantities of iron, manganese, and traces of alkali found in these slags. The sulphur removed will be in the form of CaS, which dissolves in this mixture. As to the state of alumina, which usually makes up 12% or more of the slag, there is room for doubt. By some it is considered as a base; by others, an acid. As noted under the heading of fluxes, it has the properties of both an acid and a base. Hence, being governed by the Law of Mass Action, it acts as a stabilizer to maintain a kind of equilibrium between acids and bases. In a highly silicious slag it may side with lime to form a double silicate, while in a strongly basic slag it takes the place of silica in neutralizing lime and magnesia. Since it has very weak properties in either direction, it seems reasonable to suppose that, in a case where lime and silica are in stable proportions, all or a part of the alumina may play a neutral part and dissolve in the slag. In ordinary blast furnace practice, however, the sum of the silica and alumina ($SiO_2+Al_2O_3$) is considered as the acid of the slag, while lime plus magnesia ($CaO+MgO$) is taken to represent the base.

**Relation of Acids to Bases in Blast Furnace Slags:** By chemical analysis of blast furnace slags it is found that, usually, $SiO_2+Al_2O_3=$ about 48% of the slag, the ratio of $SiO_2$ to $Al_2O_3$ being about 2 : 1. After deducting from the lime enough to satisfy the sulphur, the sum of the remaining lime together with the magnesia ($CaO+MgO$) will also be about 48%. This relation of acid to base will generally vary through a range of about 2%, any increase in one being followed by a corresponding decrease in the other. The remaining 4% to 5% is made up of CaS and small amounts of ferrous and manganous oxides. As previously indicated, the ratio of lime to magnesia may vary somewhat without noticeably affecting the properties of the slag. The following results of an analysis represent a slag production by a furnace making basic iron.

**Table 21. Showing Relation of Acids to Bases in Blast Furnace Slags.**

| Acids | | Bases | | | |
|---|---|---|---|---|---|
| $SiO_2$ | 35.02% | CaO | 44.03% | FeO | 1.16% |
| $Al_2O_3$ | 14.99" | MgO | 2.72" | MnO | 1.08" |
| | 50.01" | | 46.75" | S | 1.35" |

**Ratio of Acids to Bases in Open Hearth Slags:** Final basic open hearth slags contain a much higher percentage of bases than blast furnace slags and a much lower percentage of acids. The lime and magnesia will always be more than twice the silica, alumina and phosphorus. Some open hearth furnacemen hold that the best results are obtained when the percentage of lime plus magnesia in the final slag is three times that of the silica. The strong basic character of basic slags is necessary for the removal of phosphorus and the small and variable amounts of sulphur possible by the process. If the percentage of lime is too high, the slag will be viscous and retard the working of the heat. The following analysis is the average tapping slags from thirteen basic furnaces.

**Table 22. Relation of Acids to Bases in Basic Slags.**

| Acids, per cent. | | Bases, per cent. | |
|---|---|---|---|
| $SiO_2$ | 20.74 | CaO | 40.90 |
| $Al_2O_3$ | 3.55 | MgO | 9.67 |
| $P_2O_5$ | 2.85 | FeO | 10.84 |
| S | .04 | $Fe_2O_3$ | 5.24 |
| $SO_3$ | .23 | MnO | 5.86 |
| | 27.41 | | 72.51 |

**Acid to Base in Acid Furnaces:** Both in the acid open hearth and in the acid Bessemer processes the slags will consist, practically, of the oxides of iron and manganese silicates. In both cases the silica, $SiO_2$, is usually about 50%; that in the acid open hearth is seldom higher than 52% or lower than 48%, while acid converter slag will sometimes contain as high as 65%. The remainder of about 50% will consist of FeO and MnO, together with small amounts of lime and magnesia and traces of phosphorus and sulphur. Acid open hearth slags are self regulating as to the amount of FeO and MnO. These oxides, in such slags, are always present in such quantities that their combined percentage is equal to about 46% of the slag.

**Electric Steel Furnace Slags:** The composition of these slags is affected by the kind of steel made and the method of refinement used. However, the final slag of an electric steel, that is, the slag formed near the end of the reducing period, should be very basic, very low in iron and manganese content and show a goodly percentage of calcium carbide. The following analysis may be considered as representing a good average finishing slag for this process:

Silica, 17.90%; Iron, .32%; Lime, 61.51%; Magnesia, 7.47%; Manganese, .35%; Sulphur, 1.30%; Calcium Carbide, .51%; Alumina, 6.00%.

**Acids Formed by Silicon:** A study of slags is facilitated by a study of the acids of silicon. There are a number of these acids which chemists consider as being derived from orthosilicic acid, $H_4SiO_4$ or $(H_2O)_2\ SiO_2$, through the loss of varying amounts of water, and are called polysilicic acids. When orthosilicic acid, $(H_2O)_2 \cdot SiO_2$, is set free from its salts, it always forms $H_2O \cdot SiO_2$, which is called, therefore, metasilicic acid or normal silicic acid. The relations of these various acids are shown in the following table:

**Table 23. Acids Formed by Silicon.**

| Orthosilicic Acid | Metasilicic Acid | Polysilicic Acids | Water |
|---|---|---|---|
| $(H_2O)_2 \cdot SiO_2$ | $H_2O \cdot SiO_2$ | | $+ H_2O$ |
| $2(H_2O)_2SiO_2$ | | $(H_2O)_3 \cdot (SiO_2)_2$ | $+ H_2O$ |
| | | $H_2O \cdot (SiO_2)_2$ | $+ 3H_2O$ |
| $3(H_2O)_2SiO_2$ | | $(H_2O)_4 \cdot (SiO_2)_3$ | $+ 2H_2O$ |
| | | $(H_2O)_2 \cdot (SiO_2)_3$ | $+ 4H_2O$ |
| | | $H_2O \cdot (SiO_2)_3$ | $+ 5H_2O$ |

Besides these acids, salts of other acids, which do not fit into this table, are known to exist, such as $(H_2O)_4 \cdot SiO_2$. By substituting bases like CaO, MgO, FeO, MnO, for $H_2O$ in these formulas, silicates such as are formed in slags would be represented. In the case of sesquioxides, as $Fe_2O_3$ and $Al_2O_3$, in which the valence of the metal is increased to three, this substitution cannot be made on a basis of 1 for 1, but 2 for 3, and the formulas are, therefore, more complicated.

**So-called Acid and Basic Slags:** In substituting a base, such as CaO, in the formulas above, it will be observed that the relation of base to silica varies in the different compounds through the wide range from 4 CaO combined with 1 $SiO_2$, $(CaO)_4 \cdot SiO_2$, to 1 CaO combined with 3 $SiO_2$, $CaO \cdot (SiO_2)_3$. The salts of the meta-and the ortho-acids, $(H_2O) \cdot SiO_2$ and $(H_2O)_2 \cdot SiO_2$, in which, for example, CaO is combined with 1 $SiO_2$, and 2 CaO with 1 $SiO_2$, appear to occupy positions of equilibrium or neutrality. Any increase of lime increases the affinity of the slag for acids, whilst a decrease in lime content causes the slag to exhibit acid properties. Slags of this composition are also very fusible and flow readily.

**Classification of Slags:** Some metallurgists classify and name the slags derived from the acids of silicon according to the ratio of oxygen in the base to oxygen in the acid, as shown in table 24:

As illustrating the importance and value of this table, it is sufficient to say that it is often made the basis of calculation for the theoretical burdening of the blast furnace. These calculations are necessary in dealing with new and unfamiliar materials in order to determine the proper proportion of fuel, ore and flux in the charge. From the type of slag best suited to produce the kind of iron desired, the oxygen ratio is fixed upon, which in turn determines the relation of acids to bases. Then, with the analysis of the raw materials in hand, the impurities in each are combined according to this relation. As a result of this combination the excess acids of fuel and ore are found, and the available base of the flux. These quantities, being combined in accordance with the slag ratio, will then, with the exception of variations in fuel consumption, fix the relations of the three materials.

### Table 24. Method of Classifying Slags.

| Monoxide Base | Sesquioxide Base | Oxygen in Base | | Oxygen in Acid | Name | Fusibility |
|---|---|---|---|---|---|---|
| $(CaO)_4 \cdot SiO_2$ | $(Al_2O_3)_4 \cdot (SiO_2)_3$ | 2 | : | 1 | Subsilicate | Fusible |
| $(CaO)_2 . SiO_2$ | $(Al_2O_3)_2 \cdot (SiO_2)_3$ | 1 | : | 1 | Monosilicate | Very Fusible |
| $(CaO)_4 \cdot (SiO_2)_3$ | $(Al_2O_3)_4 \cdot (SiO_2)_9$ | 2 | : | 3 | Sesquisilicate | Very Fusible |
| $CaO \cdot SiO_2$ | $(Al_2O_3) \cdot (SiO_2)_3$ | 1 | : | 2 | Bisilicate | Moderately |
| $(CaO)_2 \cdot (SiO_2)_3$ | $(Al_2O_3)_2 \cdot (SiO_2)_9$ | 1 | : | 3 | Trisilicate | Less Fusible |

**Uses of Slags:** While to the metallurgist slags represent refuse no longer useful to his art, they may be applied to many purposes. Railroad ballast, road building, roof covering, concrete work, Portland cement, insulating materials, fertilizers, brick, and sand for mortar are some of the avenues open for the economic disposal of slags.

# CHAPTER VI.

# THE MANUFACTURE OF PIG IRON.

## SECTION I.

### SOME INTERESTING HISTORICAL FACTS.

**Early History of Iron:**[1] While the sole purpose of this chapter is to describe the manufacture of pig iron as carried on at the present time, one or two of the many interesting topics presented by the historical aspects of the subject will be found pertinent. A word as to the origin of the use of iron will serve to emphasize the process of evolution through which this wonderful industry has passed in attaining its present state of advanced development. When iron was first used, no one knows, for that date belongs to prehistoric times. Archaeological research can only establish that it has been in use by man through a period of about four thousand years. Evidence as to the extent of its use during the first three thousand years of this period is lacking, but it is very probable that the metal was used much more extensively than the few specimens uncovered would indicate. The corrosive properties of iron make it, to the archaeologist, a perishable substance that leaves no trail. If the use of iron on this continent were to cease suddenly today, no evidence of its present extensive application would be expected a thousand years hence. Therefore, only occasionally is some implement or ornament found among ancient ruins. There is doubtful evidence of its use by the Egyptians in building the pyramids, about 4000 B. C. As to its use by the ancient Hebrews, by the Assyrians about 1400 B. C., and, more recently, by the Greeks, there can be no doubt. The Greeks were followed by the Romans who became somewhat proficient in its metallurgy. These people, through their numerous and extensive conquests, the success of which they no doubt owed to the use of metals in making their instruments of war, spread the art of extracting and fashioning it throughout Europe. Some knowledge of the metal, however, preceded them, for Caesar, crossing the English Channel, found it in use among the native Britons. During the Roman occupation, the industry grew to one of importance in England. At that time it was obtained by heating a mixture of ore and charcoal, probably in a flat bottom furnace or forge, until there had collected a small body of pasty metal which was then drawn and worked by hammering to make wrought iron. Such, briefly, was the process until 1350, when the iron makers of Central Europe succeeded in producing iron that would melt in the furnace and permit of casting. This result they accomplished in a new type of furnace, built of masonry, which enclosed a shaft or vertical opening in the form of two truncated cones placed

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[1] See Metallurgy of Iron by Thomas Turner, published by Charles Griffin and Co. Ltd., London.

end to end,—in a crude way, the lines of the modern blast furnace. The lower frustum came to be known as the boshes, the bottom, as the hearth. In this furnace, ore, flux and charcoal were charged in at the top of the furnace, while air, under very low pressure, was blown in at the bottom. This method, was introduced into England about the year 1500 where, in 1619, coke was first used, to be followed, 200 years or more later, by the introduction of hot blast. In America the first iron works was established in Virginia on the James River in 1619, and about 100 years later (1710-1715) the first furnace using blast was built. Thence the industry spread, for the most part, westward.

**Old American Furnaces:** The furnaces of a period as recent as one hundred years ago were what would now be called very crude affairs. Portions of some of them are still standing, and one is within a two hour ride of Pittsburgh. They were usually in the form of a truncated pyramid, twenty to thirty feet high, and constructed of stone work which enclosed a circular shaft, some four feet in diameter at the top and about eight feet at the bosh. The hearth was either round or square in cross section. The capacity ranged from one to six tons a day. By the year 1880, this output had been gradually increased to nearly 100 tons per day, with a daily coke consumption of nearly 300 tons. With all the basic principles in use for so long a time, it is remarkable that so little progress was made. About 1880, for reasons, which would be too lengthy to explain here, very rapid advancement was made, so that now there are furnaces whose daily output of pig iron exceeds 600 tons with a fuel consumption of less than 2000 pounds of coke per ton of iron produced. Attention has been called to these facts here, because it is well to remember in beginning the study of the modern blast furnace, that the present method for the extraction of iron from its ores represents a pyrochemical process just attaining its highest state of development.

**The Importance of Iron:** This topic needs no comment here. Pig iron, besides being used directly in the form of castings, is the intermediate from which all ferrous products are derived. Its importance is emphasized by the reports of the yearly productions.

## SECTION II.

### COMPOSITION AND CONSTITUTION OF PIG IRON.

**Constitution of Pig Iron:** In the solid form, pig iron represents a very complex mixture made up of uncombined elements, chemical compounds and alloys. The amounts and relations of these constituents may vary with conditions, so that the complexity of the mixture does not depend wholly upon the number of elements present nor upon their amounts. Initial temperature and rate of cooling are two of the most important factors affecting the properties of pig iron. These matters are of great importance when the iron is to be used for castings, and to understand them fully requires a very extended study of the subject. This chapter has to do mainly with pig iron as an intermediate product in the making of steel, so it will be most profitable to discuss only the subject of its composition very briefly.

**Chemical Elements in Pig Iron:** In addition to iron, the elements commonly occurring in pig iron are carbon, silicon, manganese, sulphur and phosphorus. Of these elements iron will constitute 91 to 94%, carbon 3.0 to 4.0%, silicon .50 to 3.00%, sulphur less than .065%, and phosphorus .040% to 2.00% of the whole.

**Carbon** occurs in pig iron in two forms, called **graphitic carbon** and **combined carbon.** Graphitic carbon is practically pure carbon, existing in the iron in the form of tiny flakes which are distributed throughout the mass. It forms in the pig iron during the process of cooling, because the absorbing power of iron for carbon decreases as its temperature falls. Carbon in this form gives to pig iron the grayish black appearance so often seen. But in cooling, some of the carbon continues in combination with the iron as a definite compound, $Fe_3C$, 93.33% Fe and 6.67% C. Both forms of carbon produce marked effects upon the properties of the iron. The tendency of the graphitic is to weaken, while the combined carbon, up to the limit of about .90%, strengthens it. In Metallography the compound $Fe_3C$ is called **Cementite,** and to the uncombined iron is given the term **Ferrite.** In cooling these two substances conduct themselves in a peculiar way toward each other. In passing a certain temperature (about 700° C.) they arrange themselves in layers in the definite amounts of approximately seven parts ferrite to one part cementite. The resultant stratified segregate will, therefore, contain approximately .85% C. Under the microscope these stratifications present the appearance of mother of pearl, whence it is named **Pearlite.** Pearlite is the strongest constituent of cast iron. When heated, iron absorbs carbon, and from the fusion point this absorption becomes very rapid. The limit, called the saturation point, beyond which it will not absorb any more, varys with the temperature, and is also affected by the amount of silicon present, a rise in the percentage of silicon causing a corresponding decline in the carbon content. Silicon tends, also, to decrease the combined carbon, and increase the graphitic. Manganese and Chromium have the opposite effect. Rapid cooling tends to prevent the formation of pearlite and graphite. In general, the more rapid the cooling the less the graphitic carbon and the greater the combined carbon content will be.

**Silicon:** In small quantities silicon has little direct effect on pig iron, but an increase above 4% makes the iron very brittle, hence foundry iron will seldom contain more than 3%. In iron for basic open hearth use the percentage of silicon should not be higher than 1.25, as a high silicon content tends to flux away the lining of basic furnaces very rapidly. For the acid Bessemer process iron containing about 1.25% silicon is desirable, but the content may vary from 1.00% to 1.50%. The oxidation of the silicon in the Bessemer process produces a large quantity of heat, so that iron containing a high percentage of this element is usually referred to as hot iron. The amount reduced in the blast furnace is variable and depends on conditions of slag and temperature. Its effect on the carbon has just been noted. Since it tends to throw the carbon out of solution, silicon is used to regulate the depth of chill in chilled castings. A content of one per cent. silicon in ordinary low sulphur iron renders it difficult to obtain a chill. Below this percentage the chilling properties of the iron are, roughly stated, in inverse ratio to the amount of silicon present.[1] Silicon also prevents blow holes, and tends to decrease the shrinkage in white irons.

**Manganese** alloys with iron in all proportions. An alloy containing 10 to 25% manganese is called spiegel. Alloys containing 40 to 80% manganese are called ferro-manganese. Up to one percent manganese tends to strengthen pig iron. It decreases the bad effects of sulphur, with which it combines, replacing iron. Its presence opposes that of sulphur, so that, with uniform raw materials, furnace conditions that give a high percentage of manganese tend to decrease the percentage of sulphur. Hence, in reasonable amounts of about one per cent, it is desirable, especially for basic open hearth use, where it also aids in the elimination of sulphur. In Bessemer practice iron with a manganese content of about .50% is desirable. The element is oxidized, and unites with silica to form a slag that fuses at a comparatively low temperature and is very fluid, so that iron containing a higher percentage than that indicated by the latter figure gives rise to a condition in blowing known as a "sloppy" heat. As to whether manganese has a good or a bad effect on cast iron, there is much difference of opinion, some considering it almost as a cure for all troubles and others condemning it as a source of much trouble, especially in chilled castings. While it tends to hold carbon in solution, chill produced by increasing the manganese content alone is soft and tends to spall[1]. In moderate amounts it is said to prevent cracking of the surface and also spalling to some extent, especially in chilled rolls. Nearly 75% of the total amount of manganese charged into a blast furnace is obtained with the metal.

**Sulphur** in pig iron is generally supposed to be injurious, though recently the statement that the inferior qualities exhibited by high sulphur iron is due entirely to its presence has been questioned. Nevertheless, as sulphur in steel is considered undesirable and as the blast furnace affords the only positive means of reducing it, pig iron containing less than .05% is desirable for making steel by all the fusion processes. Sulphur with iron forms iron sulphide, which is soluble in the metal and has a melting point that is lower than the other constituents of the iron. According to some authorities[1], this sulphide in iron used for castings has a threefold influence. First, it tends to hold the carbon in combined condition, hence can be used to increase the depth of chill in chilled castings; second, its low melting point causes it to segregate as the iron solidifies, thereby causing the condition in castings known as bleeding; third, it increases the shrinkage of the iron to a marked degree, thus increasing the difficulty of making accurate castings and increasing the tendency to cracks which are a result

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[1] See The Principles, Operation and Products of the Blast Furnace, by J. E. Johnson, Jr. Published by McGraw-Hill Book Company Inc., New York.

of the high shrinkage. The chill imparted by sulphur is a very hard one, but is very brittle and somewhat unreliable.

**Phosphorus** is the only element entering the blast furnace over which the skill of the furnaceman has absolutely no control. Its compounds are completely reduced, so that all the phosphorus in the raw materials is found in the metal. Therefore, its content must be regulated by proper selection of raw materials. High phosphorus causes a slight brittleness in pig iron, and has a marked effect upon the total carbon. Ferro-phosphorus containing about 15% phosphorus is carbonless. Lesser amounts permit a proportionate increase of carbon, so that the total carbon in an iron containing .2% phosphorus may be as high as 4%. In this respect its action is not selective, since the ratio of combined to graphitic carbon is not affected. Phosphorus is known to form a compound, $Fe_3P$, with iron, but it is able apparently to combine with it in several proportions. Ferro-phosphorus containing as much as 25% phosphorus is now manufactured. In iron for casting, phosphorus exercises a beneficient effect. It tends to eliminate blow holes, decreases shrinkage, and increases the fluidity. Above .5% it begins to weaken iron, so the amount used will be governed by the use to which the casting is to be applied.

**Grading Pig Iron:** Pig Iron is graded by chemical analysis. There are several systems employed, many of which are somewhat elaborate. The following table, which includes other important blast furnace products as well as ordinary pig iron, shows one of the simplest methods of classification:

Table 25. The Metallic Products of the Blast Furnace.

| GRADE | RANGE IN PERCENT. OF | | | | |
|---|---|---|---|---|---|
| | Silicon | Sulphur | Phosphorus | Manganese | Total Carbon |
| No. 1 Foundry | 2.5 to 3.0 | Under .036 | .25 to 1.00 | Under 1.00 | 3.50—4.25 |
| No. 2 Foundry | 2.0 to 2.5 | " .045 | .25 to 1.00 | " 1.00 | 3.50—4.25 |
| No. 3 Foundry | 1.5 to 2.0 | " .060 | .25 to 1.00 | " 1.00 | 3.50—4.25 |
| Malleable Casting | .75 to 1.5 | " .050 | .2 | " 1.00 | 3.50—4.25 |
| Forge | About 1.50 | " 1.00 | 1.0 | " 1.00 | 3.50—4.25 |
| Acid Bessemer | 1.00 to 1.50 | " .050 | 0.1 or less | About .50 | 3.50—4.25 |
| Basic Bessemer | Under 1.00 | " .050 | 2.00 to 3.0 | Under .50 | 3.50—4.25 |
| Low Phos. Acid Iron | " 2.00 | " .030 | .030 | " 1.00 | 3.50—4.25 |
| Basic | " 1.25 | " .050 | .100 to 1.00 | 1.00 to 2.50 | 3.50—4.25 |
| Spiegel | About 1.00 | " .050 | .150 | 18.0—22.0 | 5.0 —6.0 |
| Ferro-Manganese | .50 to 1.00 | " .030 | .10 to .30 | 78.0-82.0 | 5.0 —7.0 |
| Ferro-Silicon | 8.0 to 15.00 | " .070 | .10 to .50 | .......... | 1.00—2.00 |
| Silico-Spiegel | 8.0 to 15.00 | " .010 | .15 | 15.00-20.00 | .......... |

## SECTION III.

### A BRIEF OUTLINE OF THE PROCESS AND EQUIPMENT FOR THE MANUFACTURE OF PIG IRON.

**Trend of Modern Improvements:** With the preceding brief summary of the history, importance, and composition of pig iron in mind, the process by which it is manufactured furnishes a theme of great interest. Apropos of this idea, however, it is to be observed that a description of the modern methods of manufacture is rendered difficult both by the complexity of the details of the process and by its recent rapid development. As already pointed out, the fundamental principles have remained unchanged since the founding of the process, because experience has demonstrated that this process is the most practical. All improvements, then, have been made with the aim of increasing the production and at the same time decreasing the cost. These objects have been attained to a degree almost approaching perfection by the use of materials of greatest purity, selected through chemical control, by increasing the size of furnaces, by economies in fuel consumption, and by improved methods of handling the materials. The result is that the small plants of 100 years ago have been succeeded by complex and gigantic affairs. As the greatest changes have been brought about since 1880, a comparatively recent date, the blast furnace plant is just approaching the uniformity of perfection. Furthermore, since the improvements have been contributed by a great number of men, it is not to be wondered at that an inspection of the industry will reveal not only different stages of development but also many different methods of attaining the same end. The aims and fundamental principles being the same, however, the numerous plants, while differing greatly in detail, will present certain similarities in their gross features which may profitably be reviewed before proceeding with the detailed description.

**Essentials of the Process:** Essentially, the present process for the extraction of iron from its ores consists in charging a mixture of ore, fuel, and flux in proper proportions through a specially constructed opening in the top of a tall cylindrically shaped furnace called a blast furnace, while heated air is simultaneously blown in near the bottom through openings, called tuyeres, the nitrogen of the air together with the products of combustion and reduction passing upward and escaping through openings at the top. These parts of the process, being almost continuous ones, are accompanied by the periodic removal of a part of the impurities in the form of slag at an opening between the tuyeres and the bottom, and by a like removal of metal through a larger opening at the bottom. In order to carry out these operations on the large scale previously mentioned, it is evident that extensive equipment is required.

**Essential Equipment:** The central feature in this equipment is the furnace, which is provided with apparatus for hoisting the materials to the top and with ladles for containing slag and molten metal, to which is sometimes added casting beds or pig machines for casting the metal into "pigs" of convenient size, and slag granulating pits. Next in importance follows the blowing engines for producing the blast, then the stoves for heating it. Of great importance is the pumping station, the function of which is to furnish the great quantities of water needed for steam, for cooling, etc. As the gases that escape from the top of the furnace are combustible, apparatus for their most efficient disposal is desirable. They are used to heat the stoves and to generate power either by burning them under boilers or in gas engines, in which case they must be cleaned of the large quantities of flue dust which they carry out of the furnace. As the moisture in the air affects the efficiency of the furnace, some modern plants will be provided with apparatus for drying the blast. Referring again to the solid materials of the charge, modern equipment requires a stock house, topped by bins, in which the ore, fuel and flux may be temporarily stored and conveniently removed for weighing or measuring before delivering it to the hoisting device. Adjacent to the bins will be located the stock yard containing the ore pile, which is spanned by the ore bridges. A car dumper, advantageously situated, will complete this part of the equipment. Finally, the various parts of the plant will be made accessible by a system of railways for transporting the materials.

## SECTION IV.

### CONSTRUCTION OF THE BLAST FURNACE PROPER.

**The Gross Features of the Furnace Proper:** The modern blast furnace is a tall circular structure, 90 to 100 feet high, built of fire brick, reinforced externally by a close fitting steel shell and encasing internally a circular space of varying diameters. This space is divided into three main parts. The bottom section, called the hearth or crucible, is cylindrical in form and some 10 to 12 feet deep in the larger furnaces. The second section, having an altitude of some 12 or 13 feet, is called the bosh. It is in the form of a frustum of a cone, which, in an inverted position, tops the crucible with its smaller base. Setting above the bosh in an upright position with an altitude of about 70 feet, is the stack. Formerly its outline was also that of a frustum of a cone, but recent studies of furnace lines indicate that the slanting lines of the cone should be changed to the vertical for a distance of 4 or 5 feet above the bosh, and for about 10 feet from the lower bell at the top. The whole is now capped by the furnace top, which completes the list of the gross features of the furnace proper.

**The Foundation:** Before proceeding with the details of the parts noted above, the foundation should be considered. In view of the immense weight which it is required to support, this part of the furnace is of great importance, because any extensive settling of the furnace after it is in operation would result in serious troubles and probably put it out of commission. The depth of the foundation will vary with the conditions of the rock materials on which it is to stand. If these be sand or clay, it may be necessary to drive piling for a depth of many feet, and upon this begin the foundation. On the other hand, if solid and firm rock underlies the location for the furnace, an excavation to this rock is all that is required. A proper bed having been found or otherwise provided, the foundation is started and built up several feet with concrete, which extends some distance outward beyond the floor of the furnace. The remainder of the foundation is then made up of common brick of good quality and strength, except the space directly beneath the hearth and walls of the furnace, where firebricks are used.

**The Hearth or Crucible** is the portion of the furnace which serves as a receptacle for the molten metal and slag. It is constructed of fire brick of the best quality; its wall is usually sixty inches or more in thickness; and it may be protected in places with water cooled plates, if the furnace is of recent construction. At the bottom the walls of the hearth are usually stepped out into the interior of the hearth for four or five courses of brick. This construction gives the bottom surface a slight basin shape, and tends to hold the bottom brick in place. The hearth varies in diameter and depth with the size and capacity of the furnace. In the larger ones, it is about eighteen feet in diameter and eleven feet deep. Externally, it is reinforced by a heavy metal jacket made of steel plates that are riveted together, or of iron castings in segments that are jointed and bolted together. Jackets are always cooled, those of cast iron by internal circulating systems, and those of steel by external sprays. The upper diameter of this jacket is smaller than the diameter at the base, so that the jacket will better hold the walls of the hearth in place by offering resistance in opposition to the buoyant forces of the bath and slag.

**The Bottom** of the crucible is built of fire brick, sometimes in the form of large blocks, which are laid on end with closely fitting joints in order to prevent intrusion of metal. Bottoms vary in thickness from about six feet in the smaller furnaces to about twelve feet in the large ones. The bricks are almost entirely replaced in time by metal, which, collecting in a solid mass, often weighing many tons, is known as the **salamander.**

**Tapping Hole:** Situated at some convenient point in the circumference of the hearth and just above the top course of stepped-in brick is the **tapping hole** or **iron notch.** If the bricks are not stepped-in, the opening will be at the bottom. It may be a square opening in the brick about 8x8 inches or an oblong or rectangular one 6x8 inches on the inside. The outside dimensions may be somewhat larger to permit of easily inserting the tapping tools. Proper provision is made for the protection of the hearth jacket at this point. During the tapping of iron, the metal structures directly above the tapping hole are protected with a **splasher.**

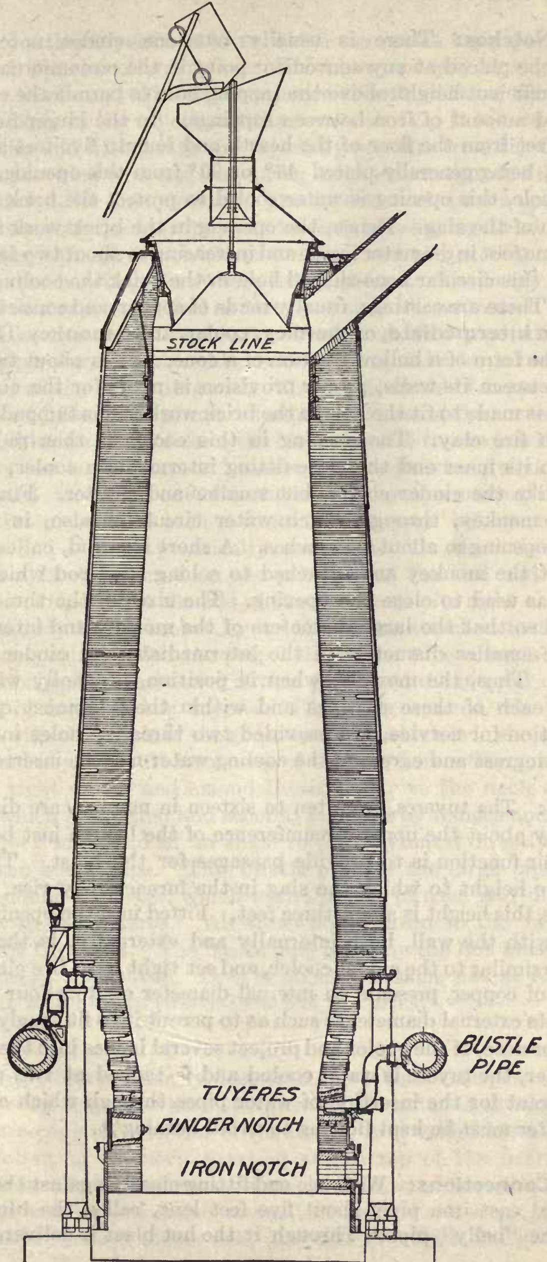

FIG. 20. Vertical Section of a modern Blast Furnace.

**Cinder Notches:** There is usually but one cinder notch. This opening may be placed at any convenient point in the circumference of the hearth at a sufficient height above the tapping hole to permit the collection of the desired amount of iron between tappings. In the larger furnaces it is about six feet from the floor of the hearth and four to five feet above the tapping hole, being generally placed 45° or 90° from this opening. Unlike the tapping hole, this opening is water cooled to protect the brick from the fluxing action of the slag. Hence, the opening in the brick work is larger, being about one foot in diameter inside and increasing to about two feet on the outside. In this circular cone-shaped hole in the brick the cooling devices are placed. These are castings, usually made of copper, and consist of a **cinder cooler, an intermediate, or monkey, cooler, and a monkey.** The cinder cooler is in the form of a hollow frustum of a cone. It is about two inches thick, and, between its walls, proper provision is made for the circulation of water. It is made to fit the hole in the brick work and is tamped securely in place with fire clay. The opening in this cooler is then reduced by inserting into its inner end the close-fitting intermediate cooler, which is constructed like the cinder cooler, but smaller and shorter. Finally, the still smaller monkey, through which water circulates also, is inserted, reducing the opening to about two inches. A short iron rod, called a **bott,** tapered to fit the monkey and attached to a long steel rod which serves as a handle, is used to close the opening. The sizes of the three coolers are regulated so that the large diameters of the monkey and intermediate cooler fit the smaller diameters of the intermediate and cinder coolers, respectively. Thus, the monkey, when in position, is wholly within the furnace. In each of these castings and within their topmost quadrant, when in position for service, are provided two threaded holes into which the pipes for ingress and egress of the cooling water may be inserted.

**Tuyeres:** The tuyeres, from ten to sixteen in number, are distributed symmetrically about the upper circumference of the hearth just below the boshes. Their function is to provide passages for the blast. They also determine the height to which the slag in the furnace may rise. In the large furnaces, this height is about three feet. Fitted into the opening in the brick, flush with the wall, both internally and externally, is the **tuyere cooler.** It is similar to the cinder cooler, and set tight with fire clay. The tuyere itself, of copper, presents an internal diameter of from four to seven inches, while its external diameter is such as to permit it to fit snugly into the smaller end, or nose, of the cooler and project several inches into the furnace. Like the cooler, the tuyere is water cooled and is tapped at two places in the top quadrant for the insertion of water pipes through which a copious stream of water must be kept flowing to avoid burning it.

**Tuyere Connections:** With one end fitting closely against the tuyere, is a horizontal cast iron pipe, about five feet long, called the **blow pipe.** sometimes the "belly" pipe. Through it the hot blast is delivered to the tuyere from the **tuyere stock**, to which the names **leg pipe, boot leg** and **pen stock** are also often applied. The blow pipe may be slightly larger in diameter at one end than at the other, and both ends are turned to fit into slight sockets in the tuyere and the tuyere stock. It is held in place with the smaller end fitting into the tuyere by pressure from the **tuyere stock,** which is provided with a spiral spring and connecting rod, attached to the hearth jacket, for this purpose. The tuyere stock curves upward immediately on leaving the blow pipe, and a hole in a lug on its under part gives an opening through which the connecting rod passes through the coiled spring to the hearth jacket where it is anchored. The heavy spiral spring, which provides pressure and at the same time allows motion due to expansion and contraction of the tuyere stock and blow pipe with changes in blast temperatures, is placed between this lug and a large brass nut on the other end of the connecting rod. The nut is made of brass so it will not rust and be difficult to operate. In the outer part of the curve in the tuyere stock, and in the center line of the blow pipe and tuyere is a small opening, closed by the **tuyere cap** or "wicket," through which a small rod may be inserted to clean out the tuyere without removing the blow pipe. The wicket must be of such a form that it may be opened readily at any time and still be practically gas tight. To meet these conditions the wicket is constructed on the principle of the ball and socket joint. The ball is attached to the end of the short arm of a right angle lever and is held tightly in the socket by a ball weight attached to the long arm. A smaller opening, called the peep hole, in the tuyere cap is covered with glass, which permits inspection of that portion of the interior of the furnace directly in front of the tuyeres. Extending upward, the tuyere stock connects with the nozzle of the **goose neck**, to which it is clamped by means of lugs and keys that fit into seats of hanging bars. The goose neck then turns at right angles and extends horizontally to the **neck** of the **bustle pipe** to which it is fitted and securely fastened by flanges and bolts; or the tuyere stock may lead at an angle to the horizontal directly to the lower part of the bustle pipe. The **bustle pipe** is the large pipe, about four feet in outside diameter, which encircles the furnace and distributes the hot blast to the tuyeres. All these pipes, down to the blow pipe, are lined with fire brick. The bustle pipe is fed by the **hot blast main** which terminates at the stoves. It is of about the same size as the bustle pipe and lined with nine to twelve inches of fire brick.

**Boshes:** As previously described the bosh is that part of the furnace, just over the hearth, where the greatest diameter is attained. No shell cr jacket covers the exterior of the bosh. A standard bosh is constructed in the following manner: Starting at the top of the hearth, the brick work, 30 inches in thickness, is stepped outward, externally, nearly six inches for each twelve inches of vertical rise. Each step-out is supported by means of a heavy steel band, or a pair of bands, called **bosh bands.**

Inserted in the walls of the boshes, through cast iron "boxes," placed in the brick spaces between pairs of bosh bands, will be found cooling plates, called the **bosh plates,** in horizontal rows about two feet apart, measuring vertically. The plates in each row will be about four or five inches apart, and the plates in the different rows will be staggered vertically, breaking joints like brick work. This construction adds to the cooling efficiency of the plates. There are several different makes of bosh plates, but the more common ones will be somewhat wedge-shaped, with a flat bottom and oval top, and about four inches thick at the point of their greatest altitude. They are hollow and have inserted in them, usually at opposite corners, two pipes through which water flows continuously. These plates are necessary to help protect the brick work, for, being just above the tuyeres in the zone of fusion, the bricks here receive the highest heat of the furnace. Formerly the plates extended almost through the wall in new work, usually to within one course of brick, but it was found that this course of brick is soon cut away after the furnace is blown in, so now the plates extend entirely through the wall from the first.

**Mantle:** At the upper limits of the bosh is found the **mantle,** conforming to the shape of the furnace at that point and totally encircling it. The mantle is made up of heavy steel plates and angles, upon which rests the weight of the stack. It is supported by a series of cast iron pillars or fabricated steel structures, which rest on foundations supported by the main furnace foundation. This construction allows the entire bosh and hearth to be removed without disturbing the rest of the furnace.

**Shaft, or Stack, and In-Walls:** The shaft comprises all that part of the furnace which is located above the boshes. The wall of this shaft is usually, in an imaginary way, divided into three almost equal parts, called the upper, middle and lower inwalls. Up to this point, the construction for all furnaces is fairly uniform as to general features. But as to the inwalls three types are employed, namely, the thick, the intermediate, and the thin wall. The construction necessarily differs for these different types. Therefore, each type is best described separately.

**Thick Wall Type:** The inwalls of this type are about five feet thick, and are inclosed in a heavy riveted steel shell about one-half inch thick. The shell is usually made oversize to provide a small space between it and the brick work, in which space is tamped lightly a packing of loam and granulated slag, to allow for the expansion and contraction of the inwalls. Thick walled furnaces are seldom water cooled above the bosh, and their walls furnish the sole support for the top.

**The Furnace Lines and Bosh Angles** of furnaces of the thick wall type differ somewhat. In modern blast furnace construction the lines of the furnace, by which is meant the lines formed by the inner edges of a vertical section through the center, with their enclosed angles, are considered of great importance. In the old furnaces, the lines of the inwalls were straight, and the boshes somewhat flat with corresponding sharp angles. But with the fine ores from the Lake Superior district, experience has taught that much better practice is obtained with more nearly vertical lines. So, in the latest type of furnace the lower inwall will rise vertically for several feet, the boshes will be steep, and the upper inwall will drop vertically for a distance of about ten feet from the stock line. Bosh angles, that is, the angles at the top of the bosh, which its wall forms with a horizontal from the center of the furnace, are now being increased from about 75° to 80°. These steeper boshes are proving to be an important improvement.

**Intermediate, or Semi-Thin, Wall Type:** In the intermediate type, the walls are about three feet thick, and to protect the brick as much as possible, cooling plates, similar to bosh plates, are inserted in the lower inwall. They may extend for a distance of from twenty to forty feet above the bosh. The top in this type is sometimes supported by columns of fabricated steel, but in the majority of cases it is supported by the walls as in the thick walled type. The inwalls are surrounded by a steel jacket as in the thicker type, the only difference being in the necessary openings for the coolers.

**Thin Walled Type:** In this type the inwalls are from nine to eighteen inches thick, the top is always supported by structural work, and the shell must be cooled throughout its entire length. This cooling may be done in three ways. One method consists in spraying the jacket with water, conducted through suitably arranged pipes and enclosed by a light "splash jacket" which conforms to the size and shape of the stack. In the second method the shell is encircled by a series of deep and narrow horizontal troughs through which water is kept flowing from the top to the bottom of the furnace, overflowing from each trough to the next succeeding lower one. Each of three or four of these troughs drain separately to a common point where the temperature of the water can be noted. In the third type, the entire outer surface of the stack is kept covered with water by means of a spiral trough which, slightly separated from it, encircles the stack from top to bottom. This trough is kept full of water by a series of feed lines that enter it at various points in the spiral.

**Furnace Linings:** The brick-work which forms the hearth, bosh and inwalls of a furnace are referred to as its linings. All the brick used in the construction of these parts are made of fire clay, and are of three kinds, known as **hearth and bosh brick, inwall brick** and **top brick,** each of which is made of such materials and in such a way as to render it best adapted to the conditions it is to be subjected to in service. The hearth and bosh brick are required to resist a very high temperature and the action of flux and slag; inwall brick must be able to withstand abrasion at a moderately high temperature; and top brick, always at a comparatively low temperature, must resist the impact and abrasive forces of the charges as they are dropped into the furnace. These different qualities in the different bricks are obtained by varying the method of manufacture especially with respect to composition, degree of grinding and temperature of burning. As to the former factor, three classes of materials, or clays, are available. These are flint clay, plastic clay and calcined clays. Mixtures employed by different manufacturers are by no means uniform, but the following may be taken as fairly representative of good practice.

**Table 26. Showing Data Relative to Fire Brick for Use in Blast Furnaces.**

| Kind of Brick | PROPORTION OF Flint Clay | Calcined Clay | Plastic Clay | Manner of Grinding | Final Temperature of Burning |
|---|---|---|---|---|---|
| Hearth and Bosh Brick | 50 to 65% | 20 to 35% | 14 to 16% | Coarse | 1350°C |
| Inwall Brick | 40% | 30 to 40% | 20 to 30% | Medium | to |
| Top Brick. . | 0 to 30% | 30 to 50% | 40 to 50% | Fine | 1450°C |

All the materials, irrespective of the kind of brick, should be and are of the best quality obtainable, and the brick are carefully inspected before being put in place in the furnace. The three kinds of brick are distinctly marked by the manufacturer, so that the danger of wrongly placing a brick, a top brick in the hearth, for example, may be avoided. Great care is exercised with respect to brick, because the life of the furnace depends in a large measure upon the lining, and the item of cost for brick is not a small one. In the construction of one of the large modern furnaces, close to the equivalent of 800,000 nine inch brick are required, and the average consumption of brick is a little more than two brick for each and every ton of pig iron produced. Fire bricks are always laid in a thin slurry composed of fire clay and water. The slurry is applied by pouring it on the top of each course with a dipper, and is followed immediately by the next course of bricks, which are hammered into place to squeeze out all the fire clay except that required to compensate the inequalities of the brick.

**Water Trough:** Encircling the furnace bosh, inside of and above the bustle pipe, will be found one or more water troughs into which the water supplying the numerous cooling plates is discharged in visible streams, thus providing means of determining when a plate is burned out. The water, flowing from these troughs into a well, may be pumped back through the cooling system, and thus be used over and over.

**Tops:** At the present time furnace tops are somewhat complicated affairs. In olden times the tops of furnaces were left open, the escaping gases being allowed to burn in the air. In the year 1814, these waste gases began to be employed in France for the purpose of burning bricks and heating small furnaces. The first attempt to heat the blast by utilizing these gases was made in 1834, and consisted in laying, across the tunnel head, pipes through which the air blast passed in going to the tuyeres. It was not till 1845 that a plan was evolved by which the gases could be used to heat the stoves. To effect this purpose, changes in top construction were necessary. At first the gases were merely drawn off by the chimney draft of the stoves through openings below the stock line. The arrangement, known as the **bell-and-hopper,** or **cup-and-cone,** was not put into use till 1850. It consisted in closing the top of the furnace by means of a large circular hopper, the smaller opening of which was closed by the **bell** that could be lowered and raised at will. With the bell raised against the hopper, the materials were dumped into the hopper; then the bell was lowered, and the charge dropped into the furnace. As large quantities of gas escaped with each lowering of the bell, this device was improved by the **double-bell-and-hopper,** which is of comparatively recent origin. Essentially, this improvement consisted in placing a second but smaller bell-and-hopper above the first, and providing a gas tight space of large size between the two. The raw material, upon being hoisted to the top, is first dropped or dumped into the upper hopper, whence it may fall into the larger hopper below when the small bell is lowered. The small bell being raised against the upper hopper, the large bell is lowered, and the charge falls into the furnace without the escape of gas. The bells are made of cast steel, in one piece, and of such a slope, 45° to 55°, as to permit the charge to slide off readily. They are usually supported from their top centers by means of a rod and a sleeve, each attached to a counterbalanced lever operated by means of a steam or air cylinder or an electric motor, controlled from the ground. The large bell is attached to the rod and the small bell to the sleeve. The hoppers, of cast steel or iron, will generally be made up in sections, which are securely bolted together. They are provided with a removable, but gas-tight, flange and extension ring, also in sections, which permit the bell to be readily removed in case a change is necessary. The details of this construction differ somewhat to conform to the introduction of improvements, with the type of hoist, and with the ideas of the different builders.

**Stock Distributor:** One of the alleged improvements in the bell-and-hopper device is that of the stock distributor. There are several types of these distributors employed, a description of which would not be profitable here. However, the object aimed at by such devices may be explained thus:—It is apparent that, in a mechanically filled furnace, when the raw materials are dropped into the receiving bell, the larger lumps of ore and stone will have a tendency to roll and thus collect either around the edges or to one side or the other. The same things will also happen upon dropping the charge into the furnace. This tendency results in more or less open and continuous channels being formed through the materials and extending from the top towards the bottom of the stack. These channels offer less resistance to the passage of the blast than the remainder of the materials, or the fuels, with the result that a disproportinate quantity of gas passes through them. This condition, called channelling, results in higher temperatures throughout these passages, with the consequent cutting away of the walls where these channels come in contact with them. It is to overcome this defect that the various devices formerly mentioned have been designed.

**Hoisting Appliances:** The old time method of charging by hand having been entirely superseded by automatic mechanical charging, there are now in use two types of these devices, namely, the skip hoist and the bucket hoist. In both cases there is an incline, a fabricated steel structure, extending from the top of the furnace to or below the bottom of the stock house; and over the tracks of this incline the materials charged into the furnace must pass. In the skip hoist, the conveying vessel is a small open-ended steel car, called a skip, that automatically dumps the materials upon the little bell-and-hopper. Skip hoists are generally provided with double tracks, so that while a loaded skip is passing up the incline an empty one is descending. In the bucket hoist the solid materials are raised in a bucket, suspended from a truck or carriage, that drops the charge into the space above the large bell direct. When in position for dropping the charge, the bucket, being itself provided with a small bell at the bottom, takes the place of the little bell and hopper. During the time the bucket is filling at the stock house, the opening left in the top is closed with a special gas seal.

**Top Openings:** The smallest opening in the top of a furnace is the **try-hole.** In operating a furnace it is necessary to be able to determine the position of the stock line. This is done by means of the **stock indicator,** which is a rod of steel passing through and fitting the try-hole loosely so that one end rests upon the stock, while the other is attached to a small steel cable that leads to the stock house or the cast house below. Some stock indicators are automatic and self-recording. For the escape of the gases, from two to four large openings, called **offtakes,** are provided. They pierce the furnace top just beneath the large bell. From these openings, about four feet in diameter, lead fire-brick lined pipes which converge into one large pipe called the **downcomer** or **downtake.** Into openings, either in the offtake pipes or in special openings in the top, are inserted the **explosion doors.** These doors, located usually in the ends of upright pipes arranged so as to prevent ejection of material from the furnace, are really valves which are adjusted, either by weights or by a mechanical means, to open at a certain pressure. They are designed to relieve pressure and so prevent possible injury to the top by slips in the furnace. **The bleeder** is a tall vertical pipe, usually inserted on the higher surface of the offtake pipe leading to the downcomer, to allow surplus gas to escape. It is closed with a valve on the top, which opens automatically, and may also be opened from the ground. Bleeders are usually lined with one course of fire brick.

**General Consideration for Top Construction:** As previously pointed out, there are many types of top, and the description above is intended to give a general idea of the essential parts and their uses only. The chief endeavor in top construction is to perfect the distribution of the stock entering the furnace stack, and either eliminate or compensate for as many irregularities as possible. However, in attaining this end, simplicity must be considered, as any great amount of mechanism on the top of a furnace is objectionable. It is important to prevent large material from being thrown out of the furnace in case of slips, and as little dust as possible should be carried out by the gases. Hence, in the most recent construction, the offtakes enter vertical **up takes,** closed at the top by explosion doors, and are taken off the furnace as high above the stock line as possible, preferably at four points equally spaced on the circumference. The downcomer connections are taken off part way up on these up-takes. In locating the uptakes in furnaces of most recent construction, care is taken to see that they do not enter the furnace directly over the tapping hole, cinder notch, or the entrance of the blast main to the bustle pipe, because, these being the most active points in the furnace, this arrangement will tend to give a more even distribution of the gases through the stock.

**Runners:** Though not given much prominence in blast furnace discussions, the runners, through which the slag and metal are carried away from the furnace, constitute an essential part of the furnace proper. These are metal castings in the form of deep troughs which are made in sections laid end to end and buried so that their top edges are flush with the floor of the cast house. The trough leading from the cinder notch will, of course, be elevated. It forms an uninterrupted passage for the slag from the cinder notch to the slag ladle or granulating pit. The metal runner is more complicated. Beginning as a very deep trough at the tapping hole, it is interrupted at the end of about 10 feet by the skimmer, a device for separating the metal from the slag that comes near the end of a cast. There are two branches here, one for carrying away the slag and another for draining the metal from this part of the skimmer trough after the cast. From the skimmer the main trough is drained by branches leading to casting beds on the floor of the cast house, or what is more common now, to hot metal ladles on a track far enough below the floor of the cast house to permit the metal to flow into them from above. Before casting, these troughs are given a heavy coating of a loam or clay wash, which acts as an insulator, protects the trough from the hot metal and facilitates the subsequent cleaning up. Without this wash the hot metal would either chill in the trough or melt it away.

## SECTION V.

### BLAST FURNACE ACCESSORIES.

**The Stoves,** of which there are nearly always four to a furnace, are first in importance under the heading of accessories, being an absolute necessity in modern blast furnace operations. This importance is due to their function of heating the blast. The first stoves used were constructed of iron pipes enclosed in a brick structure through which the blast passed to the furnace, the gases from the furnace being burned as they circulated outside and around these pipes, the recuperative principle. Then it was found that the regenerative principle is much more efficient, so that now stoves are built entirely of brick. Essentially they are brick walled cylinders, enclosing a combustion chamber and a system of regenerative flues. Externally, the brick wall of a stove is reinforced and supported by a steel shell of riveted plates. The top of the stove is dome-shaped. Generally, the stoves are as high and almost as wide as the furnace itself. They vary in size with the size of the furnace. For the largest furnaces they are approximately 100 feet in height and 22 feet in diameter. Internally, the combustion chamber will extend from the bottom to the top of the stove, and may be located at the center, in which case they are called **center combustion stoves,** or at the circumference, as in **side combustion stoves.** The regenerative flues are filled with brick checker work, the checkers being so laid as to form a system of vertical flues, from five to nine inches square, which extend from the rider walls on the bottom to the top of the stove. The arrangement of the flues also furnishes a means of classifying stoves. Stoves in which the gases from the combustion chamber pass through only one regenerative flue, are called **two=pass** stoves, while in **three=pass** and **four=pass=stoves** they pass through two and three regenerative flues, respectively. Two-pass and three-pass types are the most common. Since the combustible gases are burned at the bottom always of all stoves, it follows that in two-pass stoves the products of combustion, passing through the checkers, must leave the stove at the bottom, hence the opening to the stack on two-pass stoves is at the bottom. At some plants, stoves of this type are provided with individual stacks which rise along the side of the stove, but in other plants underground flues from a number, usually a set of four, of such stoves empty into a single stack, centrally located. In the three-pass type the hot gases are returned to the top of the stove, there to escape through an opening in the dome into a stack which tops the stove.

**Stove Burners and Valves:** Since the checkers in stoves are alternately heated by the products of combustion of a gaseous fuel in their passage to the open and cooled by the passage of the air or blast in an opposite direction and under pressure, a system of burners and gas tight valves are required. The burners are usually very simple in construction, consisting of a movable gooseneck mounted on a rack attached to the terminal of a vertical section of an underground gas flue in such a manner that the horizontal portion extends into a gas port in the side of the stove. A plate, or valve cover, is attached to the base of the goose-neck or the rack, so that racking the goose-neck back and forward automatically closes and opens the connection to the gas main. There are a number of more complicated and patented burners in use, which aim to increase the efficiency of the stove[1]. The valves present such a variety of forms that a detailed description of all cannot be attempted. The essential ones are named from their location. The **gas valve** has already been described in connection with the burner. The **chimney valve** is located at the base of the stack, its office being to prevent the escape of air through that opening when the stove is on blast. In three-pass stoves this valve is controlled from the ground by means of chain, or cable, and pulleys. The **cold blast valve** is located in the air line, which branches from the cold main from the blowing engines at a point just ahead of its entrance into the stove. As it is never subject to high temperatures, an ordinary form of gate valve may be used. In the three-pass type of stove this valve will also be at the top. The **hot blast valve** controls the exit of the blast from the stove through which the air passes. The blast being highly heated at this point, the hot blast valve must be constructed to withstand high temperature. It is usually of the mush-room type, and water cooled.

**Other Stove Openings:** Besides the openings mentioned above, the stove will be provided with a **blow off valve** to relieve the pressure and provide partial escape of air on changing the stove from air to gas. This valve may also regulate the admission of air for combustion. Numerous **clean out holes**, through which the flue dust that collects in the stove while it is being heated may be removed, will be placed at points most desirable for the purpose.

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[1] See Modern Methods of Burning Blast Furnace Gas by A. N. Diehl. Year Book of the American Iron and Steel Institute, 1915.

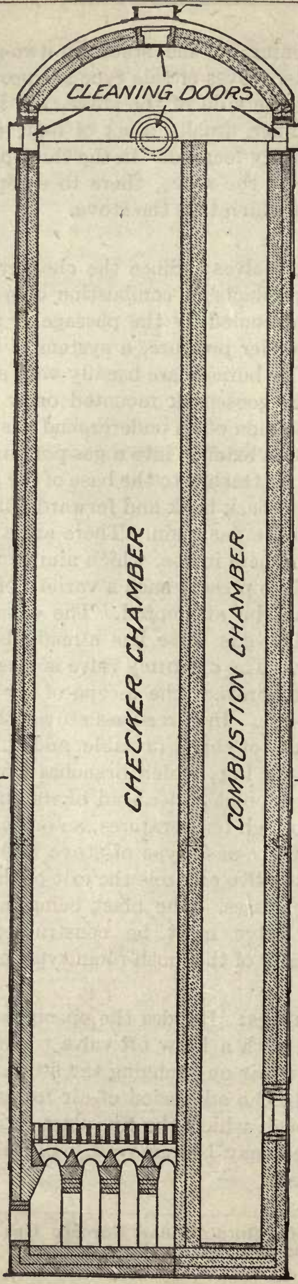

Fig. 21. Vertical Section of Standard Blast Furnace Stove. Two-pass side Combustion Type.

**Stove Linings:** Stove linings is a term that corresponds to furnace lining, and includes all the brick work enclosed by the shell. As in the case of the furnace, an expansion space of about two inches is left between the circular brick wall and the shell. For these linings a strong yet porous firebrick is required, because such brick absorb the most heat and also give it up most readily. The brick need not be very refractory, for the temperature in the stove is relatively low except in the combustion chamber, where a brick possessing fairly high refractory properties is required. The temperature of the hot blast is maintained at about 538° C. (1000° F.) which marks the lowest temperature to which the hottest part of the stove

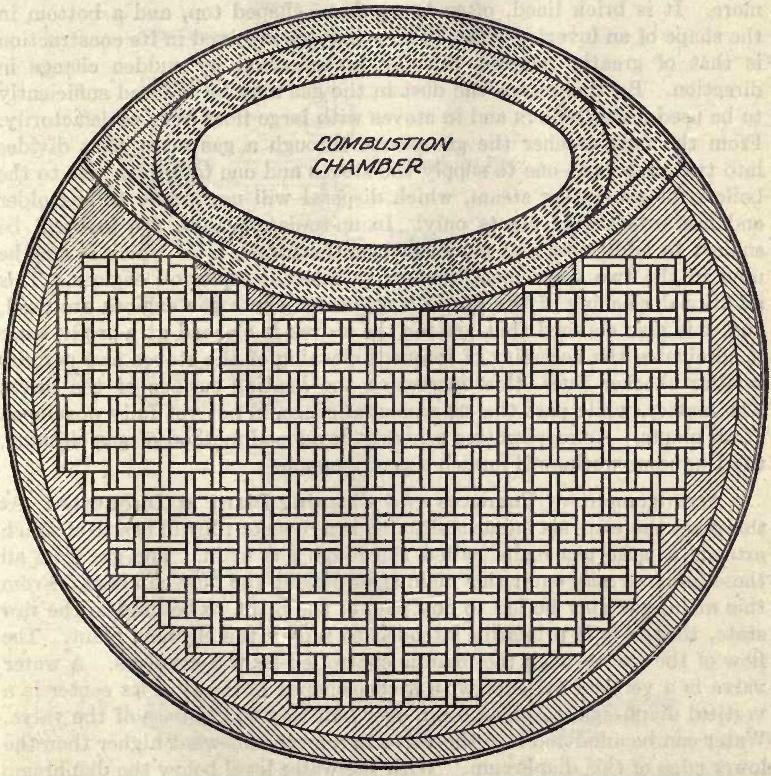

Fig. 21a. Cross Section of Blast Furnace Stove Section C C of Fig. 21.

can drop. With modern stoves, from 25 to 30% of the gas produced by the blast furnace is required to maintain the blast at the correct temperature. Of the remainder about one fifth, (12 to 20% of the whole) is used by the blowing engines, so that a little more than half of the total gas produced by the furnace is available as surplus for the generation of electrical power.

**Dust Catcher and Gas Mains:** From the down-comer the gas from the furnace passes directly into the dust catcher. Its object, as implied by its name, is to clean the gas as much as possible of the flue dust blown over from the furnace, with which dust the gas is heavily laden. If this dust is not removed, in part at least, it cakes upon the walls of the combustion chamber and small flues of the stoves and, dropping down, necessitates frequent cleaning. Besides, it acts as an insulator on the brick, preventing the full absorption of heat. Similar conditions also prevail when the dirty gas is burned under boilers. The dust catcher may be looked upon as a great enlargement of the flue, or down-comer. Its diameter is often 20 feet or more. It is brick lined, often has a dome shaped top, and a bottom in the shape of an inverted cone. The principles involved in its construction is that of greatly reduced velocity accompanied by sudden change in direction. By this means the dust in the gas may be reduced sufficiently to be used under boilers and in stoves with large flues very satisfactorily. From the dust catcher the gas passes through a gas main that divides into two branches—one to supply the stoves and one to furnish gas to the boilers for generating steam, which disposal will now apply to the older and less progressive plants only. In up-to-date plants, the gas will be subject to additional and more efficient treatment, after which it may be used in the two ways mentioned or in internal explosion engines. This additional cleaning of the gas is a necessity where gas engines are used, and it is also claimed that gas for the stoves is cleaned at a profit, since it eliminates the necessity of frequent cleaning of the stoves and permits smaller checker flues, thus increasing the heating surface of the brick. The matter, while past the experimental stage, is not yet fully developed at all plants. As representing a highly developed method of gas cleaning, the Duquesne works will furnish a good example.

**Arrangement of Furnaces and Cleaning Plant at Duquesne:** At this plant there are six furnaces situated in a row, for the full length of which extends a large gas main, called the rough gas main. The gas from all these furnaces may enter this main after passing the dust catchers. From this main, gas may be led to any part of the plant to be used in the raw state, though it is primarily intended to supply the cleaning plant. The flow of the gas through the main is controlled by water valves. A water valve is a vertical cylinder with a cone-shaped bottom; in its center is a vertical diaphragm reaching down over half way to the base of the valve. Water can be admitted into the valve to a level somewhat higher than the lower edge of this diaphragm. With the water level below the diaphragm an outlet is provided so that a current of gas may be allowed to flow through;

when water rises high enough above the base of the diaphragm to resist the pressure of the gas and prevent its passage under the diaphragm, the valve is sealed. By means of these, any furnace can be shut off from the system. The gas cleaning plant consists of two divisions called the Primary and Secondary. The primary division receives and washes all the gas that is brought from the furnace by the rough gas mains and returns the washed gas to the stoves or boiler houses when desired. The secondary division

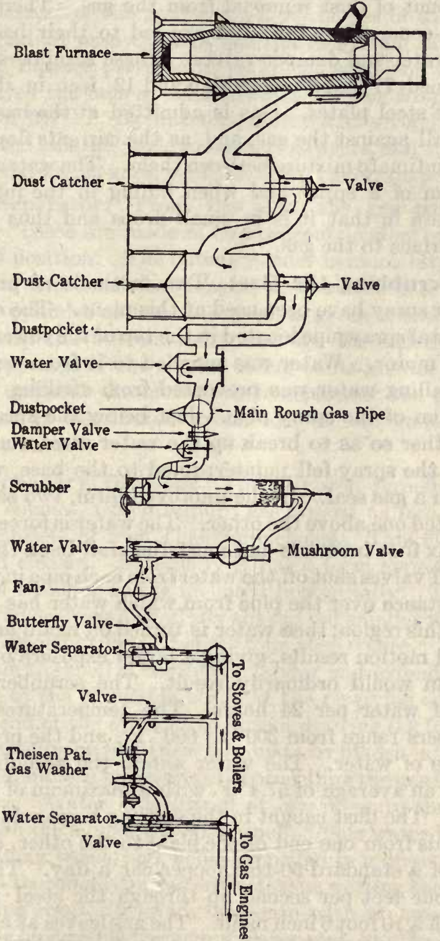

FIG. 22. Diagram showing Route of Gas from Furnace through Gas Cleaning Plant to Boilers, Stoves and Gas Engines. Carnegie Steel Company, Duquesne Steel Works.

receives only such gas as is intended for use in the gas engines.

**Primary Division:** The primary cleaning of the gas is accomplished by vertical water scrubbers and fans. It reduces the dust content of the gas to .06 grain per cubic foot of gas under standard conditions. The vertical water scrubbers are the most important part of the equipment in respect to the amount of dust removed from the gas. There are nine of them, and the gas connections for them are led to their bases from the gas main through water-and damper-valves. These scrubbers are vertical steel cylinders, unlined, 77 feet 6 inches high and 12 feet in diameter, and are built of 5/16 inch steel plates. Gas is admitted at the base. Water is admitted so as to fall against the gas, and, as the currents flow in opposite directions, there is intimate mixture between them. The water is applied to the gas in the form of a spray and when falling in the interior of the scrubbers is like rain in that it is in small drops and thus presents the greatest possible surface to the gas.

**Methods of Scrubbing the Gas:** Two methods of producing and supplying the water spray have been used at this plant. The older method employed a horizontal spray pipe located in the top of the tower and rotated by a small electric motor. Water was supplied to it from a pipe inserted at the top. The falling water was prevented from striking the shell by a vane in the bottom of the spray pipe. Just below the spray pipe were 12 screens set together so as to break up the water stream as it fell, but from that location the spray fell uninterrupted to the base, where it was drained out through a gas seal. In the improved form, two series of seven pipes each are inserted one above the other. The water is forced up through screens placed at six foot intervals and must then fall back through them. Motor-driven cut-off valves shut off the water from each pipe in turn, making an area of low resistance over the pipe from which water has been cut off. The gas rushes to this region; then water is turned on again and the gas is deflected. A spiral motion results, giving a larger exposure of gas area to cleaning water than would ordinarily result. The scrubbers use about 6,000,000 gallons of water per 24 hours. The temperatures of the gas entering the scrubbers range from 300° to 600° F., and the pressure varies from 8 to 16 inches of water. The water enters the scrubbers at river temperature and at an average of 57.4° F. with a maximum of 84° F. and a minimum of 33° F. The dust caught in the settling basin, which is built in duplicate and extends from one end of the plant to the other, averages half to three-quarters of a standard 50-ton hopper car a day. The gas passes at a velocity of four feet per second up through the steel shell into a pipe connecting with a 10 foot 6 inch main. The gas leaves at a temperature varying from 96° F. to 37° F., or at an average of 68°F. The dust in the gas is reduced from 3.5 grains per cubic foot to .22 grain at standard conditions; the moisture in the gas entering the scrubbers is 34 grains per cubic foot and on leaving is 8.5 grains. About 25 cubic feet of gas is cleaned per gallon of water used.

**The Fans:** From the scrubbers, a large gas main, 10 feet 6 inches in diameter and about 40 feet above the ground, conveys the gas to a number of fans that complete the primary cleaning of the gas. The connections to these fans are provided with water valves. The fans are located in a gas cleaning building, or fan house, and are four in number. Each fan has a rated capacity of 84,000 cubic feet of gas per minute at 100°F. The fans raise the pressure of the gas to about six inches of water and thus give it sufficient head to pass through the entire system of stoves, boilers and engines; the furnace pressure alone is not sufficient to supply this head. The gas leaves the fans at temperatures varying from 93° F. to 35°F., or an average of 69° F. By introducing water at several points into the shell of each fan, the fans are made to serve as cleaners, and the dust content of the gas is reduced from .22 grain per cubic feet to .06 grain per cubic feet.

**Water Separator:** From the fans, the gas passes through water separators. These are made of two concentric steel cylinders which stand in a vertical position. The outer cylinder is much larger in diameter than the inner one and somewhat longer, so that the gas, entering at the top of the outer cylinder and on a tangent, is given a downward spiral motion and escapes at the bottom rising through the inner pipe. In this way, the greater portion of the water, owing to its greater inertia, is deposited by the gas current. From the water separator the gas enters the clean gas main and is distributed to the stoves and boilers and also to the secondary division.

**The Secondary Division:** This division furnishes gas for internal combustion engines, which require gas almost as free from dust as the air itself. It consists of four Theisens cleaners. This cleaner is a combination fan and cleaner. Externally it has a form approximately like that of a large steel cylinder and is mounted horizontally. This outer cylinder is stationary and encloses a similarly shaped but smaller revolving cylinder on the shell of which is riveted twenty-four steel vanes. These vanes project 12 inches from the shell of the inner cylinder and extend longitudinally in a slight spiral to the circumference. At the receiving end the vanes project beyond the end of the cylinder to form a drawing fan for receiving the gas, while at the delivery end they terminate in blades, attached to the same cylinder, that act as a booster fan for propelling the gas through the succeeding apparatus. Water is admitted at low pressure through six pipes half way up and on the side of the outer shell. This water is dashed to a spray by the revolving vanes, and, being propelled in a direction opposite to that of the gas, is thoroughly mixed with it, thus wetting the last small particles of dust, which must, therefore, separate with the water. This water is let out of the apparatus through a water seal at the bottom. The gas flows through the shell and out into a water separator, thence to the gas main leading to the gas engines. The Theisens cleaners have a rated capacity of 14,000 cubic feet of gas per minute at standard conditions. The gas leaves the Theisens at an average temperature of 64.2° F., or a maximum of 91° F. and a minimum of 35° F. The water enters at an average of 57.5° F. The dust in a cubic foot of gas is reduced from .06 grain to .009 grain. 45.44 cubic feet of gas is cleaned per gallon of water consumed.

## SECTION VI.

### EQUIPMENT FOR HANDLING RAW AND FINISHED MATERIALS.

**The Boiler House, Power Plant, Pumping Station, Blowing Engines, etc.** while constituting a very vital part of the blast furnace equipment present features of more interest to engineers than to metallurgists and are therefore, best omitted from this discussion.[1]

**Dry Blast:** About 60% by weight of all the materials entering the blast furnace is air. As air always contains moisture and since the decomposition of water is an endothermic reaction, the heat absorbed by the amount of water thus entering the furnace may be very great. It has been estimated that during the month of July, for instance, the average quantity of water, per hour, entering a furnace using 40,000 cubic feet of air per minute is approximately 224 gallons. That this quantity of water may seriously affect the operation of the furnace is now well recognized, and installations for drying the air have been made at a few plants. Without discussing in detail the apparatus used, the principle employed is that of refrigeration. By cooling the air to a low temperature by drawing it over a system of pipes cooled with brine, (a solution of common salt, $NaCl_2$, or calcium chloride, $CaCl_2$, which has a less corrosive action on the pipes), which in turn is cooled with liquified ammonia, the moisture is condensed and frozen on the pipes, leaving the air practically dry.

**Cold and Hot Blast Mains:** It is still the most common practice to use undried air, which, compressed by the blowing engines, is forced normally under the high pressure of about 15 pounds per square inch through the cold blast main into the stoves, from which it issues highly heated; and passing successively through the hot blast main, the bustle pipe and the tuyeres, begins its work in the furnace. In this connection one or two apparently minor details of construction referring to temperature regulation and pressure control should be noted. Leading around the stoves from the cold blast main into the hot blast main is a small pipe called the **by-pass.** It provides a means of controlling the temperature of the hot blast. The **Snort Valve,** also located in the cold blast main, is used to reduce the pressure of the blast at the end of a cast while the tap-hole is being stopped, or to release the pressure in case of a hanging furnace.

**Appliances for Handling Ores, Coke and Stone:** As was pointed out in Chapter III, all ore is shipped over the Lakes from May until December. Consequently the ore required to operate the furnaces during the months intervening between shipping seasons must be stored until used, either at the docks or at the works. This storing of ore requires a stock

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[1] For details on construction of the blast furnace and equipment, see Blast-Furnace Construction in America by J. E. Johnson, Jr., published by McGraw-Hill Book Company, New York.

yard with suitable provision for an ore pile, rapid means of unloading cars, and convenient and economical methods and appliances for handling large quantities of ores. For unloading the cars, **car dumpers** have been installed, while for piling and delivering the ore to the bins over the stock house, **ore bridges** are employed. The ore, arriving at the works in train load lots, is switched to a siding ahead of the car dumper, and the cars are unloaded one by one in rapid succession. A car, being pulled up an incline to the platform of the dumper, is bodily lifted and turned over so as to empty its contents into large larry cars, or into bins, if small larry cars are used. The dumper then resumes its former position, and the car is pushed off the platform by the next car of ore to an incline, down which the empty car moves to a car siding. Larry cars, designed for the purpose, carry the ore to the ore pile, where the ore bridge picks up the ore and dumps it in its proper place in the pile. The details of this operation will vary much, but the general scheme is essentially as stated. Aside from the mere storing of the ore other aims, while more or less incidental, must be kept in mind. In order to obtain uniform conditions necessary to keep the furnace operation under good control, it is desirable to mix the ore of each kind or grade as much as possible; again, the uniformity of the ore may be affected by dumping on large, sharply peaked piles, because dumping in this manner causes a separation of the coarse and the fine material, which always differ widely in chemical composition. For similar reasons, the use of ore direct from hopper cars unloaded from the trestle into the bins is undesirable. The ore is the only material stored, both the limestone and the coke being brought in as required. All up-to-date plants are provided with an ore trestle running out over the bins above the stock house. The bins are used for storing smaller amounts of ore, fuel and flux, which are then conveniently available for immediate use. The bins are large hoppers, the bottom openings of which are closed in such a way as to permit the withdrawal of fixed quantities of materials as desired. The bins for the three materials are alike except that those used for coke are provided with screens for removal of the "fines." In the most modern plants the open tops of the bins are covered with a heavy grid-iron grating, which serves the two-fold purpose of preventing accidents, resulting from workmen falling into the bins, and the stoppage of the chutes below, due to oversize pieces of material that might otherwise be dropped in.

**Stock House Equipment:** Under the trestle and bins is a large space known as the stock house. Here are found the mechanical devices which have superseded the old and original method of charging by hand. The equipment will be different for each type of hoist. If the skip hoist is in use the arrangement in general will be as follows:—The skip tracks will extend down beneath the floor of the house far enough to permit the lowering of the skip beneath chutes, which lead from the floor so as to deliver the materials into the mouth of the skip. These materials will be delivered to the chute by means of a small trolley car, running on tracks that extend under the bottom openings of the bins. This car—a small hopper car—is provided with a scale to weigh the ore and stone as it falls into the hopper of the car. In this way any mixture of ores or stone desired may be accurately made up by weight for charging. In the bucket hoist the bucket itself is placed, on descending, upon the weighing car, which is transported by trolley or dinkey from bin to bin for the different ores required in making up the charge. Only the ore and stone are weighed, the coke being charged by volume.

**Disposal Equipment for the Iron:** The old method of casting the metal in beds of sand has, for many reasons, been replaced by casting machines. Of the two types of these machines, the endless chain carrying a series of parallel moulds or troughs with over-lapping edges is the one most commonly used. In the operation of this machine, the molten metal from the furnace is allowed to flow into ladles, which are pulled at once into the casting house. Here, the metal is poured slowly into a trough from which it flows onto two lines of moving moulds, which have been previously prepared, to prevent sticking of the iron, by being either "limed" or "smoked." The chains may carry the iron directly through a trough of water, or dump the half cooled pigs upon a second conveyor to be so cooled. A number of modifications of this machine are in use.

**Equipment for Slag Disposal:** The greater portion of the slag produced cannot be used except as waste, so most of it will be transported while molten to a convenient spot and dumped. When the slag is to be used for certain purposes, as for making Portland cement, it is best granulated. This condition is produced as the slag flows from the furnace by allowing it to fall into a large concrete lined pit, partly filled with water and known as the granulating pit. By forcing a small stream of water against and from behind the stream of molten slag as it drops into the pit, the stream of slag is broken up and the fineness of the slag is increased. Merely allowing the slag to fall into the water is a much less effective method.

## SECTION VII.

### OPERATING THE FURNACE.

**Blowing In:** Upon being completed and provided with as much of the equipment described above as is necessary or desired, the active career of the furnace is begun. In blast furnace parlance, the process of starting a furnace is called blowing in. It is carried out in three steps; these steps are drying, filling and lighting.

**Drying:** Newly constructed furnaces and stoves, or new linings, must be carefully and thoroughly dried before being put into operation. In the case of a furnace fully equipped and ready to operate, the drying may be accomplished by either wood fires built in the hearth or by gas. The heat is applied very gradually, and the drying is continued for about ten days.

**Filling:** After the furnace is sufficiently dried, it is allowed to cool slightly, and then the important process of filling is begun. While different individuals will pursue slightly different methods, the general scheme will be rather uniformly carried out. Briefly stated, it consists of first placing wood and coke on the bottom to a height somewhat above the tuyeres, about which fine kindling, shavings, oily waste or any material easily ignited is piled; then following the wood with a large quantity of coke, mixed with enough lime stone to flux its ash, and gradually introducing ore with the proper amount of flux. Good practice requires that this initial volume of coke should be about half the cubical contents of the furnace. Sometimes, to get an easily fusible slag and a good volume of it, blast furnace slag may be introduced ahead of the ore. These are called the blowing-in burdens, and additions are made till the furnace has been filled to the stock line, when it is ready for **lighting.**

**Lighting:** Starting the burning of the wood in the bottom of the furnace may be done in several ways. If the space in front of the tuyeres has been filled with light kindling wood, as is customary, oil is poured or sprayed in at the tuyeres until the wood is thoroughly soaked with it. Then with all the gas burners and valves in the gas mains and the bells closed, the bleeder and explosion doors are opened, a light blast is turned on and the wood ignited by inserting hot bars through the tuyeres. Often, instead of the hot bars, a wood fire is built in the stove nearest the furnace, and the oil is ignited by blowing sparks over with the blast. With a light blast on, the wood soon burns away, and the stock begins to settle, after which the blast pressure is gradually increased. Some furnacemen start off, after the fires are well caught, with a fairly high blast pressure for a few minutes, in order to drive the flames well in toward the center of the furnace and consume the wood quickly, as it is thought that a better initial settling of the stock is thus obtained. As soon as the stock gives signs of settling, the blast pressure is reduced to that normally used for the remainder of the blowing-in period, which is at first about ¼ that used when the furnace is in full blast. Up to this point a great deal of gas and smoke escape from the furnace openings, and great care must be exercised, for the gases contain a high percentage of carbon monoxide, and are very poisonous. Great care is also required to prevent explosions, because mixtures of furnace gas and air in a wide range of proportions are explosive. Since the interstices of the stock in the furnace and all the gas mains are filled with air to start with, an explosive mixture may be formed any time soon after the lighting, and if this mixture should be ignited it might cause serious damage. The difficulty is generally overcome by providing outlets for the gas at the ends of the gas mains. These outlets are kept open until all the air has been expelled, which condition is indicated by the color and odor of the escaping gas. Both men and fires are kept away from these openings until it is time to use the gas and the outlets are closed.

**Heating the Bottom:** Another feature connected with the lighting of the furnace is **heating up the bottom,** which is warmed by the drying-out fires to only a slight degree as compared with the temperature required to keep the slag and iron that form in a molten state. In order to have the bottom at the proper temperatrue when slag begins to form, two methods are employed, both of which involve leaving an opening at the tapping hole so as to draw the flame downward from the tuyeres upon the bottom. In the first method a round tapered wood plug, three or four inches in diameter at the smaller end, is placed in the tap-hole and the space about it is packed full and tight with clay. With the rise in temperature due to the burning of the wood and coke in the bottom, the clay sets, and this plug is then removed, which permits the flame from within to shoot forth, thus heating up the runner outside as well as the bottom inside of the furnace. When slag begins to flow from the tap-hole, the opening is closed until time for tapping the first iron has arrived. In the second method, an iron pipe, about four inches in diameter, is placed in the furnace, before it is filled, so that one end protrudes from the tap-hole outside of the hearth, while the other extends to the center of the furnace. The space about the pipe where it passes through the wall of the hearth is tamped with clay or ball stuff, which is also built up about the part of the pipe within the furnace for a foot or so from the hearth wall. When the furnace is lighted the gas flame is drawn to the center of the bottom to pour forth from the exterior end of the pipe. This pipe need not be moved until a fairly large flow of slag is attained, when it is drawn from the tap-hole, which is immediately closed, as in the case of the wooden plug.

**The heating of the stoves** is another factor connected with the lighting of the furnace. The temperature of the hot blast when the furnace is in full operation is 500 to 550° C. (930 to 1020° F.), and it is a great help if the stoves can be heated nearly to this point for the lighting of the furnace, especially as the furnace and filling are cold to the bottom. But this stove temperature can be obtained by the use of gas only, so that in the case of isolated furnaces where gas is not available before starting up the furnace, the stoves must be heated as hot as possible for the lighting by means of wood and coal fires.

**Tapping:** At the end of ten or fifteen hours after the blast is on full, there will be a sufficient accumulation of slag to tap. This is done by removing the bott from the monkey, and pricking through the solid slag closing the opening, if the cinder does not flow immediately. The bleeder is closed after the first cinder is tapped, as the gas can now be used in the stoves, and boilers or gas engines. It requires from 30 to 40 hours before much iron accumulates. When the iron is ready to tap, a hole is bored by means of a long auger or drill, electrically or otherwise operated, almost through the clay plug of the tapping hole. During the boring, the dust is blown out of the hole by a jet of compressed air. The splasher having been put in place, the opening is then completed by driving a long pointed bar into the furnace. When this bar is removed, the iron will usually flow out, at first slowly. As the flow of iron progresses, the opening is enlarged and the metal flows out rapidly. The iron will then flow out through the runners under the skimmer to the ladles provided to receive it. During the flow of the metal, samples of the iron for chemical analysis and fracture tests are taken by collecting small spoonfuls from the main runner. The slag, which follows the iron near the end of the cast, is stopped by the skimmer, where it may be run off through a more elevated runner to the slag ladle or granulating pit. When the iron has almost ceased to flow from the tapping hole, and gases are pouring forth, the blower signals the engineer to reduce the blast and opens the snort valve on the cold gas main to relieve the pressure. Then, the iron and slag having been drained from the skimmer, the **clay gun,** hung on a crane, is swung into the opening, either by hand or mechanically. This gun is provided with a steam cylinder which operates a rammer that forces a quantity of clay mixed with a little coke dust into the tap hole. The clay forms a plug that closes the opening. This plug of clay is then backed up with more of the mixture, which is fed into the gun, through an opening for the purpose, in the form of moist balls. As soon as the hole is stoppered, the snort valve is closed and the furnace goes on blast till next tapping time—four, five or six hours afterward.

**Care of Runners:** After the tapping hole has been closed, from one to three minutes being required, the troughs are emptied, and preparations for the next cast are begun. The runners are cleaned carefully of both metal and slag, and their inside surfaces are carefully brushed with a thick clay or loam slurry which, when dry, protects the trough, and prevents the iron from sticking to the runner.

**Sampling the Iron:** Sampling pig iron is a very important part of every tapping. As the iron is graded by chemical analysis, care should be taken to secure a sample for the chemical laboratory that will be representative of the whole cast. This sample, therefore, is generally made up of a number of equal portions taken from the main runner at the farther side of the skimmer and at periods corresponding to the middle of each ladle of metal in the cast. These samples may be in the form of shot made by pouring the molten metal slowly into water or upon a cold iron plate, or they may be small castings made by pouring the metal into a mould. In addition to these laboratory tests, samples called **sand tests** or **chill tests,** according to the manner of casting them, are also taken. In these tests the iron is allowed to cool in small moulds about two inches square in cross section and four inches long. The moulds may be either of sand as in "sand tests" or of metal, when they are called "chill tests." When cold, the small casting is broken with a hammer, and from the fracture thus exposed, if the test has been cooled properly, the blower is able, generally, to judge very closely as to the quality of the iron. Chill tests of all slags are also taken and carefully inspected.

**Tapping Slag:** In about two hours, the slag will have risen near the tuyeres, and another flush will be necessary. If the iron is tapped six times a day, only two flushings of slag are necessary between tappings, but if the tapping is on a five hour schedule three flushings will be required.

**Changing Stoves:** The temperature of a furnace at the hearth is a matter of great importance, as this is one of the two main factors which control the quality of the iron produced. One of the means of regulating this temperature is by changing the slag composition, as has been suggested. Another way by which quicker results may be obtained is by control of the hot blast temperature. This may be raised or lowered by use of the by-pass, and can be kept high by proper manipulation of the stoves. As a part of the routine of blast furnace work, the tending of stoves is of importance. They must be kept clean and be changed regularly and at not too long intervals. Usually but one stove at a time is employed for heating the blast, and the stoves are changed once each hour. Thus, each stove is heating for three hours. In changing stoves the hot stove must be put on the furnace before the cold one is taken off. To put a stove on hot blast, the gas burner is racked back from the gas port, and the **blow off** and chimmey valves are closed. Then in quick succession the cold blast valve and the hot blast valve are opened, when the blast is free to pass through the stove, which it does in the direction opposite to that by which the stove was heated. The cold stove is nov taken off, the procedure being the reverse of the above. The cold air valve is closed, and then quickly, the hot blast valve. To relieve the pressure in the stove, the blow-off valve is slowly opened, which permits the chimney valve to be opened. The stove is then ready for the gas, which is admitted by racking the burner forward.

**Charging the Furnace:** The charging of the furnace is a part of the routine that must be done with great care and cannot be interrupted. The furnace tends to empty itself rapidly, and constant vigilance is necessary to keep the stack full. The proportions of the materials used is a predetermined quantity. Therefore, all the materials are carefully weighed before charging into the furnace. The charging is usually done in **rounds.** The basis of charging is the weight of fuel in each round. The fuel remains a fixed quantity, and any variations in the charge are made with the ore and flux. Usually the coke in the round is measured by volume and not weighed, but, of course, the weight of the given volume in a round is known. The weight of this coke unit varies at different plants, because it is subject to no fixed rule, the opinions of furnacemen differ as what it should be, and it is affected by the size of the furnace and other conditions. The weights most often used are 10,000, 12,000, and 15,000 pounds. Under present conditions the weight of ore in the rounds will approximate twice and the limestone half the weight of the coke. The manner of charging the materials is also subject to much variation. Often it will be found that all the coke in a round will be charged, followed by the ore and limestone mixed together. To charge in this manner, each skip or bucket of coke is first dropped upon the small bell or placed over the gas seal which is lowered to allow the coke to fall upon the big bell. This operation is repeated until all the 10,000, 12,000 or 15,000 pounds of coke has been dropped upon the big bell, which is then lowered, allowing the coke to drop into the furnace. The ore and stone are then charged in the same manner. To illustrate the variation to be expected in the manner of charging, the simple scheme outlined above may be compared with the following, which was once found in use at a certain plant.

1 skip of ore—mixture of ores A. and B. Weighed. **Small bell lowered.**

1 skip of stone and ore—mixture of stone and ore C. Weighed. **Small bell lowered.**

1 skip of coke—not weighed. **Small bell lowered.**

1 skip of coke—**small bell lowered.**

**Big Bell Lowered.**

1 skip of stone and ore—mixture of stone and ore C.—**small bell lowered.**

1 skip of ore—mixture of ores A., B. and C.—**small bell lowered.**

1 skip of coke—**small bell lowered.**

1 skip of coke—**small bell lowered.**

**Big Bell Lowered.**

**Some Irregularities of Furnace Operation:** The blast furnace, even in its highest development, is by no means the even-going, easily-regulated monster the casual observer may take it to be. Although furnace operations are under better control now than ever before, the furnacemen still refers to his furnace in the feminine gender, because, he knows she is a fickle maid capable of acting in most unexpected and astonishing ways. Therefore, a full discussion of this subject would lead to possibilities and probabilities almost without end. However, the subject lends itself to at least one positive statement. It is this: there are few situations in life where promptness and decision, forethought and good judgment, skill and experience are more needed than about a blast furnace in times of trouble. A few of these troubles are here enumerated.

**Slips** are due to a wedging of the stock in the upper part of the stack. They are thought to be caused by carbon deposition, which may, in some cases, be more in volume than that of the ore. This deposition fills up the interstices of the stock, so that the gas can penetrate it only with difficulty. When this condition occurs the stock beneath the wedged portion settles from that above, the blast pressure rises and the wedged stock finally falls. The sudden release of pressure on the gases produces a result like that of an explosion. Slips of great violence have been known to tear off the top and do very serious damage.

**Scaffolding** occurs near the top of the bosh. This condition is often due to irregularities in the working of the furnace, the following explanation often being suggested: If the zone of fusion is suddenly lowered, the pasty mass at its top tends to adhere to the encircling wall, with the result that an incrustation is formed which projects toward the center of the furnace. This mass offers obstruction both to the gases and to the descent of the stock. If this condition is not soon remedied, the blast gases will channel, perhaps on one side, in which case serious damage to the lining would result. Dynamite is sometimes necessary to break a scaffold. This condition is often referred to as **hanging.**

**Chimneying and Hot Spots:** Chimneying is caused by the improper distribution of the charge with the coarser material segregating to the center of the furnace. The hot gases naturally seek the lines of least resistance, and the principal reaction is up through this more open center, with a corresponding slower movement of the finer and more compact material along the side walls. With the coarser materials segregating next the side walls, the more violent reactions are next the brick work, with a cold column in the centre, and the condition is sometimes called pillaring. If the latter condition becomes localized, the action of the stock and the hot gases soon cut away the walls adjacent to the area affected, if the condition continues for any length of time. Eventually, this may develop a hot spot, showing on the shell. By the generous use of water sprayed against the hot spot the furnace can sometimes be kept in operation for a considerable length of time after a hot spot shows. In either case the colder material from the inactive zone causes a cold hearth and poor quality of iron.

**Loss of Tuyeres and Chilled Hearth** may be brought about by burning out the coolers due to failure of the water and by filling during a slip. Bad slips always throw a great deal of the molten slag up into the tuyeres, blowpipes and tuyere stock where it immediately solidifies, necessitating a shut down. The large amount of comparatively cold stock that drops into the hearth from a severe slip may lower the temperature of the molten iron and slag below the fusion point, thus producing a **chill** in the hearth. When the tuyeres are finally opened in case of a bad chill, and the furnace is on blast, if necessary, before the tap hole can be opened, the iron can be tapped through the cinder notch after the removal of the coolers.

**Uncertainties and Variables in Furnace Control:** Besides the irregularities just mentioned which affect and occur in the furnace itself, there are many others which may arise from outside sources, because to obtain uniform working of the furnace it is necessary that all the raw materials, the limestone, the coke, the ore, and the air, be kept uniform, a feat that is manifestly impossible. Again, the furnace plant may be looked upon as a composite mechanism containing many vital parts, of which the furnace itself is but the central figure. The prolonged failure of any one of these parts, the boiler plant, the blowing engines, the pumping station, the gas mains, the water lines, or the stoves, is sufficient to close down the furnace. All of these things are of great interest to the furnaceman, but their discussion cannot be undertaken in as brief a discourse as the present one is intended to be.

**Banking:** Whenever it becomes necessary to close down a furnace temporarily, it is **banked.** This is done by charging coke blanks, beginning a few hours before banking. The amount of the blanks varies with the time the furnace is to be off. After the blanks have been charged, the furnace is drained as "dry" as possible of iron and slag, the connections to the rest of the plant are closed, the blast is shut off, the blow pipes and the tuyeres are removed, and the openings are bricked up tight. The bleeders, explosion doors and then the bells are opened, and the gas is allowed to pass out at the top. The furnace may now remain inactive for several days or weeks. In starting up, the furnace is filled up with coke and a little ore, the ashes are raked out through the tuyere openings, the tuyere connections are made and the blast is turned on. The same precautions with regard to gas must be observed here as in blowing in. A week or more, depending upon the length of the banking peroid, may be required for the furnace to return to normal condition.

**Blowing Out:** In blowing out, charging is merely stopped and the stock is allowed to settle. Streams of water are allowed to flow into the try holes to keep the top cool and prevent warping of the bells. As soon as the stock line descends near the tuyeres, the blast is taken off, the tuyeres are removed, and the rest of the stock is later removed with shovels. This done, the career of the furnace is ended.

## SECTION VIII.

### THE BLAST FURNACE BURDEN.

**Burdening the Furnace:** The amounts of ore and stone charge per ton (or other fixed quantity) of fuel is referred to as the burden, the fuel or coke being constant in amount. Any increase in ore and stone above the normal is spoken of as a **heavy burden,** while the reverse of this results in a **light burden.** The regulation of the proportions of ore, flux and coke is called **burdening.** It has two objects; namely, the most efficient operation of the furnace and at the same time the production of the grade of metal desired. The subject is of the greatest importance in the operation of a furnace, and is a problem that may be solved either by practical experience or by calculations based on theoretical considerations. With a furnace well started and on familiar materials, practical knowledge only may be required to operate successfully. But in dealing with unknown materials, theoretical burdening based on chemical analysis must be resorted to. A full discussion of these matters would make this Chapter too technical for the purpose it is intended. However, as illustrating the problems that confronts the blast furnace operator, the following will supply concrete examples:

Given: A furnace with a certain capacity and raw materials of the composition shown in the following table:

Required:
1. To produce 1 ton (2240 lbs.) pig iron with 2000 pounds coke or less.
2. To produce metal containing silicon, less than 1.25%; sulphur, less than .040%; manganese, as high as possible; carbon and phosphorus, not specified.

To determine:
1. In what proportions the ores shall be mixed.
2. Weight of ore mixture in the charge.
3. Weight of flux in the charge.

**Table 27.* Analysis of Raw Materials Used in the Blast Furnace.**

| ELEMENTS AND RADICALS | Formula | ORES | | | | Limestone | Coke |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | | |
| Dry Basis | | % | % | % | % | % | % |
| Silica.................. | $SiO_2$ | 6.48 | 9.04 | 12.78 | 5.86 | 3.43 | 4.40 |
| Iron.................... | Fe | 56.80 | 54.84 | 52.93 | 55.59 | .30 | 1.35 |
| Manganese............... | Mn | 1.14 | 1.09 | .83 | .16 | .08 | .07 |
| Phosphorus.............. | P | .082 | .096 | .083 | .618 | .006 | .030 |
| Alumina................. | $Al_2O_3$ | 3.22 | 2.70 | 3.34 | 3.63 | .86 | 2.80 |
| Lime.................... | CaO | .11 | .18 | .25 | 1.22 | 51.45 | .25 |
| Magnesia................ | MgO | .14 | .26 | .21 | .87 | 1.66 | .15 |
| Fixed Carbon............ | C | ..... | ..... | ..... | ..... | ..... | 90.00 |
| Carbon Dioxide.......... | $CO_2$ | ..... | ..... | ..... | ..... | 41.43 | ..... |
| Sulphur................. | S | ..... | ..... | ..... | ..... | ..... | .940 |
| Sulphuric Anhydride..... | $SO_3$ | .03 | .04 | .04 | .06 | .060 | Undetermined |
| Alkalies................ | $Na_2O$-$K_2O$ | Trace | Trace | Trace | Trace | Trace | Trace |
| Titania................. | $TiO_2$ | .018 | .009 | .012 | .019 | Trace | Trace |
| Water, (Wet Basis)..... | $H_2O$ | 14.06 | 14.50 | 15.00 | 12.10 | .50 | 1.50 |

*N. B. The preceding table is intended to give a complete list of the elements and radicals which make up the solid materials entering the furnace, or the charge. The gases, i. e., the blast, may be looked upon as a mixture of oxygen and inert gases composed mainly of nitrogen. In this mixture the oxygen content is 20.8% by volume or 23.2% by weight.

**Outline of a Method for Solving a Burdening Problem:** In a general way the solution of the problem is arrived at in the following manner: From the physical condition of the various ores and the amount of each on hand, their relative cost or other considerations, the furnaceman first decides the approximate proportions in which it is desirable to use the ores. From these proportions he is able to determine the average composition of the ore mixture in each charge, the size of which he has also decided upon. From this average he is able to calculate the amount of ore required to produce one ton of pig iron, and the weight of the impurities therein. Then, since he must make one ton of iron with one net ton of coke, or less, he is able to arrive at the total impurities in the ore and coke required to produce one ton of iron. These impurities, he separates into acids and bases, and then combines them according to the slag ratio of acid to base which experience has taught is the best to produce the kind of iron desired. This process gives the excess acids which must be fluxed with limestone. From the analysis of the stone he determines the available base, from which the amount of limestone required to flux the excess acids in accordance with the accepted ratio can be found. The next thing to consider is the slag volume, or the amount of slag to be made per ton of iron, which experience has taught must be within certain limits to be consistent with good furnace practice. If the volume of slag is very low, its ability to remove sulphur from the iron may be seriously interfered with, while if it is very high, the fuel consumption will increase above that desirable, because coke must be consumed to furnish the heat necessary to form and fuse the slag. If the slag volume falls outside the limits which the furnaceman's judgment from experience has set for it, he must begin all over again, starting with a different mixture of ores, or different limestone or coke. Evidently, with new materials the solution of the problem involves a great deal of try-work with different combinations of the materials that may be available.

**The Burden Sheet:** During the operation of a furnace, the burden may be changed from time to time to meet the ever changing conditions. These changes are governed by observation and by the analysis of the pig iron and slag produced. An accurate record is kept of all changes made, and of the weights and analyses of all materials charged, and for purposes of record and of comparison between the theoretical and actual conditions, this data is all assembled at certain times, usually once each week, placed on a burden sheet, and the theoretical amounts of the various ingredients of the raw materials and the products are calculated. To illustrate the calculations involved, the following burden sheet is appended. The figures given are based on a single charge instead of on amounts of materials used for any given length of time, otherwise they represent actual conditions and show a typical charge for a furnace making basic iron. In studying the sheet it should be kept in mind that only the weights of the ores, cinder, scale, scrap, coke and stone, together with their analyses, and the theoretical analyses of the pig iron are given to

## Blast Furnace Burden Sheet

| Material | % | Lbs. | IRON | | SILICA | | ALUMINA | | LIME | | MAGNESIA | | PHOSPHORUS | | MANGANESE | | SULPHUR | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | % | Lbs. | % | Lbs. | % | Lbs. | % | Lbs. | % | Lbs. | % | Lbs. | % | Lbs. | % | Lbs. |
| Ore—No. 1... | 53.26 | 15 978 | 49.80 | 7 957.044 | 5.8 | 926.724 | 3.0 | 479.340 | .2 | 31.956 | .2 | 31.95 | .068 | 10.865 | .77 | 123.031 | .010 | 1.598 |
| Ore—No. 2... | 5.51 | 1 653 | 46.80 | 773.604 | 8.2 | 135.546 | 2.3 | 38.019 | .2 | 3.306 | .2 | 3.31 | .064 | 1.058 | 1.12 | 18.514 | .062 | 1.025 |
| Ore—No. 3... | 26.31 | 7 893 | 47.00 | 3 709.710 | 10.6 | 836.658 | 2.3 | 181.539 | .2 | 15.786 | .2 | 15.79 | .078 | 6.157 | .65 | 51.305 | .014 | 1.105 |
| Ore—No. 4... | 3.42 | 1 026 | 53.30 | 546.858 | 3.2 | 32.832 | 2.3 | 23.598 | .1 | 1.026 | .2 | 2.05 | .072 | .739 | .43 | 4.412 | .016 | .164 |
| TOTAL ORE | 88.50 | 26 550 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| Cinder, Scale, Scrap, etc... | 11.50 | 3 450 | 61.25 | 2 113.125 | 7.9 | 272.550 | 1.3 | 44.850 | 1.5 | 51.750 | .4 | 13.80 | .155 | 5.348 | .59 | 20.355 | .112 | 3.864 |
| TOTAL—MIX | 100.00 | 30 000 | 50.33 | 15 100.341 | 7.3 | 2204.310 | 2.6 | 767.346 | .3 | 103.824 | .2 | 66.90 | .081 | 24.167 | .73 | 217.617 | .026 | 7.756 |
| Coke......... | 51.68 | 15 505 | .... | .... | 5.3 | 821.765 | 3.1 | 480.655 | .3 | 46.515 | .2 | 31.01 | .021 | 3.256 | .... | .... | .921 | 142.801 |
| Stone......... | 25.78 | 7 733 | .... | .... | 2.7 | 208.791 | 1.5 | 115.995 | 51.5 | 3982.495 | 1.3 | 100.53 | .031 | 2.397 | .... | .... | .070 | 5.413 |
| Dolomite..... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| TOTAL CHARGE... | .... | .... | .... | .... | .... | 3234.866 | ... | 1363.996 | .... | 4132.834 | .... | 198.44 | .... | 29.820 | .... | 217.617 | .... | 155.970 |
| Reduced...... | .... | .... | .... | .... | .... | 341.791 | ... | .... | .... | .... | .... | .... | .... | 29.820 | .... | 145.078 | .... | 4.819 |
| Slagged...... | .... | .... | .... | .... | .... | 2893.075 | ... | 1363.996 | .... | 4132.834 | .... | 198.44 | .... | .... | .... | 72.539 | .... | 151.151 |

### PIG IRON PRODUCED

| | THEORETICAL | | ACTUAL |
|---|---|---|---|
| | Pounds | % | % |
| Fe.......... | 15 100.341 | 94.00 | .......... |
| Si.......... | 160.642 | 1.00 | 1.25 |
| S.......... | 4.819 | .030 | .030 |
| P.......... | 29.820 | .185 | .158 |
| Mn.......... | 145.078 | .903 | 1.03 |
| TOTAL,.... | 16 064.2 | 100.000 | .......... |

TOTAL TONS PRODUCED............

### SLAG PRODUCED

| | THEORETICAL | | ACTUAL |
|---|---|---|---|
| | Pounds | % | % |
| $SiO_2$....... | 2 893.075 | 32.70 | 34.82 |
| $Al_2O_3$..... | 1 363.996 | 15.42 | 14.71 |
| Ca O....... | 4 132.834 | 46.72 | 48.24 |
| Mg O...... | 198.440 | 2.24 | 1.50 |
| Mn O...... | 93.641 | 1.06 | 1.01 |
| Fe O...... | .......... | .15 | .15 |
| S.......... | 151.151 | 1.71 | 1.73 |
| TOTAL.... | 8 846.407 | 100.00 | 102.16 |

### PRODUCT RATIOS

| | | | |
|---|---|---|---|
| Slag per Ton | | 1 234 | Lbs. |
| " " " | = | 55.1 | % |
| $\frac{\text{" CaO+MgO}}{\text{SiO}_2}$ | = | 1.4 | |
| Coke per Ton | = | 2 162 | Lbs. |
| Mix to Coke | = | 1.93 | |
| Stone to Mix | = | 25.78 | % |

begin with, and that all the other figures are supplied by calculation. Also, it will be observed that the analyses of the raw materials are based on these materials in their undried, or natural, state.

## SECTION IX.

### CHEMISTRY OF THE PROCESS

**Methods of Investigating the Reactions of the Blast Furnace:** A question, which the non-technical reader is usually much interested in, is this: What changes do these numerous ingredients of the raw materials undergo during their passage through the furnace? Now, the reactions as they take place in the furnace are beyond the reach of thorough investigation; but from a study of the chemical properties of these elements and compounds under conditions similar to those existing in the furnace and from the chemical composition of the products, which is easily obtained by analysis, together with observations made in working with the furnace, reliable conclusions as to the reactions that must bring about the various transitions may be formed. Nearly all the data necessary to this study has already been supplied. However, the following brief review of the chemical properties of the elements under furnace conditions may profitably be made. These properties are revealed by laboratory experiments properly conducted under conditions approximating those of the blast furnace.

**The Functions of Oxygen and Carbon:** 20.8% of the blast by volume is oxygen, which enters the furnace at a high temperature, about 530° C., and, coming in contact with hot coke, immediately reacts with carbon giving off heat thus:

(1) $C+O_2=CO_2$ (+97200 cal.) 4

In the presence of an excess of carbon at a high temperature, $CO_2$ is at once reduced to CO, and 68040 cal. are absorbed (2) $CO_2+C=2\,CO$ (—68040 cal.) The net heat, then, from (1) and (2) is 29160 cal. (+97200—68040=29160 cal.)

At moderately high temperatures the CO gas formed acts as a powerful reducing agent and will liberate heat at the same time, thus:

(3) $3CO+Fe_2O_3=2\,Fe+3CO_2$ (+8520 cal.)
—87480 cal.—195600 cal. +291600 cal.=8520 cal.

At temperatures ranging from 250° C. to 700° C., a dull red heat, the reduction of $Fe_2O_3$ by CO may take place in three steps, the $Fe_2O_3$ being successively reduced to $Fe_3O_4$, FeO and finally to Fe. That the reduction of the ore in the blast furnace does take place in this way is shown by the fact that a large part (60% to 75%) of the flue dust, ejected from the top of the furnace, is magnetic, though only $Fe_2O_3$, may have been charged. The total heat liberated by these three reactions would be a little more than twice and the total iron reduced one-half as much as that in reaction (3) for equal weights of CO. A very interesting reaction that takes place between $Fe_2O_3$ and CO at low temperature is (4), in which carbon is deposited and heat is liberated thus:

(4) $2\,Fe_2O_3+\ 8\,CO=\ \ 7\,CO_2+4\,Fe+C$ (+55920 cal.)
—391200 cal.—233280 cal.+680400 cal.

Carbon is not deposited with magnetite and CO reacting together, but it may be deposited at temperatures below 600°C by the action of metallic iron upon CO, thus; $Fe+CO=FeO+C$. The $CO_2$ formed in the preceding reactions and from the decomposition of limestone may act as an oxidizing agent, absorbing or giving off heat, as shown in reactions (5) (6) (7).

3 (5) $Fe + CO_2 = FeO + CO$ (—2340 cal.)
—97200 cal. + 65700 cal. + 29160 cal.
(6) $3FeO + CO_2 = Fe_3O_4 + CO$ (+5660 cal.)
—197100 cal. — 97200 cal. + 270800 cal. + 29160 cal.
(7) $3Fe + 4CO_2 = Fe_3O_4 + 4CO$ (—1360 cal.)
—388800 cal. + 270800cal. + 116640cal.

These reactions will take place at temperatures ranging from about 350° C. to 800° C., and their extent will be governed by the relative amounts of $CO_2$ and CO in the furnace gas, obeying, in this respect, the law of mass action. To be reducing the volume of CO in the gas mixture must equal or exceed twice the volume of the $CO_2$.

Carbon alone is also a reducing agent toward oxides of iron at low temperatures (450° C. to 700° C.), but the reduction of ore by carbon alone absorbs much heat as shown by the following reactions:

(8) $3\,Fe_2O_3+C = 2\,Fe_3O_4 + CO$ (—16040 cal.)
—586800 cal. + 541600 cal. + 29160 cal.
(9) $Fe_3O_4 + C=3\,FeO + CO$ (—44540 cal.)
—270800 cal. + 197100 cal. + 29160 cal.
(10) $FeO + C=Fe + CO$ (—36540 cal.)
—65700 cal. + 29160 cal.

Under proper conditions the reduction of $Fe_2O_3$ by solid carbon may take place in a direct way, thus:

6 $Fe_2O_3 + 3C=2\,Fe+3CO$ (—108120 cal.)
—195600 cal. +87480 cal.

At very high temperatures—say around 1500°C.—carbon in large excess may reduce manganese, silicon and phosphorus oxides, the reactions being represented thus:

(11) $Mn_3O_4+C=3\,MnO+CO$—Heat is absorbed.
(12) $MnO+C=Mn+CO$—Heat is absorbed.
(13) $SiO_2+2C=Si+2\,CO$.—Heat is absorbed.
(14) $P_2\,O_5+5C=2P+5CO$—Heat is absorbed.

Some oxygen also enters the furnace as water vapor in the blast, where the following endothermic reaction occurs: $H_2O+C=CO+H_2$.

The hydrogen formed may do work temporarily by reacting with iron oxide and reducing it thus:—(15) $FeO+H_2=H_2O+Fe$.

But the water so formed is again decomposed as shown by the presence of hydrogen in blast furnace gas. Therefore, the net energy result from water vapor is a loss.

In this connection it should be noticed that, since carbon is the only fuel employed, the carbon-oxygen reactions must be relied upon to furnish the heat required in the process, and that only a few of these are heat producing. Reactions (1) to (4) produce most of the heat absorbed by other modes of reduction, also that required to dry the raw materials, to decompose the limestone, to flux the impurities, to melt the iron and slag, and to replace the waste. On this account they are among the most important reactions occurring in the furnace.

**Behavior of Nitrogen in the Furnace:** Nitrogen and the other inert gases of the air, totalling 79.2% of the blast by volume, pass through the furnace, for the most part, unchanged chemically. Since they equal in weight about six-tenths of all the other materials entering the furnace, they play an important part in heat conduction, and make a source of unavoidable heat waste. Some nitrogen, however, may react with alkali carbonates and carbon to form salts of hydro-cyanic acid.
(16) $K_2CO_3+4\,C+N_2=2K\,CN+3\,CO$.

This reaction explains the small amount of cyanogen, CN, always present in blast furnace gases.

**Action of Phosphorus in the Furnace:** Phosphorus enters the furnace with the charge in the form of phosphates. At very high temperatures and in the presence of coke (carbon) these compounds are completely reduced, as shown in reaction (14). Phosphorus reacts with iron to form $Fe_3P$, thus: (17) $3Fe+P=Fe_3P$.

This phosphide, being soluble in iron, becomes a part of the metallic bath in the blast furnace. Hence, the phosphorus in the pig iron can be controlled only through the selection of materials.

**Disposition of Sulphur in the Furnace:** Sulphur is carried into the furnace mainly by the coke, though small amounts are found in both the ore and the limestone. The greater portion contained in the coke enters in the form of FeS, which, when melted, alloys with the iron in the furnace; a smaller portion, in the form of sulphates, as $CaSO_4$, enters as an impurity in the ore, limestone and coke, and is reduced to sulphide at a low red heat and in the presence of carbon. At a very high temperature and in the presence of a very basic slag, or CaO, and carbon, the following reaction may take place. (18) $FeS+CaO+C=CaS+Fe+CO$. Owing to lack of proper conditions in the blast furnace, this reaction is never complete, so a small portion of the sulphur remains in combination with the iron. This iron sulphide, being soluble in iron, becomes a part of the metal.

**Behavior of Silicon:** Silicon enters the furnace as $SiO_2$, some of which may be combined with bases as silicates. At temperatures of about 1200° C., corresponding to the fusion zone in the blast furnace, the greater portion of this silica combines with lime, CaO, and other bases to form silicates, which have already been discussed under the heading of slags. However, at a high temperature, such as exists in the hearth of the furnace, and in the presence of carbon, silica is reduced, and the resultant silicon

combines with the iron. 9 (19) $SiO_2+2C=Si+2CO$.
(19A) $Fe+Si=FeSi$.

**Action of Calcium and Magnesium:** Calcium and Magnesium enter the furnace mostly as carbonates. Small portions may be in the form of silicates, in which CaO and MgO are combined with $SiO_2$, and may undergo no chemical change in the furnace. The carbonates, however, are decomposed at temperatures above 800° C., liberating $CO_2$.

8 (20) $CaCO_3=CaO+CO_2$. (21) $MgCO_3=MgO+CO_2$.

At the proper temperature for their formation the caustic lime and magnesia in intimate contact with $SiO_2$ will both combine with it to form slags.

**Action of Aluminum:** Aluminum, in the form of alumina, $Al_2O_3$, and alumina silicates, is found in ore, flux and fuel. Neither alumina nor its silicates are reduced under the conditions that prevail in a blast furnace. $Al_2O_3$, as already pointed out, may exert a marked influence upon the fluidity and fusibility of the slag.

**Action of Less Abundant Elements:** Titanium, potassium, sodium, zinc, arsenic, copper and chromium, are elements, a few of which are present in very small amounts in the materials used in the Pittsburgh district. Titanium enters the furnace as titania, $TiO_2$, combined with some base. Titania is similar to silica, $SiO_2$, except that it is more difficult to reduce at temperatures attainable in the blast furnace, and all but traces of it, which is found in the iron, passes out with the the slag. Under the conditions prevailing in the furnace, titanium exhibits a slight tendency to combine with carbon and nitrogen to form titanium cyano-nitride. This substance is sometimes found in the salamander on the hearths of furnaces being repaired. Here, it occurs in the form of small cubes that have the appearance of copper. The alkalies, soda and potash, are found in nearly all blast furnace slags, and when they are present in the raw materials to a considerable extent, they are partly volatilized and driven over out of the furnace with the flue gases, from which they may be separated with an installation of suitable apparatus. Zinc is a very troublesome element when present in blast furnace material. Its compounds may be reduced in the lower regions of the stack; but, if so, the zinc is volatilized, driven upward by the blast, and oxidized to zinc oxide, which condenses on the walls of the colder part of the flues and in time closes up the passages to such an extent as to seriously restrict the flow of the gases. Zinc oxide also tends to combine with the alumina in the fire brick lining of the furnace, causing the brick to expand with consequent evil, or even disastrous, results. Arsenic acts very much like phosphorus. All of its compounds are reduced, and the resultant elementary arsenic then combines with iron to form iron arsenide which dissolves in the metal. Copper compounds are readily reduced, yielding metallic copper, which alloys with the iron. Chromium is separated from its oxides only with great difficulty in the blast furnace, an exceedingly high temperature and a special slag being required for the reduction of its oxides.

**The Reactions Within the Furnace:** With these facts concerning the properties of the various ingredients of the raw materials in mind, the changes that take place in the blast furnace are easily understood. The accompanying chart (Fig. 23) gives a graphic representation of these changes, showing the relative weights and volumes of materials, the reactions and the temperatures at which the changes take place and the final disposition of the products. In studying this chart, however, one important fact should be kept in mind. It is this: Owing to the conditions prevailing within the furnace, very few, if any, of the reactions will be complete, that is, use up all the material at hand at the location indicated. Thus, the first reaction, showing the reduction of the ore to metallic iron with the deposition of carbon, affects only a part of the ore and gas. This condition, with but one exception holds for all these reactions. Even limestone, which will decompose completely into lime and carbon dioxide at 1000° if given sufficient time, will often reach the tuyeres as calcium carbonate. The fact that iron and manganese oxides are not completely reduced is established by their presence in the slag. The one exception to this rule is phosphorus. Its compounds, down to small traces, are completely reduced.

The explanation for these statements is to be found only in a careful study of chemical laws in connection with the conditions prevailing in the furnace. Such a study reveals the fact that the reactions in the upper part of the stack of the furnace are subject to conflicting tendencies. Thus, there are in constant contact with the solid substances $Fe_3O_4$, FeO, Fe, and C the gaseous substances CO and $CO_2$. Of these, $Fe_3O_4$ and $CO_2$ are oxidizing agents. FeO and CO may act as either oxidizing or reducing agents, while C and Fe are reducing agents. With these substances in contact at any given temperature and in any given proportions as shown on the chart the reversible reactions would proceed in a given direction until equilibrium should be established, and no further change would occur until either the concentration of one of the reacting substances or the temperature should change. Then the reactions, subject to the law for mass action, would proceed in a direction that would again establish equilibrium. But the slow downward movement of the stock to regions of higher and higher temperatures, the presence of an excess of carbon and the rapid upward flow of the gases, which has the effect of giving a constant surplus of CO and of carrying $CO_2$ out of the field of action, tend to prevent the establishment of equilibrium, and to force the reactions to proceed in a direction that will result in the final reduction of the iron oxides, with the consequent oxidation of either the C or the CO. These same conditions, however, which tend to reduce the oxides of iron, prevent the complete oxidation of the CO to $CO_2$, because the CO, passing so rapidly over the stock, does not have time to become wholly oxidized, and the presence of the reducing agents, Fe, FeO, and C, tend to oppose the formation of $CO_2$. The escaping top gases, therefore, always show a large content of CO much in excess of the $CO_2$ content. In modern furnaces, operating according to the prevailing practice with respect to coke consumption, the relative volumes

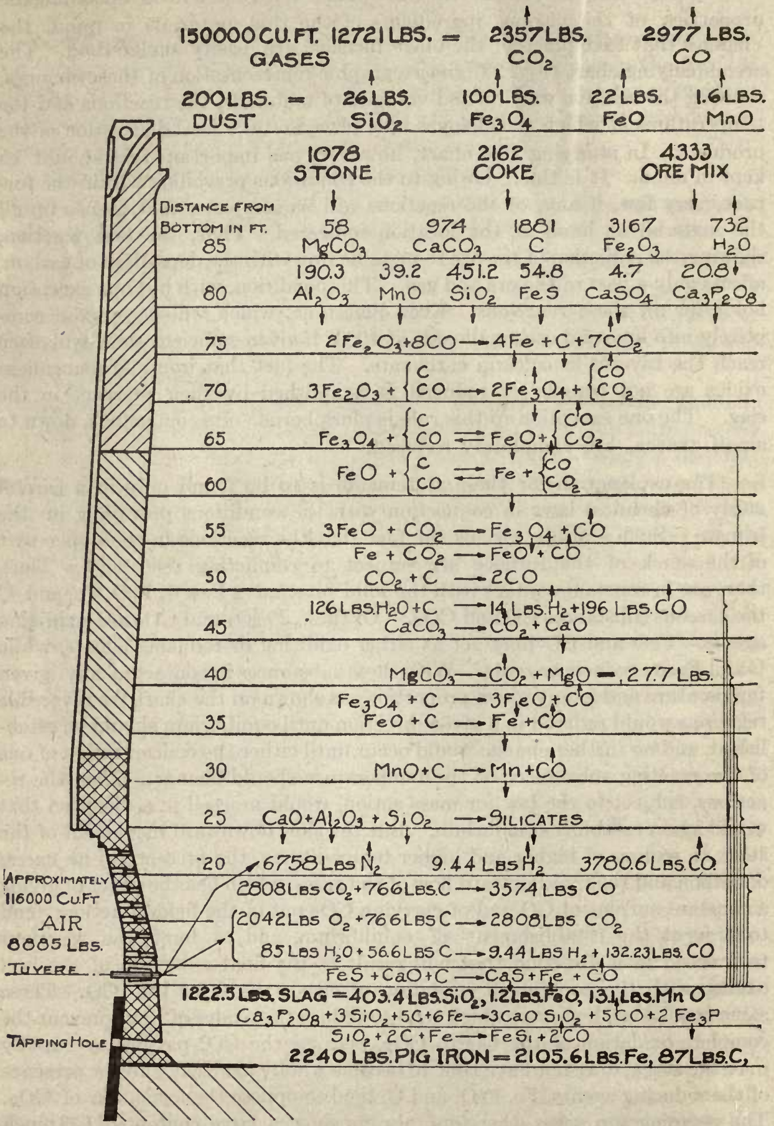
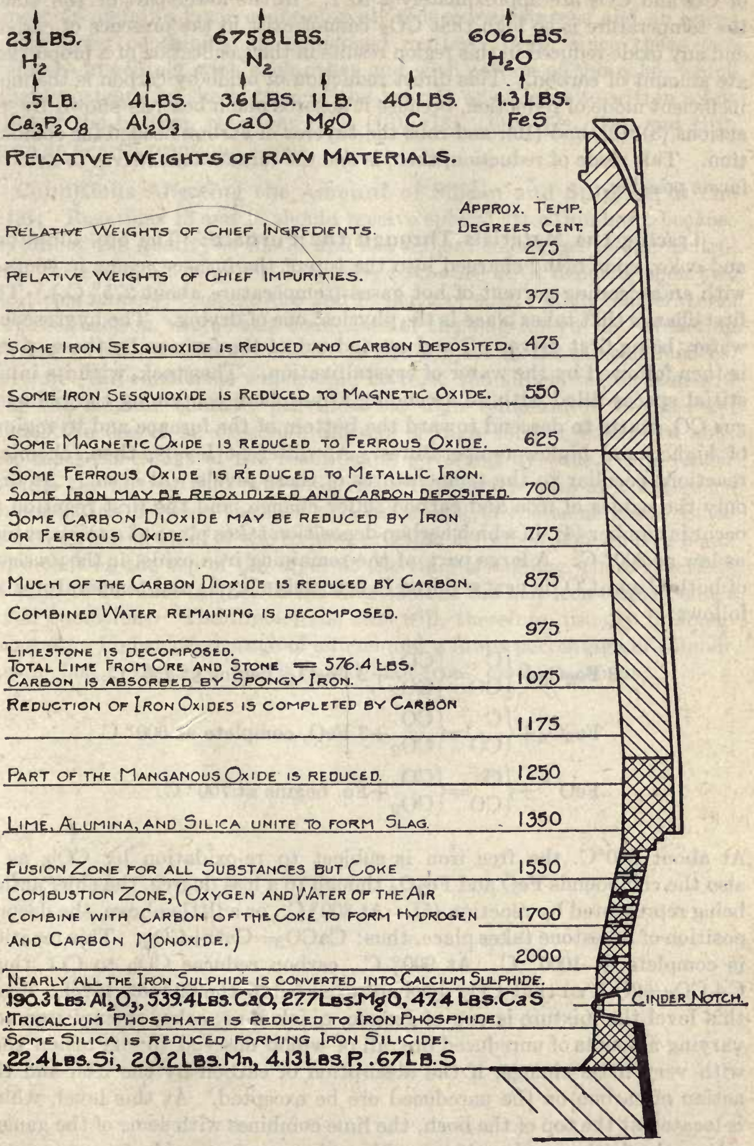


FIG. 23. The Making of a ton of Pig Iron. A diagram showing the raw changes that take place therein.



materials and the products of the blast furnace; their relative weights and the of CO and $CO_2$ are approximately 2 to 1. In the lower part of the stack, the temperature is so high that $CO_2$ cannot exist in the presence of carbon, and any oxide reduced in this region results in the gasification of a proportionate amount of carbon. This direct reduction of oxide by carbon is the most inefficient mode of reduction, because it absorbs much heat, as shown by reactions (8), (9), and (10), and robs the tuyeres of carbon needed for combustion. This mode of reduction, then, is one the furnaceman strives to avoid so far as possible.

**Tracing the Materials Through the Furnace:** The ore, limestone and coke, upon being charged into the top of the furnace, come in contact with an ascending current of hot gases (temperature about 275° C.). The first change that takes place is the physical one of drying. The hygroscopic water, being first driven off and carried out of the furnace by these gases, is then followed by the water of crystallization. The stock, with its interstitial spaces filled with an ascending atmosphere containing the reducing gas CO, starts to descend toward the bottom of the furnace and to regions of higher and higher temperatures. At different levels, then, chemical reactions peculiar to the temperatures of these levels will occur. At first only the oxides of iron and carbon suffer change, and the first reaction to occur is number (4), in which carbon deposition takes place at a temperature as low as 300° C. A large part of the remaining iron oxide, in the presence of both C and CO, is next reduced in successive levels and temperatures as follows:

$$3\,Fe_2O_3+\begin{cases}C\\CO\end{cases}=\begin{cases}CO\\CO_2\end{cases}+2\,Fe_3O_4,\ \text{begins at } 450°\ \text{C.}$$

$$Fe_3O_4+\begin{cases}C\\CO\end{cases}=\begin{cases}CO\\CO_2\end{cases}+3\,FeO,\ \text{complete at } 600°\ \text{C.}$$

$$FeO\ +\begin{cases}C\\CO\end{cases}=\begin{cases}CO\\CO_2\end{cases}+Fe,\ \text{begins at } 700°\ \text{C.}$$

At about 800°C. the free iron is subject to re-oxidation by $CO_2$, as is also the compounds FeO and $Fe_3O_4$ though to a less degree, the chief action being represented by reaction (5). At 800° C., or a little above, the decomposition of limestone takes place, thus: $CaCO_3=CaO+CO_2$. This reaction is complete at 1000° C. At 900° C., carbon reduces $CO_2$ to CO. thus: $C+CO_2=2CO$, so that $CO_2$ does not exist below the 60 foot level. From this level the mixture is one of gangue, quick lime, coke, spongy iron and varying amounts of unreduced ore, all of which descend to the fusion zone with very little change, if the absorption of carbon by the iron and the action of carbon on the unreduced ore be excepted. At this level, which is located at the top of the bosh, the lime combines with some of the gangue and, with a little unreduced iron oxide and manganese oxide, forms a part of the slag. The slag, such as is already formed, and the iron, both now in the liquid state, trickle down through the interstices of the coke to the hearth, where they become separated by gravity, forming these two layers; a lower or metallic layer containing all reduced substances and an upper or slag layer containing all unreduced matter. Here, since these two layers are in contact with each other and with carbon of the coke, which probably extends to the bottom of the hearth, or at least to within a few inches of the bottom, reactions (11), (12), (13), (14), (17), (18), and (19), known as hearth reactions, occur.

**Conditions Affecting the Amount of Silicon and Sulphur in the Metal:** Reactions 13 and 18 should receive special attention here, because they affect the quality of metal and are subject somewhat to the control of the furnaceman. Number (13), $SiO_2+2C=Si+2CO$, depends upon two conditions, namely, temperature and basicity of slag. High temperatures favor the reaction, while basic conditions of the slag retard it. Reaction (18), $FeS+CaO+C=CaS+Fe+CO$, is also subject to the same influences. Therefore, the conditions which tend to raise the silicon in the iron will lower the sulphur content, provided the high temperature is obtained without the use of an excessive amount of high sulphur coke. In both these cases the extent of the reactions is governed by time. The longer the time the farther they will progress. This fact results in a difference in composition between the first and last metal in the same cast. Since the iron on the bottom of the furnace crucible is formed four or five hours before that on the top of the layer at the time of tapping, these reactions will tend to advance farther in the first than in the last iron formed under normal conditions. The first of the cast will, therefore, usually be found to contain a higher percentage of silicon and a lower percentage of sulphur than the last. This first iron is called "hot iron" on this account.

# CHAPTER VII.

# THE BESSEMER PROCESS OF MANUFACTURING STEEL.

## SECTION I.

### THE CLASSIFICATION OF FERROUS PRODUCTS.

**Introductory:** In beginning this chapter it is desirable to decide the question as to what constitutes steel. Owing to the many varieties of iron now classed as steel, a concise and wholly satisfactory definition is well nigh impossible. Attempts have been made to restrict the usage of the term, but without success, because in defining any term, the name must be taken as it is used. Therefore, since an adequate definition of steel is lacking, a brief resumé of the commercial products of iron may be profitable. In beginning this survey, it is to be born in mind that the basis for the preparation of the various ferrous products is pig iron and that this substance, a direct product of the blast furnace, represents the crudest form of commercial iron. All higher grades are the products obtained by different methods of refinement and the degree to which this refinement is carried. The ferrous products may, therefore, be placed under two classes, namely, pig iron and refined iron.

**Pig Iron and Cast Iron:** As pointed out in the preceding chapter, pig iron may vary, or be varied, very much in chemical composition and constitution. This variation gives the different grades of pig iron and determines the use to which the metal can be applied. On cooling, the crude forms first undergo a slight expansion, which is followed by a slight contraction. This fact makes it particularly suitable for mould casting, in which form it is called **Cast Iron.** Cast iron offers a high resistance to crushing, but all forms of unrefined iron are lacking in tenacity, elasticity and malleability.

**Malleable Cast Iron:** In the second class will be found a series of products, which may be classified according to the initial method of refinement. This refinement may be brought about in two ways,—namely, one in which the metal remains in the solid state throughout the process and another in which the purification involves fusing the metal. Malleable cast iron is an example of the first method. Products of this class are obtained from crude pig iron of a certain composition chemically, which, upon being cast into the desired form, is subsequently subjected to a combined annealing and oxidizing process by which the malleability is developed. In carrying out the process, the clean casting is packed in iron oxide and subjected to a temperature of about 700° C. for three or more days, when it is allowed to cool in the furnace very slowly. By this treatment the greater portion of the combined carbon is converted into graphite that takes the form of very minute particles evenly distributed throughout the casting, and so does not have the weakening effect that flakes of graphite have. Some carbon, say twenty per cent of that originally present in the iron, is oxidized and eliminated from the metal. It is said that a slight reduction in the sulphur content also takes place.

**Wrought Iron:** At present there are two classes of iron products recognized as being produced by the method of purification by fusion. To these are given the names of **wrought iron** and **steel**. Wrought iron, as indicated in the study of the blast furnace, may be produced directly from the ore. This method, however, has now been superseded by the indirect process, in which pig iron is melted in a reverberatory furnace, called a puddling furnace, the hearth of which is lined with iron oxide. This treatment results in the oxidation and consequent removal, from the metal, of all but small amounts of carbon, silicon, manganese, phosphorus and sulphur. The purification brings about a rise in the fusion temperature of the iron above that of the furnace, and at this point the metal is removed from the furnace in the form of pasty balls in which more or less slag is incorporated. As much as possible of this slag is at once removed by hammering or squeezing, after which the bloom thus produced is rolled into **muck bar.** In this form it may be converted into steel as noted below, or subjected to further treatment to produce **merchant bar.** Wrought iron is soft, tough and very malleable. It welds easily, and is characterized by a fibrous structure, due to the presence of the intermingled slag and the mechanical treatment it receives. Various modifications looking to improvement in the process of producing wrought iron have been devised.

**Steel** is the term applied to all refined ferrous products not included under the classes described above. It is distinguished from pig iron by being malleable at temperatures below its melting point, from malleable iron by the fact that it is initially malleable without treatment subsequent to being cast, and from wrought iron by the circumstance of its manufacture. In the case of wrought iron, the metal was in a fused state during a part of the purifying process only, whereas the purification of pig iron to produce steel takes place at a higher temperature, and the metal remains in the molten state throughout the period of purification. From a chemical analysis it is practically impossible to distinguish wrought iron from soft steel, but the one, being obtained in a state of complete fusion and free from slag, may exhibit physical properties very different from the other, which is obtained in a semi-fused state and retains small amounts of the slag incorporated with it. Between pig iron and steel, however, a marked difference in chemical composition as well as in physical properties is observed. All three substances show a wide variation in chemical composition. The following table may be studied with profit.

### Table 28. Chemical Relations of Pig Iron, Wrought Iron and Plain Steel.

| | PER CENT. OF | | | | | |
|---|---|---|---|---|---|---|
| Name | Iron | Carbon | Manganese | Sulphur | Phosphorus | Silicon |
| Pig Iron. | 91—94 | 3.50—4.50 | .50—2.50 | .018—.100 | .030—1.00 | .25—3.50 |
| Plain Steel. . | 98.1—99.5 | .07—1.30 | .30—1.00<br>(.03—.10 as cast) | .020—.060<br>(.120) | .002—.100 | .005—.50 |
| Wrought Iron. . | 99.0—99.8 | .05—.25 | .01—.10 | .020—.100 | .050—.20 | .02—.20 |

This table would indicate that wrought iron is not the purest form of commercial iron, as is often asserted. However, in wrought iron part of the manganese, sulphur, phosphorus and silicon shown in the table above may be derived from the incorporated slag, in which case they would exert little influence upon the metal itself.

**Methods of Making Steel:** Formerly it was possible to make a much finer distinction between wrought iron and steel than that indicated above. Prior to 1856, there were but two kinds of finished steel; they were known as **shear steel** and **crucible**, or **cast, steel**. Both were at that time manufactured from blister steel made by the cementation of wrought iron. Shear steel was made by piling and welding blister steel bars into faggots, which were then forged or rolled into strips or bands suitable for cutlery. Crucible steel was produced by melting blister steel and scrap in graphite crucibles, casting the fluid metal into moulds, and then forging these small ingots into bars of the required size and shape. These products were distinguished from wrought iron by the fact that they could be hardened and tempered, and this property was, therefore, made the basis for a definition of steel. But the introduction of the Bessemer and open hearth processes, with their numerous grades of products, many of which can also be hardened and tempered and all of which are quite different from wrought iron, necessitated a revision of this definition for steel, because, lacking a better name, the term steel was applied to the products from the new processes also. Then, still more recently, the advent of the electric furnace added another variety to the ferrous metals. Finally, the cementation process has been superseded almost entirely by the crucible process, and the introduction of alloying elements has made a definition based on the purity of the metal inapplicable. It appears therefore that the only general definition for steel that can be offered is one based on the method of refinement. On this basis, then, steel is a ferrous metal, derived from pig iron or wrought iron, which has been subjected to a refining process by complete fusion.

**General Principles of the Methods of Purifying Pig Iron:** From a commercial standpoint, the fundamental principle by which the purification of pig iron is effected is that of oxidation in all cases, excepting the electric furnace, which employs both oxidation and reduction. For the purpose of purifying by oxidation two substances are available. These substances are air and iron oxide, the application of which requires different types of apparatus. The two chief methods of purification, then, represent attempts to meet these requirements. These methods are known as the pneumatic, or Bessemer, and the open hearth, or Siemens' processes. In both, the purification may be brought about by oxidation alone, in which case they are called **acid processes,** or by oxidation in conjunction with strong bases, such as lime, when they are designated as **basic processes.** By the first class of process, only the elements carbon, silicon and manganese are removed from the iron, while the second method also removes phosphorus and, to a limited extent, sulphur. The **basic Bessemer process** has been named after its inventors, the **Thomas-Gilchrist,** and the basic open hearth is generally spoken of as the **basic.** Each of the five purifying processes mentioned above, namely, the acid Bessemer, the basic Bessemer, the acid open hearth, the basic open hearth, and the electric, produces steel having certain peculiar properties, and with the exception of the electric process, each requires pig iron of a composition different from any of the others. Owing to the composition of iron ores available in this country, the pig iron produced is best adapted for treatment by the basic open hearth or the acid Bessemer process; hence, these are the leading methods employed.

## SECTION II.

### PRINCIPLES AND HISTORY OF THE BESSEMER PROCESS.

**Principles of the Process:** Of all the processes for the purification of pig iron, the Bessemer is the simplest. Essentially, it consists of blowing air under pressure through a bath of molten metal contained in a vessel constructed of proper refractory materials, whereby a portion of the iron, all of the silicon and manganese, and then the carbon are successively oxidized. The first three elements, upon combining with oxygen, go to form a slag, while the carbon is eliminated in the form of the gases, carbon-monoxide, CO, and carbon dioxide, $CO_2$. As noted elsewhere, the oxidation of these elements are exothermic reactions, from which the heat required to maintain the metal in the liquid state is derived. Since steel produced in this way, without recarburization, contains deleterious oxides which render it unfit for use, it is necessary to add deoxidizers to the metal after blowing. This fact was not realized at first, and the history of the process serves to emphasize its importance.

**Some Incidents Connected with the Early History of the Process:** The history of this process also furnishes an example of the way in which a method is developed, and illustrates the fact that the perfecting of a process is seldom accomplished by one mind alone, but by many minds thinking toward one goal. The method was almost concurrently, but independently, originated by two men: one, an American named Wm. Kelly of Eddyville, Ky.; the other, an Englishman, the illustrious inventor, Henry Bessemer. Although Kelly did not apply for patents until 1857, almost two years after Bessemer's English patent was granted, his application was allowed on grounds of priority, because he was able to prove that he had worked out the idea as early as 1847. In the same year that he made application for patents, Kelly erected a tilting converter for the Cambria Steel Works at Johnstown, Pa. This vessel is still preserved. Lacking financial means, however, Kelly was unable to perfect this invention, and after much litigation with the Bessemer interests, a settlement was made, whereby Kelly dropped out of the game. Bessemer, on the other hand, in addition to conceiving the idea and putting it to trial, continued his experiments in the face of great difficulties and many failures until he had brought the process to a high degree of perfection. At first Bessemer accidently employed only Swedish iron, which had a low phosphorus and a high manganese content, and was very successful in converting it. Then, it having been adopted by many manufacturers, the process failed when applied to English irons which were high in their phosphorus and low in their manganese content, and prejudice and opposition to the method became so great among steel makers that, in order to save his process, Bessemer was obliged to build a steel works himself. His plant, built at Sheffield, began to operate in 1860.

**Importance of Manganese:** At the Sheffield works the process was used at first to produce high carbon steels from Swedish pig iron only, because low carbon steels, obtained by subjecting the metal to a full blow, were almost invariably hot short, even when made from the excellent Swedish iron. This defect was later overcome by the addition of manganese in the form of spiegeleisen, the beneficial effects of which were first recognized by R. Mushet as early as 1856. With the adoption of the use of manganese, mild or soft steels produced by the process came into so great demand that the former practice in blowing was abandoned in England, though it is still employed in Sweden. The first Bessemer plant in this country was erected in 1867.

**Thomas and Gilchrist:** The removal of phosphorus by the use of a basic lining and the addition of lime to the bath was first conceived by Thomas, who made known the success of his scheme in 1878. In the development of this process, Thomas was assisted by his cousin, the chemist Gilchrist, hence the name Thomas-Gilchrist.

**Other Improvements:** While the process was highly developed along mechanical lines by Bessemer, himself, it remained for Alexander Holley, an American Engineer, to introduce many improvements in the erection of Bessemer plants. The most important of these was his invention of the detachable bottom, which will be described later. Another important invention was that of the hot metal mixer, since it furnished a ready supply of molten metal of fairly uniform composition, thus allowing the process to be operated much more rapidly and economically. This vessel, also to be described later, was the invention of W. R. Jones of the Carnegie Steel Company's Edgar Thomson Plant at Braddock.

**Plan of Study:** Before beginning a more minute description of the process as it is carried on with these modern improvements, it is well to note that the details of the operation will vary much in different plants as well as in different countries. The description, therefore, must be either very general in character, or be restricted to some one plant which will suffice as an example for all. For the present purpose, it is best to follow the latter course, and the Carnegie Steel Company's plant at the Edgar Thomson Works is selected to serve as such an example. General features of great importance may then be introduced in connection with the discussion of the various topics. At these works, the product from eleven modern blast furnaces is available to supply both the open hearth plant of fourteen 90-ton furnaces and the Bessemer plant of four converters, the maximum capacity of which is twenty tons.

## SECTION III.

### EQUIPMENT AND ARRANGEMENT OF THE EDGAR THOMSON PLANT.

**The Converter House:** The four converters are arranged in a row along one side of the converter building, which is located in one corner of the works in close proximity to the rail mills. The converters, being of the concentric type, tilt in two directions, in one direction for charging and in another for pouring. On the charging side of the vessels the building is erected three-story fashion. The ground floor extends under the converters and offers space for the removal of bottoms, slag, etc. The second floor, designated as the charging floor, is on a level with the trunnions. From this floor all molten materials are charged into the vessels. From the third floor, called the scrapping floor, all cold materials are charged. Serving the four converters on the pouring side, are two jib cranes for handling the steel ladles into which the metal is poured after

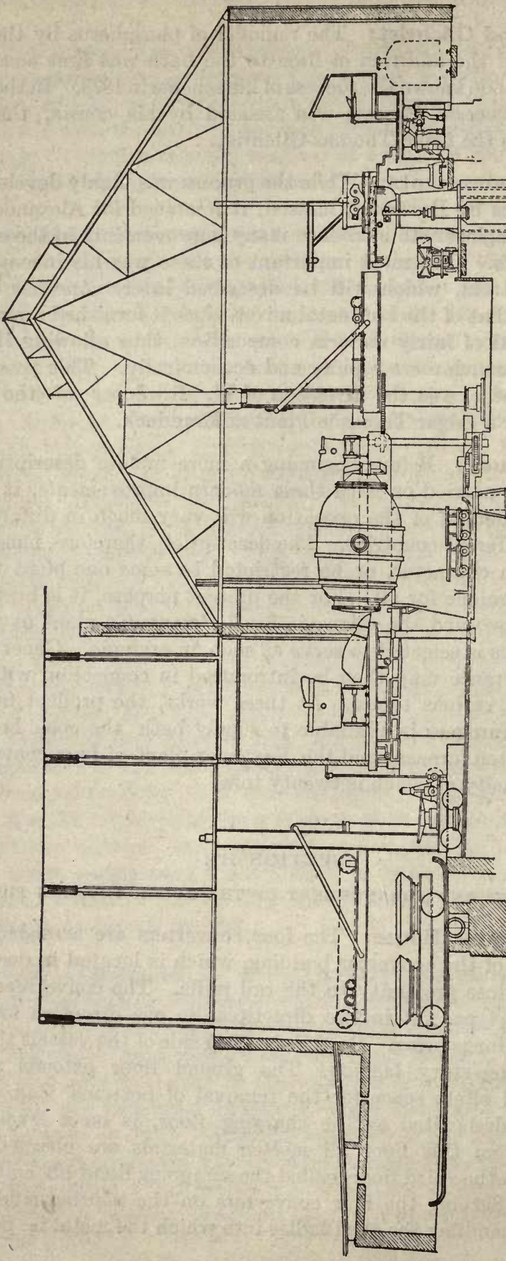


FIG. 24. Cross Section of a Converter Plant.

each blow. These cranes may be swung around so as to deliver the steel to stationary teeming tables located in front of the teeming platform which extends along the side of the building opposite the converters. Between this platform and the tables, which support the ladles during the teeming process, is laid a narrow gauge track, along which the ingot moulds, set upon small cars, are moved during and after the teeming. This motion in front of the platform is imparted by means of dogs attached to three hydraulically operated cylinders that lie between the rails of the tracks. All the operations of the converters and jib cranes are controlled from two pulpits in opposite corners of the building and above the teeming platform. Just back of the converter building and inter-communicating with it through an open side beneath the charging floor, is the **bottom house,** equipped with over-head cranes and buggies for handling bottoms. Here the frequent repairs to bottoms are made. As these repairs must be made with wet refractories, new bottoms require thorough drying before being put into service. For this purpose six **drying ovens,** each large enough to contain two bottoms, are provided. Built against one end of the converter house, like the wing of a building, is a cupola house. It also is inter-communicating with the converter building on its charging floor. In the angle formed by the cupola and bottom houses are kept the stores of cold pig iron, spiegel, and ferro manganese, while beyond these will be found a building in which is housed suitable rock crushing machines and Chilean mills for crushing and mixing the refractory materials used in making up the various mixtures required for bottoms and repairs about the plant.

**The Larger Accessories:** The cupolas, blowing engines, mixers and strippers, are each separately housed and are located at various distances from the converter house. All these accessories play a very vital part in the process and in the operation of the plant, hence are deserving of special consideration.

**The Cupolas:** In former times, when converter plants were operated as independent units, detached and far removed from the blast furnaces, cupolas were used to melt the cold pig iron preparatory to charging. At this plant furnaces are used only for melting the pig iron and spiegel mixtures employed as recarburizers. In construction a cupola is cylindrical in shape and resembles a miniature blast furnace. Those at Edgar Thomson Works are eight feet in diameter outside and some twenty feet in height, measuring from the mantle to the charging doors. Like the blast furnace, there is an opening at the bottom of the hearth for tapping out metal and another for slag. Above these openings are inlets for ten tuyeres, through which cold air, under a pressure of six to ten ounces, is blown by fans. Near the top are the two large openings or doors for charging, directly opposite each other and opening upon the charging floor. A little above these openings, a contraction of four or five feet in the outside diameter of the shaft forms the stack, also about twenty-four feet high, for the escape of gases. The entire furnace rests vertically on a mantle which is supported by a number of columns fixed upon a firm foundation. This construction permits the use of the drop bottom, which facilitates the removal of worn-out linings, the frequent repairing required by the lower lining, and the rapid discharge of the stock in case of emergency. For the sake of economy, the lining, or wall, is made of different materials. The upper wall, for a distance of about four feet below the charging doors, is made of fire brick and is nine inches thick. Below this brick work, the wall is built of firestone and is gradually increased in thickness, forming a kind of bosh above the hearth, the walls of which are about eighteen inches thick. No attempt is made to cool these walls, so it is customary to back up the firestone of the hearth-wall with fire brick in order to safeguard the steel shell. The shell, like that of the blast furnace, supports and re-enforces the masonry. It is made of steel plates, which are riveted together.

**Charging the Cupola:** The cupola charge is composed of coke, spiegel and pig iron, in alternate layers of metal and coke, to the last of which is added sufficient limestone to flux the ash. When the orders call for steel with a high content of silicon, ferro-silicon is also added to the charge. The ratio of coke to metal varies a little. At all times the amount of fuel will be as small as possible, both for the sake of economy and to exclude sulphur and phosphorus, which are absorbed by the metal, as much as possible. Sulphur in the charge does not result in a rise in the sulphur content of the molten spiegel, but in a waste of the manganese, which reacts with the ferrous sulphide to form manganous sulphide, and goes off with the slag. Ordinarily, the coke will be about 8% and the stone about 2½% of the metallic charge.

**The Blast:** Just outside the converter house, on the pulpit side, is the blowing room. Here are located three steam blowing engines of the compound vertical type, which create the air blast for the converters. The blast from these engines is delivered into a common main, through which it is conducted into the converter building, where it is distributed through a manifold to lines leading separately to the four vessels. The admission of air to the vessels and its pressure are nicely regulated by a system of valves under the control of the blower. Thus, the pressure on the main is maintained at about 25 pounds per square inch by means of a blow-off valve, which is used to regulate the pressure while the vessels are charging or pouring. In case some of the converters are not being operated, one or more of the blowing engines is stopped. By means of a second valve, operated from the pulpit by a screw control, a pressure of 18 to 20 pounds per square inch is maintained on the line leading to each vessel. Under this pressure the blast may be almost instantaneously admitted to or shut off from the vessel by means of a third valve of the butter-fly type. A fourth valve provides a means by which steam may be admitted to the blast line as required. The limits of blast pressure to the converter are about 10 and 25 pounds per square inch. The lower pressure is just about sufficient to keep the metal out of the tuyeres in a normal charge, while if the higher pressure be exceeded, large amounts of metal are blown out of the converter.

**The Mixers:** The supply of molten pig iron is obtained from two 200-ton hot metal mixers located near the blast furnaces and some three hundred yards from the converter mill. They are large vessels constructed of steel plates riveted together to form a shell, which is lined with silica or a good grade of fire brick. The vessels at this plant represent the oldest type. They have a rectangular horizontal section and discharge the metal by tilting. This type has a slightly arched roof and a bottom which slopes from the front or pouring end toward the rear. The axis of rotation is located at the bottom near the center line of the vessel. Molten iron from the blast furnaces is conveyed to the mixer in tipping ladles, from which the metal is poured into the mixer through an opening in its top at the rear end. In the opposite end another opening, provided with a spout, permits the drawing off of hot metal as required by merely tilting the mixer, thus permitting the metal to be weighed with a fair degree of exactness. These mixers are not provided with gas burners, as is customary, for very little heat above that held by the metal is ever required to keep the contents molten.

**Importance of the Mixer:** The hot metal mixer is almost indispensable to a modern Bessemer plant, or for that matter, to any steel making plant. Primarily the mixer serves as a storage place for the hot metal from the blast furnace, and in performing this function bestows great benefits. Thus, not only is the heat from the hot pig iron conserved, but the metal delivered to the vessel, or vessels, is of a more uniform composition than could be otherwise obtained. Again, since the capacity of the modern mixer permits it to contain casts from several furnaces, iron low in some elements may be mixed with some that is high in the same ingredients; and so it is possible to extend the chemical limits of the iron receivable. Mixers have been constructed of various shapes and sizes. Their capacities will range from 150 to 1200 tons, but the tendency in all modern construction is toward the larger size. Purification of the metal is said to take place to a slight extent in the mixer, sulphur being the chief impurity removed. The reduction in sulphur, however, is only noticeable when the manganese content of the iron is high. This removal is at all times so small as to be of minor importance.

**The Stripper:** One of the most efficient and economical inventions contributed to the steel business is the stripper. As its name indicates, it is a device whereby the moulds are pulled, or stripped, from the ingots after the metal has cooled sufficiently to form a solid shell on their outside surfaces. Those at the Edgar Thomson Works are of a late type and are electrically operated. A stripper of this type is in the form of a strong over-head crane, from which is suspended a vertical arm, provided, in place of a hand, with two jaws that fit over lugs cast on either side and near the top of the mould. Operating between the jaws is a ram, or plunger, capable of exerting pressure on the top of the ingot, while it is being stripped, sufficient to balance the pull. In stripping an ingot, the jaws engage the lugs and exert a powerful pull upward, while the ram, having been inserted through the top of the mould, holds the ingot on the stool till the mould is loosened. The mould is then raised high enough to clear the ingot and placed upon an empty car standing, ready to receive it, on a track next and parallel to that on which the stripped ingot stands. Electric strippers, owing to the fact that they are travelling, possess a decided advantage over the older type of hydraulically operated machines, which are stationary.

**The Casting Equipment** includes the teeming ladles, ingot moulds, stools, and cars. **The teeming ladle,** which acts as a container for the finished steel while casting, is a large cup-shaped vessel made of steel and lined with a few inches of "ball stuff." As slag is liable to spoil the ingots if allowed to flow into the moulds, steel cannot be poured from a vessel by tipping, but must be teemed from a small hole in the bottom. For opening and closing this hole, the vessel must be fitted with a stopper that can be operated from the teeming platform. This stopper consists of a steel rod, protected with fire-clay sleeves, to the lower end of which is fastened a stopperhead, made of plumbago bonded with clay, that fits neatly into a nozzle placed in the bottom of the ladle. The upper end of this stopper is fastened to a goose neck that fits over a vertical sliding bar attached to the outside of the ladle. This bar is provided with a lever by which it may be raised or lowered, causing a like movement of the stopper. To guard against a leaking, or "running," stopper the nozzle may be filled with dry sand or loam, which is held in place by a sliding plate on the outside. When the ladle is ready to teem, this sand is easily punched out of the nozzle after removing the plate.

**The Ingot Moulds** into which the finished metal is teemed are made of cast iron and may be of almost any convenient form and size to suit the respective blooming mills. At these works, the standard moulds are about 6 feet high, have a square section of 23⅝ inches at the bottom, with corners slightly rounded, and taper sufficiently to allow the mould to be stripped readily from the ingot. The moulds are open at both ends, and, when ready for teeming, rest, big end down, on heavy cast iron plates, called **stools.** The stools are mounted in twos on small cars, or buggies, which are so constructed that their sides form aprons that protect both the track on which the cars run and their own running gear from splattering by hot metal during the teeming of the metal from the steel ladle. The care of the moulds is very important, since defects here are very likely to show up in the finished material after rolling. Their sides must be kept smooth and clean, and the teeming must be done so as to avoid splattering their sides, if possible.

After being stripped, the moulds are inspected and, if their condition is satisfactory, may be used again. So, after cooling to a point where the hand may be held against them, they are cleaned, then sprayed inside and around the tops with a clay wash to prevent the steel from sticking, and marked for size of ingot required. As soon as the clay wash is dry, the mould is ready to receive the molten steel. Usually about seventy ingots may be cast in one mould before it is scrapped.

## SECTION IV.

### CONVERTER CONSTRUCTION AND REPAIRS.

**General Features Pertaining to Converters:** As to the form and size of converters, methods of admitting the blast, and removing the steel after blowing, there are several possible arrangements, and converters have undergone many modifications. Thus, as was originally the plan, the air might be admitted horizontally through the wall of the vessel near the bottom, in which case the vessel would be of the **side-blowing** type; or a blast of air will be forced upward through openings in the bottom of the vessel, to which method the term **bottom blown** is applied. To facilitate the charging of materials into the vessels and the removal of metal from them, converters are now always constructed so that they may be rotated on their shorter axis through arcs of varying size. Such converters are of the **tilting** type. The first vessels were of the **fixed** type, the metal being tapped through a hole in the wall at the bottom. In both size and shape, vessels still vary much. The capacity will range from 5 to 25 tons. The vessels at Edgar Thomson are 11 feet in diameter, outside and measured along their axis of rotation, and almost 18 feet long. As to form, converters were at first somewhat pot-shaped. Attempts to design vessels that would retain heat and prevent the ejection of materials has led to two general forms, each with its own advantages. In both forms the upper diameters are shortened, forming the **nose** of the vessel and leaving a small opening in the top, which forms the **mouth.** The body may retain the form of the cylinder, as in the **straight-sided** type, or be narrowed at the bottom also, in which case the body has a **curved** contour and somewhat resembles an egg in shape. The mouth may be located at the top **concentric** with the bottom and in a plane parallel to it, or it may be placed to one side, in which case the opening lies in a plane at an angle to the bottom and is then called **eccentric.** The vessels at Edgar Thomson Works are all of the bottom blown, curved body, tilting, concentric type.

**Parts of Converter:** For convenience in constructing the vessel to allow for contraction and expansion and for making repairs later, these converters, as are all bottom blowing types, are constructed in three separate parts, known as the **nose,** the **body,** and the **bottom.** The shell for each of these parts is made of heavy steel plates, all firmly riveted together. The nose section is bolted to the body, but the bottom is held in place against the lower edge of the body by linked key bolts. The links of these key bolts fit over lugs on the body, while the key bolts themselves fit between lugs on the bottom, making it easy to key the two parts firmly together. When it is necessary to replace an old bottom with a new one, the keys can be very quickly knocked out or driven in with sledges in the hands of the workmen. The shell for the body is, itself, made up of three parts, known as the nose section, the journal section, and the shoulder section. The journal section is made up of a heavy band to which the two trunnions that support the vessel are attached. All these parts are firmly bound together by a great number of long key bolts attached to the shoulder and nose sections, respectively. The trunnions rest on bearings in a frame work which is supported by cast iron columns. On the end of one of the trunnions, both of which are hollow, is the connection, made through a packed joint, to the blast line. From capped openings on this same trunnion between the bearing and the vessel, a copper goose neck leads to the bottom of the vessel, thus forming a continuous passage for the blast from the main, which is stationary, to the wind box, which must move with the bottom of the vessel. To the other trunnion is attached a pinion which meshes with a toothed rack that slides horizontally. By means of a double acting hydraulic cylinder, the piston of which is connected to this rack, the vessel may be rotated through an arc of 270°, the pinion and rack being geared so that the vessel may be completely inverted for dumping slag or relining the vessel. All this mechanism is carefully covered to protect it from slag, dust and other dirt.

**Lining of the Converter:** The lining for the shell may be composed of any first class silicious refractory material. At most works a highly silicious sandstone, known as firestone, is used, while a mixture, composed of about five parts crushed ganister and one part best quality fire clay and called ball stuff, serves as a kind of mortar. The lining varies in thickness from ten to sixteen inches for the different parts of the vessel, being thickest on those parts subject to the greatest wear. When lining a new vessel or relining an old one, the bottom is detached, the vessel is inverted and the lining is begun in the nose. The method pursued in starting the lining will then depend largely upon the materials available and the shape of the vessel. At the Edgar Thomson Works, the customary procedure is as follows: A wooden frame, some five feet square and with a hole in the center of the same shape and size as the mouth of the vessel, is laid on suitable cross pieces and then suspended from the vessel so as to press firmly against the nose and in such a position that the hole is superimposed upon the mouth. In this way a ledge upon which to begin the wall is formed. Upon this ledge is placed a three inch layer of ball stuff, which is followed by a course of large, flat, undressed firestone, set in on edge. All the interstices are rammed full of wet ball stuff, so that the stones are securely keyed into place and the side and top present a smooth surface. Upon this nose wall, which is about sixteen inches thick and thirty inches high, the body wall is built. It consists of two courses. A thin course of split brick is laid next to the shell, while within this, the inner course, about twelve inches thick, is built up of rough blocks of firestone laid in a mortar of ball stuff. The stones for the top course of this wall are cut to shape and keyed in so as to hold the wall in place when the vessel is righted and also to form a smooth joint, or shoulder, against which the bottom is to fit. The lining is now completed by plastering the interior of the vessel with ball stuff, after which it is carefully and thoroughly dried. The coat of plaster, aside from giving a smooth surface, protects the stone and overcomes its tendency to spall. To prepare the vessel for use, the bottom is put on, the vessel is inclined, and then heated to a high temperature with natural gas fires in the vessel itself. In case of a shortage or absence of gas, coke or wood may be substituted for the gas. With careful patching this part of the lining may last for several weeks, or even months, of continuous running.

**The Bottom** of the converter warrants special mention. It is the part of the vessel subject to the greatest wear and seldom lasts longer than twenty heats, when it must be removed for repairs and replaced by another. This change can be made with a delay of less than twenty minutes, and is carried out in the following manner: The bottom of the wind box is removed while the vessel is pouring, then as soon as the slag is dumped, the converter is righted, and a small but strongly built truck provided with a hydraulic jack, or lift, is run beneath it. The water connection having been made with the hydraulic cylinder, the pressure is applied to the jack, which raises a small table against the bottom. In some plants the jack is placed beneath the track, in which case the whole truck is raised. The keys are next knocked out, which leaves the bottom free to descend with the table or the truck. The truck is then pulled into the bottom house, where an overhead crane picks up the bottom and carries it to one side. By reversing this procedure, a new bottom is soon in place, and the converter is ready for charging.

**Relining the Bottom:** The repairing of the old bottom is immediately begun. What remains of the old tuyeres and filling is quickly cooled with water, and that on the bottom is loosened with suitable tools, when it may be removed from the bottom by dumping it with the crane. The removal of this material makes it easier to inspect the construction of the bottom. The shell is made of heavy steel plates riveted together in the shape of a shallow bowl with an open bottom. Closing this opening from within the bowl, is the false bottom, a flat circular casting, with openings through which the tuyeres may be inserted. It is a little larger in diameter than the opening which it closes, thus making it unnecessary to fasten it in any way. It supports the bottom stuff in which the tuyeres are packed. Covering this same opening from without is the tuyere plate, a similar casting containing bevelled openings into which the tuyeres fit when in place. This plate is prevented from making a tight joint with the bottom by means of the splice plates that hold the riveted plates together. Thus, an open space about one inch in depth is left between the tuyere plate and the false bottom. The plate forms the top of the wind box, the two being firmly bolted to each other and to the bottom with the same bolts. The side of this wind box is a large casting, oval in shape, and about twelve inches in depth. The bottom of the box is a steel plate which is firmly keyed to the casting to make an almost air tight joint when the vessel is blowing. Connecting the wind box with the interior of the bowl, are nineteen to twenty-one circular bevelled holes, through which the tuyeres are inserted. The tuyeres are cylindrical bricks, flared for a distance of about six inches from one end. They are about thirty inches long, seven inches in diameter, and each one contains about twelve holes, one-half inch in diameter and extending longitudinally. To place a tuyere, the flare is covered with a mortar, composed of fire clay and Portland cement, and the tuyere is inserted upward through the opening in the bottom, where it is held in place with clamps until the filling has been put in. When all the tuyeres have been thus placed in position, the top of each is covered with a metal plate to keep dirt out of the tubes, some bottom stuff is placed on the bottom in the space around the tuyeres, and on this large tiles are set in as reinforcement to the tuyeres. The space remaining about the tuyeres and brick is then tamped full with more of the bottom stuff, which is a moist mixture composed of 28 parts crushed ganister, 12 parts blue fire clay, 3 parts ground brick bats, 3 parts old bottom stuff and 4 parts coke dust. The bottom is then pushed into a drying oven, fired with coke oven gas, and carefully dryed, then finally baked for several hours. The time required to dry and bake a bottom properly is about forty-eight hours, though bottoms will often be used at the end of thirty-six hours. Upon being required for use, it is withdrawn from the oven, and a heavy layer of a stiff clay mixture is placed around the upper edge to form a tight joint with the shoulder of the vessel when the bottom is in place. The mortar is then sprinkled heavily with coke dust, after which the bottom is put into service as previously described. The function of the coke dust is to prevent the bottom from cementing itself to the shoulder joint. When in service the position of the bottom is such that the long axis of the oval wind box is parallel to the axis of rotation of the vessel. The advantage of this shape is obvious, for it is easily seen that with the wind box in this position a greater volume of metal may be held in the vessel while in the horizontal position without filling the tuyeres than would be possible with a round box, which is the form used on eccentric vessels. The double bottom, mentioned above, is also of great advantage. Since the space between the upper and lower plates connects with the outside, it not only gives warning of a worn out tuyere, but also prevents the wind box from being filled with hot metal in case of a break out. When a tuyere becomes defective or badly and dangerously worn during a blow, it may be plugged by turning the vessel down, removing the wind box lid, and stopping its openings with clay.

## SECTION V.

### THE CONVERTER IN OPERATION—PURIFYING THE METAL.

**Charging the Vessel:** With the bottom fastened in place and the vessel at the proper temperature, it is ready for the charge. The charging is a matter of much importance. Besides being a factor in determining the composition or grade of steel produced with respect to phosphorus and sulphur, it also offers a means of controlling the temperature during the blow. It must always be predetermined by the blower, who has charge of the blow. In acid practice the charge consists of molten pig iron, to which is added cold pig iron or steel scrap in amounts sufficient to meet the heat requirements of the blow. As the only source of heat is the oxidation of the iron, silicon, manganese and carbon, the composition of the pig iron is important, and the blower must be kept informed in advance as to the composition of the iron. In operating a hot vessel on hot iron there is much more heat generated than is required to keep the metal molten, in which case the temperature may be kept under control by charging steel scrap. Scrap may be added to the heat at any time during the first part of the blow. The addition of scrap also has the advantage of increasing the output. In beginning on a new lining or a new bottom, or after a delay, the vessel will be cold and will, itself, absorb much heat, which condition precludes the use of cold materials in the charge. In an attempt to lessen the loss of iron through oxidation and shorten the time of a blow, roll scale or other oxides of iron are often charged. Such additions may reduce the blowing period by about one-third, and are made regularly at some plants, but this is not the practice at Edgar Thomson. On making a steel that requires a high sulphur content, like screw steel, the required amount of this element, in the form of pyrite, may be added along with the molten metal. The blower, having been informed as to the requirements of the rolling mills, decides upon the charge best suited to the conditions, then sends an order to the mixer for a certain weight of pig iron. At these works this amount will vary from 30,000 to 36,000 pounds. The molten iron is weighed at the mixer as it is poured into the ladle, the truck of which sets on a scale platform. Some coke breeze is then thrown upon the molten metal to keep it from skulling the ladle, when it is taken by a dinkey to the charging floor of the converter. Here, the vessel is turned down to a horizontal position, so as to bring the tuyeres well above the bath, and the molten iron is poured into the mouth of the vessel by slowly tipping the ladle. The scrap is added from the scrapping floor shortly after the vessel is brought to the vertical position.

**The Blow:** Immediately after the vessel has received the charge of molten metal, the blast, under a pressure sufficient to prevent the metal from flowing into the tuyeres and also force the air through the liquid, is turned on, and the vessel is racked to the vertical position. With this act the air of the blast is forced to pass up through the molten mass, and chemical action between the oxygen of the air and the various ingredients of the metal immediately begins. This oxidation takes place in successive stages, each of which, provided the blow is a normal one, produces its own peculiar effect in the metal and upon the kind of matter ejected from the mouth of the vessel. Their order, therefore, may be followed by the naked eye or through colored glasses. As the vessel is righted a shower of sparks is emitted from its mouth. Then a stream of dense brown fumes pours forth, to be succeeded shortly by a dull red, short, pointed flame that protrudes from the mouth of the vessel. This action occupies but five or six minutes, when this flame is gradually replaced by a short luminous one that plays about the mouth. This flame soon begins to increase, both in length and luminosity, until it has reached a maximum length of thirty feet or more, which it maintains steadily for about eight minutes. During this period, known as the **boil,** a dull roaring coming from the vessel may be heard. This noise is caused by the violent agitation of the bath by the blast and the rapid generation of carbon monoxide gas within it. Just before the end of the blow, the flame begins to drop, or "die," that is, it suddenly becomes less luminous, giving an effect similar to that to be expected if a smoked glass or a cloud were placed between it and the eye; and if it is being observed through blue glasses, purple streaks are visible in it. If the blow should be continued, this flame would disappear entirely, but the metal is always poured before this point is reached. Thus, the entire time required to convert fifteen to eighteen tons of pig iron into steel is only about fifteen minutes.

**Controlling the Blow:** The appearance of the flame just described serves as an index to the change going on in the vessel, and so is very important to the blower, upon whom rests the responsibility for the proper operation of the vessel. He is also held accountable for the quality of the steel he produces. He has an assistant who turns the vessel for charging and pouring and operates the ladle crane, but the control of the process is in the hands of the blower himself. He must decide the best proportions of hot metal and scrap to use, regulate the temperature, determine the time for turning down and over-see the recarburizing of the blown metal. As to the kind of recarburizer and the amount to use per ton of steel, he receives instructions from his superintendent's office. Factors that enter into the making up of the charge have already been explained. The importance of a high temperature was also alluded to as necessary to keep the bath molten. In this connection it remains to be pointed out that temperature is an important factor in controlling the blow, and so exerts an influence on the quality of the product. As it is impossible to regulate the charge so as to meet all the variations in the conditions, other means of regulating the temperature must be resorted to during the blow itself. To raise the temperature after a blow is in progress, the vessel may be turned so as to expose a few tuyeres above the metal. The combustion of the carbon monoxide gas over the bath generates heat, which raises the temperature of the vessel and consequently of the metal also. This method wastes some metal, as iron is excessively oxidized. Ferro silicon is also used for this purpose, the oxidation of the silicon being the source of heat in this case. Either method is expensive and should be avoided. With rapid working, and with iron of proper grade, cold heats are the exception, occurring mainly on new linings or in the first blow on a new bottom. To lower the temperature is a much easier matter. The vessel may be tilted and allowed to cool by radiation, or cold metal in the form of steel scrap may be added, if the heat is not too far advanced. A more convenient method is that of introducing steam with the blast, and as it is very convenient, it is often employed. The water coming in contact with the highly heated metal is decomposed according to the following reaction: $H_2O+Fe=FeO+H_2$. Steam thus introduced is not very efficient because the oxidation due to air is not retarded and very little, if any, heat can be absorbed. However, less heat is generated in oxidizing iron with water than with air, besides, steam is easily controlled, is always at hand, and can be introduced in varying amounts without delay to the blow or turning the vessel. The blower will, then, keep close watch on the flame, and introduce steam during the blow as often as required to hold the temperature at the proper level. The speed of the blow, and, indirectly, the temperature, may be controlled to a limited extent, also, by varying the blast pressure. In this connection it should be stated that there are so many variables connected with the operations that no uniform method can be established. Even with metal of uniform composition and other conditions apparently alike, two consecutive heats made to the same specification will seldom require the same manipulation. Thus, the success of the entire operation depends upon the judgment of the blower.

**The End of the Blow:** Owing to the rapidity of the reactions and other peculiar conditions, the composition of the steel cannot be well regulated by stopping the blow. While it is possible to blow a heat to approximately any carbon content desired, the method is not practiced in America, because it slows down the operation too much. It is much cheaper and surer, therefore, to blow full, and add both carbon and manganese with the recarburizer. This is the practice at Edgar Thomson. At these works, if the blow is stopped at the first indication of the drop of the flame, it is said to be turned down young; if continued till the drop is pronounced, the blow is full. In either case the silicon will have been completely eliminated, while only small amounts of manganese and carbon will remain. The residual manganese may be as high as .06 or .08%, depending upon the extent of the blow and the percentage in the pig iron. If the blow is turned down young, .08% to .10% carbon will remain, while in a full blow this amount is decreased to .03 or .04%. The percentage of phosphorus and sulphur is slightly higher than in the original pig iron, owing to a loss in weight due to oxidation and elimination of the silicon, carbon, manganese and part of the iron, and also to the ejection of metallic iron from the vessel. The total loss will amount to something between 8% and 10% of the charge, nearly half of which is oxide of iron and manganese which can be recovered by using the slag in the blast furnace.

## SECTION VI.

### FINISHING OPERATIONS—CONVERTING THE PURIFIED METAL INTO STEEL.

**Deoxidation and Recarburization** must always immediately follow the blow. At Edgar Thomson this is done in the ladle as the metal is being poured, though at certain other plants some of the additions are made in the vessel. In general the objects sought are: 1st., control of the carbon content; 2d., deoxidation of the steel; and 3d., introduction of elements, such as manganese, to improve the quality of the steel. The following table shows the difference in the analysis of steel before and after recarburizing, and partly illustrates the many grades produced.

Table 29. Showing Chemical Relation of Purified Metal to Different Grades of Steel.

| Kind of Steel | Per Cent. Carbon | Per Cent. Manganese | Per Cent. Sulphur | Per Cent. Phosphorus |
|---|---|---|---|---|
| As Blown... | .03 to .10 | Trace to .06 | .03 to .06 | .08 to .100 |
| Skelp...... | Not over .08 | .30 to .40 | Not over .06 | Not over .100 |
| Sheet Bar.. | " " .10 | .30 to .50 | " " .06 | " " .100 |
| Screw Steel. | " " .08 | .60 to .80 | Not under .085 | " " .100 |
| Special Billet Steel | .25 to .30 | .40 to .50 | Not over .085 | " " .100 |
| Light Splice Bar...... | .08 to .10 | .35 to .60 | " " .06 | " " .100 |
| Rail Steel.. | .30 to .50 | .70 to 1.10 | " " .06 | " " .100 |

Needless to say, the different grades of steel require different methods of recarburizing to meet the requirements, which fact calls for different recarburizers. The various recarburizers and deoxidizers most commonly employed are ferro manganese, spiegel, anthracite coal, ferro-silicon, and pig iron, analyses of representative samples of which are given in the subjoined table.

Table 30. Analyses of Representative Samples of Deoxidizers and Recarburizers.

| | Per Cent. Iron | Per Cent. Carbon | Per Cent. Manganese | Per Cent. Sulphur | Per Cent. Phosphorus | Per Cent. Silicon | Per Cent. Ash |
|---|---|---|---|---|---|---|---|
| Ferro Manganese.. | 11.95 | 6.50 | 80.40 | Trace | .160 | 1.00 | .... |
| Spiegel.......... | 73.20 | 5.00 | 20.40 | " | .100 | 1.10 | .... |
| Ferro-Silicon...... | 86.70 | 2.00 | .50 | .050 | .080 | 10.60 | .... |
| Pig Iron......... | 93.05 | 4.50 | .67 | .047 | .088 | 1.67 | .... |
| Anthracite Coal... | ..... | 85.50* | ..... | .... | .... | ..... | 4.50 |

*Fixed carbon only.

**Loss of Recarburizer and Deoxidizer:** In adding the recarburizers, a loss always takes place, for which an allowance must be made. The amount of this loss is fairly uniform under similar conditions, and is determined by experience. In the case of manganese it amounts to about 20% of the manganese added for full blown heats, in which the per cent. of manganese does not exceed .60. The loss is somewhat less, not over 15%, if the blow is stopped young. The loss varies, also, with the amount of manganese added, increasing rapidly as the per cent. in the steel is raised above .60. Similar data is required in using ferro-silicon and anthracite coal, the loss of carbon in using the latter being about 50% of the total amount added.

**Examples of Recarburizing:** Some simple examples of recarburizing will illustrate the methods employed. 1. Suppose it is required to produce a soft steel, such as the skelp shown in the table above. The metal will be given a full blow to reduce the carbon content to about .04%, and **hot** ferro manganese will be added in sufficient quantity to raise the per cent. of this element to .40. A simple calculation, if proper allowance is made for both residual manganese and manganese lost, will show that this amount of ferro will raise the per cent. of carbon to .08. 2. In the case of a medium soft steel, say .20% to .25% C., .40% to .50% Mn., the recarburization after a full blow may be made with molten spiegel mixture containing about 12% Mn. and 5% C., or, as it is difficult to handle and weigh small amounts of molten metal, coal and ferro-manganese are more often used. In the latter case, the blow may be turned down young. 3. In the case of a rail heat the blow is turned down young, and recarburized with molten spiegel mixture. Molten pig iron and ferro manganese could also be used, but this is not the practice at the Edgar Thomson Bessemer plant. At this plant the cupola charge for the spiegel mixture used to recarburize rail heats consists of spiegel, ferro silicon, and pig iron, in proportion to produce a mixture containing 12% Mn., 4.50% C., and 1.50% Si. For determining the quantity of deoxidizer and recarburizer to add, the blower is provided with a set of factors, one for each grade of steel produced, the numerical values of which are fixed by experience. Thus, for sheet bar the factor giving the amount of 80% ferro manganese to add, is .0045, but for skelp it is .0055 because this steel is blown very full. Similarly, factors for finishing rail steel with spiegel are given.

**Ladle Reaction:** The addition of the recarburizer is usually followed by a violent boiling of the metal in the ladle, causing much slag to be thrown out over the sides. This is often referred to as the spiegel reaction or ladle reaction. With the addition of the recarburizer, precautions will be taken to mix it thoroughly with the metal. At Edgar Thomson this mixing is accomplished in the case of rail heats by using molten spiegel and pouring it into the ladle with the metal from the vessel, and in the case of soft steels by poling the metal in the ladle.

**Teeming:** The history of the heat may now be resumed. Soon after the recarburizer has been added, the pouring of the metal will have been completed. The converter is then inverted, and the slag which did not flow out with the metal is dumped upon a small flat car beneath the vessel, which is then ready for the next charge. While this is going on, the steel has become quieter in the ladle and has been raised to the proper level by the steel crane, which then transfers it to the teeming table in front of the pouring platform. Here the teeming hole in the bottom of the ladle is opened by removing the small plate and digging out the sand, when the metal may be allowed to flow at will by raising and lowering the stopper lever. The metal is now teemed, consecutively, into four ingot moulds, which have been prepared as previously described. As each mould is filled to the mark, the next is moved under the nozzle by means of the "dog," hydraulically operated and provided for the purpose. During the teeming of each ingot of soft or medium soft steel, small pieces, about four ounces in all, of aluminum may be added, as the judgment of the teemer directs, to assist in further deoxidizing the steel. This metal will always be added if the steel is very wild, which condition is often found in soft steel made by this process. After all the steel has been teemed into the moulds, the little train is pushed along the track to the end of the teeming platform, where the ingots are allowed to cool. If the ingots show a tendency to grow in the moulds, the tops may be sprayed with water, and heavy caps of cold iron will be placed on them. This treatment is intended to chill the top and stop the growing, which invariably increases the number and size of the blow holes and pipe in the top of the ingot. Growing is peculiar to soft steels; rail heats seldom exhibit this tendency. When the ingots have cooled sufficiently to form a thick, strong shell on the outside, they are taken to the stripper, where the moulds are at once removed. This done, they are ready for the soaking pits, which are more properly treated under rolling mills.

**Sampling the Steel for Chemical Analyses:** A sample for chemical analysis is taken during the teeming of each heat. This matter is of much importance, and has received the attention it deserves. The sample is obtained when half of the ladle of steel has been teemed by holding a large steel spoon beneath the nozzle and allowing a small stream of the metal to flow therein until the spoon is full. This metal is then poured from the spoon into a specially constructed mould where it is allowed to cool or set, after which it is stamped with the heat number and is then taken to the chemical laboratory for analysis. Everything has been done to insure this sample is truly representative of the whole heat, which is seldom true of samples taken in other ways.

## SECTION VII.

### CHEMISTRY OF THE PROCESS.

**The Order of Elimination of the Elements:** As previously indicated, the heat required for the process is generated by the oxidation of the iron and the metalloids, silicon, manganese, and carbon. An examination of the blow will show that, during the first period, the oxygen of the blast attacks first the iron, then, both directly and indirectly, as will be explained shortly, the silicon and manganese, producing exothermic reactions which rapidly increase the temperature of the bath. The converter gases during this period are mainly nitrogen with some carbon dioxide and traces of oxygen and hydrogen. These reactions produce no flame, since all the products of the oxidation are solids, but with the rise in temperature, carbon begins to be oxidized to carbon monoxide, which will burn at the mouth of the vessel to carbon dioxide and produce a flame outside the vessel. So, the heat generated by combustion of the CO to $CO_2$ is wasted. The rapid generation of CO in the metal produces the "boil," and the increasing speeds at which the formation of this gas takes place causes the flame to grow to a maximum size and finally subside with the elimination of the carbon. The escaping gases during this period consist mainly of nitrogen and carbon-monoxide with small percentages of carbon dioxide and traces of hydrogen. Thus, at no time during the blow, except for a short period at the beginning, does any but traces of the oxygen of the air escape from the bath uncombined, though the layer of metal is but some twenty inches thick, and the volume of the blast is more than 6000 cubic feet per minute. This fact is not surprising, if it is remembered that the temperature of the bath from the first is much above the kindling temperature for any element in the bath, and that the blast is delivered by the tuyeres almost in the form of a spray. Under these conditions, the combination of these elements with oxygen must be almost instantaneous, resulting in all the oxygen being consumed at the mouth of the tuyere. Concerning the brownish fumes ejected by the converter, especially at the beginning of a blow, various suppositions have been advanced to account for them. It has been suggested that they may be volatile compounds of iron and manganese with carbon, which, upon coming in contact with the air at the mouth of the vessel, are immediately oxidized, the metallic oxides producing the brown color. Analysis of deposits made by this fume have been made, and they are found to be composed roughly of one part ferrous oxide, two parts silica and three parts manganese oxide. Manganese is volatile at a comparatively low temperature, which fact may account for a part of the fume, but with respect to iron and silicon or silica, the most plausible explanation is that they are carried out mechanically in a finely divided state by the blast.

**The Laws and Conditions Governing the Reactions in the Converter:** A review of the laws of chemical action and of the conditions of the blow will render an explanation of the changes that take place to bring about the results enumerated above very easily understood. If reference be made to the laws controlling chemical action in Chapter I., it will be found that, under normal conditions of blowing metal, only two are applicable to the matter under consideration. One of these, the law of mass action, states, in effect, that the rate or speed of a chemical reaction may be increased by increasing the active masses, or amounts, of the reacting substances; and the other law says that when chemical reactions take place without the aid of heat supplied from an external source, those substances which have the greatest heats of formation, that is, those that give off the most energy, will tend to form. As to the conditions, these can be very briefly and simply stated. They are, that at the beginning of the blow the bath represents a solution of approximately 4 parts carbon, 1.5 parts silicon, 1 part manganese, .1 part phosphorus and .05 parts sulphur in 93.35 parts iron at a temperature that is several degrees, say 100°, above the fusion point of the mixture; but this temperature is rapidly raised during the first part of the blow. The phosphorus and sulphur are not affected, so they need not be considered, but the elimination of the other impurities presents an interesting study.

**Reactions of the First Period:** Chemical knowledge does not tolerate the idea that these impurities are oxidized by the action of oxygen directly, but indicates that the reactions occurring at the beginning of the blow are governed by the law of mass action. According to this law, iron, by far the most abundant element present, is first oxidized almost to the entire exclusion of the other three elements. This reaction, which liberates a large amount of heat, is represented thus:

$$(1)\ 2\,Fe+O_2=2\,FeO\ \ (+131400\ \text{cal.})$$
$$2\ (65700\ \text{cal.})$$

With the oxidation of the iron to FeO, this oxide, being soluble in the metal, is distributed throughout the bath, and the oxidation of the silicon and manganese take place in the order of the heats of formation of their oxides, as shown in the following reactions:

$$(2)\ 2\,FeO\ +Si=SiO_2+2Fe\quad (+64600\ \text{cal.})$$

Heats of formation:—2(65700 cal.)+(196000 cal.)

$$(3)\ FeO+Mn=MnO+Fe\quad (+25200\ \text{cal.})$$

Heats of formation:—65700 cal. +90900 cal.

With the oxidation of silicon and manganese, a slag is immediately formed by the combination of silica with the excess FeO and the MnO according to the following:

$$(4)\ FeO + SiO_2 = FeO.SiO_2\quad (+9300\ \text{cal.})$$

Heats of formation:—65700 cal.—196000 cal. +271000 cal.

$$(5)\ MnO + SiO_2 = MnO.SiO_2\quad (+5400\ \text{cal.})$$

Heats of formation:—90900 cal.—196000 cal. +292300 cal.

In comparing the ratio of acids to bases as determined by actual analysis with ratios calculated from formulas, evidence is obtained that the slag is made up, in part at least, of trisilicates, in which case these reactions would be represented thus:

(4 A) $2\,FeO+3\,SiO_2=(FeO)_2\cdot(SiO_2)_3$
(5 A) $2\,MnO+3\,SiO_2=(MnO)_2\cdot(SiO_2)_3$

This slag, itself a solution of the two silicates thus formed, will dissolve some of the FeO, and being mixed with metal by the violent agitation of the bath, will also help to oxidize the impurities. Reactions (1) and (4) also account for the rapid wearing away of the bottom. This period is then preeminently one of slag formation. Some carbon, especially toward the end of the period, however, may be oxidized directly to CO and then to $CO_2$ by the FeO, thus:

(6) $2C+O_2=\ 2\,CO$ (+29160 cal.)
29160 cal.

(7) $FeO\ +CO\ =Fe+CO_2$ (+2540 cal.)
—65700 cal.—29160 cal.+97200 cal.

These reactions account for the presence of both $CO_2$ and CO in converter gases during the first part of the blow. At the beginning of the blow, CO is subject to reduction by both silicon and manganese, especially if the iron contains a high per cent. of these elements.

(8) $2\,CO+Si=SiO_2+2C$ (+137680 cal.)
—2(29160) cal.+196000 cal.

(9) $CO\ +Mn=MnO+C$ (+71740 cal.)
—29160 cal.+ 90900 cal.

**Reactions of Second Period:** With the elimination of silicon and manganese, reaction (8) and (9) cannot take place. Furthermore, the rise in temperature brings about reaction (10) or (10A).

(10) $FeO\ +C=Fe+CO$ (—36540 cal.),
—65700 cal. +29160 cal.

(10A) $FeO+Fe_3C=4Fe+CO$ (—45000 cal.)
—65700 cal.—8460 cal. +29160 cal.

These reactions, in conjunction with reaction (6), rapidly burn out the remaining carbon. According to the law involving heats of formation, these reactions should not take place, and it becomes necessary to explain certain apparent exceptions. At ordinary temperatures the law has no exceptions, but at elevated temperatures it holds true through certain ranges of temperature only, so that, as the temperature in any particular case is raised, a point, which may be called the critical temperature, is reached, where the energy supplied from the external source overbalances that absorbed by the reaction. The law then becomes reversed, and the reaction proceeds in a direction that will absorb the excess heat. This fact suggests the possibility that with hot iron, that is, iron high in silicon, which is also initially at a very high temperature, it might be possible to eliminate the carbon before the silicon and manganese could be oxidized, and the testimony of the older and more experienced operators of converters is to the effect that just such a result as this has often occurred when the conditions noted were present. Furthermore, in the elimination of the carbon, the law of mass action here becomes prominent again, for with the elimination of the silicon and manganese the active mass of the ferrous oxide rapidly increases until a second equilibrium is established, this time with carbon. The reaction is also probably influenced by the volatility of the carbon monoxide, one of the products of the reaction. Comparatively little heat is available in the bath during this period. The net heat generated is the difference between the heat of formation of FeO (65700 cal.) and that absorbed in reaction (10) (36540 cal), or 29160 cal. which is the heat of formation for CO. The carbon reaction occurs concurrently with the phenomenon commonly spoken of as the boil. There is, during this period, very little, if any, iron oxidized above that required to eliminate the carbon, so each volume or molecule of oxygen in the blast will produce two volumes or molecules of CO. The converter gases, therefore, show a high content of CO, very little $CO_2$ and a marked decrease in $N_2$. The phosphorus and sulphur suffer no oxidation from the action of FeO until all but traces of carbon is eliminated, and then only in the presence and under the influence of a strong base, such as lime. If the loss in weight in the bath be taken as 10%, then steel made from iron containing .045% sulphur and .089% phosphorus would show approximately .050% sulphur and .100% phosphorus immediately after the blow. These percentages are affected but slightly by the recarburizer.

**Chemistry of Recarburizing and Deoxidizing:** The importance of this part of the operation is more fully appreciated when it is recalled that the Bessemer process was made a commercial success only through deoxidizing with manganese. This element, then, plays a very vital part, the effect in the product most evident being the prevention of that combination of hot and cold shortness commonly spoken of as rottenness. It is due to the presence in the metal of iron oxide, FeO, which is dissolved by molten iron. This oxide is reduced by metallic manganese, thus: (a) $FeO+Mn=MnO+Fe$. As MnO is not soluble in iron to any appreciable extent, reaction (a) will result in ridding the steel of all but traces of metallic oxide. Carbon may act as a deoxidizer, according to some authorities, as shown by reaction (b).

$$\text{(b)}\quad FeO+C=Fe+CO.$$

However, the evolution of CO gas that produces the violent boiling of the metal in the ladle, which boiling often continues also in the ingot mould after the metal has been teemed, is probably caused by CO and other gases passing out of solution in the metal as the latter cools. Small amounts of these gases retained by the steel produce the blow holes previously alluded to. It is to be noted, also, that manganese offsets the evil effects of sulphur as will be explained in a later chapter. The silicon as well as the carbon and manganese in the ferro or spiegel and pig iron will also serve as a deoxidizing agent. Besides, silicon, by attacking CO, prevents the formation of blow holes. For the greatest effectiveness a considerable excess of silicon and manganese over that required by their respective reactions should be used. This is one of the reasons why the manganese in steel will range from .30 to 1.00%. Additional losses of the manganese in the recarburizer are likely to occur by reacting with the silicate of iron oxide, thus:

(c) $FeO \cdot SiO_2 + Mn = MnO \cdot SiO_2 + Fe.$

A study of Bessemer slags shows that a slight decrease of iron oxide without a corresponding increase of MnO takes place on recarburizing. This circumstance is usually explained by assuming that one of the following reactions takes place:

(d) $FeO + C = Fe + CO$ or
(e) $2FeOSiO_2 + CO = FeO \cdot (SiO_2)_2 + CO_2 + Fe.$

As was pointed out under the head of teeming, other deoxidizing agents may be added to the ingot as the metal is being teemed. The one most commonly employed is aluminum. This element is one of the most powerful deoxidizers known. Upon being heated to a sufficiently high temperature it will react violently with all the metallic oxides, and also many others.

(f) $3\,FeO + 2Al = Al_2O_3 + 3Fe.$

Various alloys are beginning to be used for this purpose, also. One of the best is known as "A. M. S." metal; it is an alloy of aluminum, manganese and silicon, and is said to be very efficient for this purpose.

# CHAPTER VIII.

# THE BASIC OPEN HEARTH PROCESS.

## SECTION I.

### SOME GENERAL FEATURES OF THE SIEMENS PROCESS.

**Early History of the Process:** The ever increasing demand for steel, which even the phenomenal success of Bessemer was not able to meet entirely, soon led many other inventors into the same field. But the only process which was destined to become a rival of the Bessemer was developed through the invention of the regenerative principle by that prolific inventor, William Siemens. In this connection it may be of interest to note that Siemens first developed and employed this principle in the construction of steam engines, but while several of these engines were built and put into use, they were finally abandoned because of the severe wear on the heating chambers caused by the high temperature attainable. But it was shown that a great saving of fuel and very high temperatures could be obtained by the use of the principle, and at the suggestion of his brother, Frederick, Siemens then turned his attention to the application of the principle for producing high temperatures in furnaces. The first experimental furnace was built in 1858, when it was developed that, with large furnaces especially, many difficulties were to be overcome, if the full efficiency which the use of the principle promised was to be obtained. After two years or more of experimentation, Siemens fell upon the plan of gasifying the fuel prior to burning it in the furnace, when he found that most of his difficulties had been overcome. The first furnace burning gaseous fuel, patented in 1861, was used for making glass. Here, the great advantages of the furnace in economy and regularity of working were fully proven, and it was not long until it was adopted in other industries, also. Some of these early uses of the furnace were for zinc distillation, for puddling, for reheating iron and steel, and for melting crucible steel. Siemens then turned his attention to the manufacture of steel in his furnace, and, though many trials were made at many different works, he met with only indifferent success. Finally, like Bessemer, he found it necessary to erect a steel works of his own in which the success of the process could be demonstrated. These works were located at Birmingham, England, and were at first employed in a remelting process by which steel of the best quality was obtained from such scrap as old iron rails, plates, etc. In the meantime, Siemens was busy developing an idea of decarbonizing pig iron for making steel by means of iron ore, and by the year 1868 he had proved that this process could be successfully employed. Siemens next turned his attention to evolving a method whereby steel could be produced directly from the ore, thus dispensing with the blast furnace. In this feat he actually succeeded, but the cost of production was many times that of producing steel from pig iron. Nevertheless, he continued his experiments until his untimely death in 1883 put an end to his endeavors. He died firmly believing that his direct process would eventually supplant all conversion methods. Subsequent endeavors have shown this idea is wrong, and that his pig and ore process is the most practicable and economical.

**Principles of Siemens Pig and Ore Process:** Briefly, the method of Siemens was as follows: He used a rectangular covered furnace to contain the charge of pig iron or pig iron and scrap, and provided most of the heat for the chemical reactions by passing burning gas over the top of the materials. The gas, with a quantity of air more than sufficient to burn it, was introduced through ports at each end of the furnace, alternately at one end and the other. The gaseous products of combustion passed out of the port, temporarily not used for entrance of gas, into chambers partly filled with checker brick, which absorbed some of their sensible heat, and from these chambers out through a stack. After a short time, the gas and air were shut off at the one end and introduced through the heated checker chambers at the opposite end, absorbing some of the heat stored in the bricks. These gases then entered the furnace with a high sensible heat and gave a higher temperature in combustion than could be obtained without preheating. In about twenty minutes, the course of the gas and air was reversed, so that they entered through the port first used; and a series of such reversals, occurring every fifteen to twenty minutes, was continued until the oxidation had reached the desired point. The elements in the iron attacked by the oxygen of the air and of the iron ore fed in were carbon, silicon and manganese, all three of which could be reduced to as low a limit as in the Bessemer process. Thus, as in all the other processes for purifying pig iron, the basic principle of Siemens process was that of oxidation. But in other respects it was unlike any other process. True, it resembled the puddling process in both the method and the agencies employed, but the high temperature attainable in his furnace permitted him to secure in the liquid state a perfectly malleable metal which could be cast into ingots and be free of slag. In this respect the same result was produced as in the Bessemer process, but by a different method and through different agencies, both of which imparted to it many advantages over the older pneumatic process.

**Advantages of the Process:** These advantages may be briefly summed up as follows: 1. By the use of ore as an oxidizing agent and by the external application of heat, the temperature of the bath is made independent of the purifying reactions, and the elimination of the impurities can be made to take place gradually, so that both the temperature and the composition of the bath are under much better control than in the

Bessemer process. 2. For the same reasons, a greater variety of raw materials can be used and a greater variety of products can be produced by this than by the Bessemer process. 3. A very important advantage is due to the increased output of finished steel from the same amount of pig iron, which means that fewer blast furnaces are required to produce a given tonnage of steel. 4. Finally, with the development of the basic process, the greatest advantage of the Siemens over the Bessemer was revealed through the elimination of phosphorus. Comparing the basic open hearth with the Thomas-Gilchrist process it is to be noted that, due to the different temperature conditions, phosphorus is eliminated in the former before the carbon, whereas it is not oxidized in the latter process until after the carbon, in what is known as the after-blow. Hence, while the basic Bessemer process requires a pig iron with a phosphorus content of 2.00% or more in order to maintain the temperature high enough for the after-blow, the basic open hearth permits the use of iron of any phosphorus content. In the United States this fact is of the greatest importance, since, for reasons already explained, it makes available immense ore deposits which could not otherwise be utilized. For this reason the basic open hearth process has become the leading method in this country.

**Mechanical Changes and Improvements in Siemens Process:** As would be expected, many variations of the process, both mechanical and metallurgical, have been worked out since Siemens first put his method into operation. Along mechanical lines various improvements in the design, the size and the arrangement of the parts of the furnace have been made. Originally, the furnace had a capacity of only four or five tons, but now the size ranges from 40 to 100 tons capacity, and in new plants the capacity will seldom be less than 75 tons. But the greatest departure from Siemens' original plan was made by the invention of the tilting or rolling furnace. These furnaces are of two types, and are known as the Campbell and the Wellman furnaces, respectively. In each case the furnace is built of brick, which are held firmly in place by a strong framework of steel, and is mounted upon rollers or rockers, thus permitting it to be tilted either forward or backward. In the Wellman type the hearth and ports are built solid, so that both move together; and as tilting the furnace breaks the connections with the regenerator flues, the furnace can be fired only when in an upright position. This fault is overcome in Campbell's invention, in which the hearth only is movable, and the center of rotation is coincident with the center line of the ports. By the use of water cooled castings, fairly tight joints are made between the hearth and the flues, so that the furnace may be tilted in either direction, forward or backward, without turning off the gas and air.

**Metallurgical Improvements:** The hearth of Siemens' furnace was of acid brick construction, and the bottom was made up of sand—essentially as in the **acid process** of today. Later on, in order to permit the charging of limestone for the removal of phosphorus, the hearth was constructed with a lining of magnesite brick, which were covered with a layer of burned dolomite or magnesite to replace the sand of the acid furnace. These furnaces were, therefore, designated as **basic** furnaces. **The pig and scrap process** was originated by the Martin Brothers. By substituting scrap for the ore in Siemens' **pig and ore process** they found it was possible so to dilute the charge with steel scrap that little oxidation was necessary. Since the time of the Martins, these processes have undergone various modifications, chief of which are those known as the Talbot, the Campbell, the Bertrand-Thiel, and the Monell processes. By using a basic lined tilting furnace in which a large bath of the purified molten metal is always retained, Talbot succeeded in hastening the oxidation of the silicon, manganese, phosphorus and carbon to such an extent that the operation is made more nearly continuous, and the time between heats or tappings is greatly reduced. Campbell's tilting furnace permits him to apply the pig-and-ore process to molten metal, because, by tilting the furnace forward, the frothing of the bath, produced by the violent reactions, is prevented from throwing the slag through the doors as would be the case in a stationary furnace. By a combination process, he also aims to make acid steel from basic pig iron. In a basic lined furnace he eliminates the silicon, manganese, phosphorus and a little of the carbon, then pours this semi-purified metal into an acid furnace, where the remainder of the carbon is worked down as in the regular acid process. The Bertrand-Thiel process is applied to pig iron with a very high phosphorus content, and makes use of the two-period scheme of purification, also. In the first period, the furnace is tapped in order to separate the metal from the slag, which contains such a high percentage of phosphoric acid, $P_2O_5$, that it is valuable as a fertilizer. The metal is then poured either back into the same furnace or into another basic furnace for the final purification. In developing his process, Monell had the same objects in mind as Talbot, namely, the rapid conversion of basic iron into steel; but he wished to avoid the reservoir of molten metal, and make his process adaptable to the stationary furnace. He accomplished his object by first charging limestone and ore into a basic furnace, heating these until the batch became pasty, then adding molten pig iron, when the silicon, manganese, and phosphorus were rapidly oxidized and, with the lime, formed a slag that, as the carbon began to be oxidized, foamed up and ran from the furnace through slag notches provided for the purpose.

**The Process for the Pittsburgh District:** Most of the pig iron available in the Pittsburgh district contains a fairly high percentage of phosphorus, and the mills produce considerable scrap. Hence, the furnaces are practically all basic—the Carnegie Steel Company no longer operates any acid open hearth furnaces—and a combination of the pig-and-ore, pig-and-scrap, and Monell processes is employed. It has been briefly described as follows: Limestone is charged on a basic bottom, ore is charged on top of the stone, and scrap on top of this; if molten pig iron cannot be obtained in sufficient quantity to complete the charge, some cold pig is charged with the scrap; and the entire mass is heated in the furnace for about two hours, or until the scrap is white hot and slightly fused. Molten pig iron is then added, when a lively reaction occurs, in which almost all of the silicon, manganese, phosphorus and part of the carbon are oxidized, the first three forming compounds that slag with the iron oxide, and join the iron and lime silicates that are already melted. About 80% of this slag is drawn off by the end of two or three hours more. The ore acts on the carbon for three or four hours longer, during which time, and continuing afterwards, the limestone is being decomposed by the heat, and its $CO_2$ is bubbling up through the bath and exposing part of the metal to the flame, thus oxidizing it and completing the purification started by the ore reaction. What is known as the lime action, or boil, lasts two or three hours longer; and then, if the charge was calculated correctly, the carbon content will be somewhat greater than that at which the metal is to be tapped. Ordinarily, of course, the carbon is too low or too high, in which cases more pig or more ore must be added. In about another hour the carbon content will have been reduced to the proper amount for tapping, which is usually about .10%.

## SECTION II.

### EQUIPMENT FOR A MODERN BASIC OPEN HEARTH PLANT.

**The Modern Plant:** Besides the furnaces themselves, the modern open hearth plant requires considerable additional equipment. Thus, there must be provided ladles for containing molten metal; moulds for ingots; cranes and charging machines for handling materials; boxes for the solid materials; dinkeys or electric-engines for hauling the materials; a stripper for removing the moulds from the ingots; a great number of small articles, like shovels, wheel barrows, rabbles, etc.; and, finally, apparatus for preparing or controlling the fuel supply. In addition the more modern plants will be provided with a mixer, a calcining plant, and also spiegel-cupolas, if liquid recarburizers are used. A brief description of the more essential items enumerated above is given herewith.

**Calcining Plant:** At most of the plants there are cupolas for roasting dolomite. These furnaces are cylindrical in form, and each one is so placed that one base forms the bottom, the other the open top of the furnace. In the usual construction the cupola is made up of an outer shell of boiler plate, one-half inch thick, and a double refractory lining made of two courses of brick, the inner one being of first quality and the outer one next to the shell of second quality fire brick. On the floor of the furnace, there is a cone shaped casting which deflects the burnt dolomite, in its descent, toward the circumference, where it may pass out through openings provided for the purpose in the base of the cupola. For fuel, coke is employed, and it must be burned by an air blast. This blast is supplied at a pressure of five to six ounces. A bustle pipe distributes the air and is provided with about eight tuyeres, or connections, with the cupola. Built on the charging platform and extending about three feet above it, there is a seat upon which the charging bucket is deposited by a crane and from which its contents, through a bell and hopper arrangement in the bottom of the bucket, may be dropped into the cupola. Usually the ratio of materials in the charge is two buckets of dolomite to one bucket of coke. Thus, the fuel consumption is about 15% of the weight of dolomite calcined. The operation of burning, in which the $CO_2$ is expelled from the stone, leaving calcium and magnesium oxides ($CaO$ and $MgO$) in place of their carbonates ($CaCO_3$ and $MgCO_3$), requires from ten to twelve hours. The burning period is controlled by the rate at which this material is withdrawn. As fast as the dolomite is burned it is shoveled out at the bottom, crushed to pass a half-inch mesh, then conveyed to the loading bins, whence it is later taken as required to the open hearth.

**Fuels:** For fuels in open hearths, natural gas, coke oven gas, producer gas, powdered coal, fuel oil and, sometimes, tar are used. The choice of fuel depends largely upon the location of the plant. Natural gas is, of course, preferable when it can be obtained, as it is of uniform composition, is easily controlled and imparts no sulphur to the bath, while coke oven gas, producer gas and powered coal are of varying composition and quality and may impart some sulphur to the bath. The great demand for petroleum products has made fuel oil too costly, while the supply of tar is so limited that it is not always available as an open hearth fuel. There remains, then, as the principle substitutes for natural gas, only powdered coal, coke oven gas and producer gas, all of which have already been discussed in the chapter on fuels. (See Chapter IV., Section 6). In either case, coal of the best grade obtainable is desired, especially with respect to sulphur, as there is always danger of its being absorbed by the bath. In using coke oven gas from which the benzol has been removed, it is found necessary to burn with it some substance like tar, for example, that will impart luminosity to the flame, as otherwise the poor visibility within the furnace makes it difficult for the melter to control the temperature. In the new plants of the Carnegie Steel Company, the producers are connected in sets of four—five in one or two cases— and each set serves two furnaces, the gas mains from the producers being arranged so that any one or all of the producers in a set may discharge into either one or both of the furnaces.

**Fuel Consumption:** It is a difficult matter to arrive at any conclusion as to the amount of heat required to produce a ton of steel. It is subject to a number of conditions such as kind of fuel used, condition of the furnace and checkers, continuity and rate of production, and the care and intelligence with which the furnace is operated. In actual practice the number of heat units per ton of steel produced is found to vary from 5,000,000 B. t. u. to 6,000,000 B. t. u. when natural gas is used, and from 6,000,000 B.t.u. to 8,500,000 B.t.u. when other fuels are employed. An inspection of the fuel records of several different plants and a consideration of averages for long periods of time, varying from six months to a year, indicate that the fuel consumption per gross ton of steel produced, to be considered good practice, should be about as follows: natural gas, 5,000 cubic feet; coke oven gas, 8,000 cubic feet, with 16 gallons of tar; tar alone, 45 gallons; producer gas equivalent to 600 pounds of coal; and powered coal, 500 pounds.

**Hot Metal Mixer:** The advantages of the hot metal mixer have already been discussed in connection with the Bessemer process; and although the conditions in the open hearth plant, where large quantities of metal are needed at irregular and uncertain intervals of time, are exactly the reverse of those in a Bessemer plant, which requires small quantities of metal at short and comparatively regular intervals, these advantages are as applicable to the one case as to the other. In order that these advantages may be realized to the fullest, open hearth mixers should have a large capacity. One large mixer of 1000 or 1200 tons capacity is to be preferred to two of 500 tons capacity.

**Spiegel Cupolas:** In plants manufacturing large quantities of medium high carbon, high manganese steels, such as is used for railroad rails, for example, the use of spiegel for recarburizing may be advantageous, in which case cupolas for melting the spiegel mixtures are an important adjunct to the open hearth plant. In construction and operation, these cupolas are similar to those already described for the Bessemer plant. For collecting and weighing the different ingredients of the charge, a larry car equipped with a multiple beam scale is most convenient. In charging, the metallic parts of the burden, consisting usually of spiegel and pig iron, are charged into the cupola together, while the coke, with which is mixed enough limestone to flux its ash, is charged separately. The proportion of coke required in each round will vary somewhat, but in good practice it will seldom exceed seven per cent. of the weight of the metallic part of the charge. To secure greater uniformity and provide an ever-ready supply of molten recarburizer, the cupolas attached to the most modern plants are provided with a small mixer. By means of brick and clay lined runners the metal from the tap hole of each cupola is conducted directly into this mixer, from which definite amounts may be taken as desired. For weighing the recarburizing metal, a track scale, on which the transfer ladle may rest during the pouring, is placed on the track directly in front of the mixer. The manganese content of the molten recarburizer is varied to suit the requirements of the different grades of steel by varying the amount of pig iron with which the standard spiegel is diluted. Varying the proportion of pig iron to spiegel also changes the carbon content of the mixture slightly. With a given weight of standard spiegel, the more pig iron charged the lower the carbon content of the mixture will be, as can readily be seen by comparing the analyses of these materials.

**The Steel Ladles:** The ladle for receiving the steel is made of boiler plate and is lined with two courses of brick each 2½ inches thick. The first layer, next to the shell, is usually of fire brick, while the second layer is of white river brick. Both courses are laid on end in a motar of fire clay, to which a little loam is sometimes added. The capacity of the vessel is dependent on the amount of steel to be handled in each heat, which in turn is fixed by the capacity of the open hearth. The opening at the bottom of the ladle is provided with a fireclay nozzle about two inches in diameter, which may be closed by a stopper. The stopper is made of [clay bonded graphite and is mounted on a rod, protected by fireclay sleeve brick, that reaches to the top of the ladle; there it is connected to a sliding bar on the outside that can be raised or lowered by a lever near the base. Both the stopper and the nozzle must be replaced after each heat. Great care is necessary both in placing the nozzle and in setting the stopper in the nozzle, for a bad fit results in a running stopper, which may cause a great waste of metal. To prevent the steel from chilling about the stopper, powdered coal is often thrown into the depression around the nozzle just before tapping a heat.

**The Stripper:** The action of this machine has already been described in connection with the Bessemer process. The ingots must all be sufficiently cooled before stripping, so that there will be no danger of breaking the solidified wall of metal. After being stripped, the ingots are then ready to be sent to the soaking pits previous to the rolling. To strip an ingot, it is only necessary, in the majority of cases, to place the jaws of the stripping machine under the lugs on the mould and apply the lifting force, when the mould will slip from the ingot and can then be raised to a sufficient height to transfer. It is only at times, usually due to a defective mould or to metal being splashed over the top edges from a running stopper, that the moulds are not slipped off easily, and then the plunger is rested on top of the ingot as the mould is drawn upward. When this treatment fails to loosen an ingot, it is sent to the mould yard where more time is available for extracting it and where it may be subjected to various treatments according to the means at hand and the cause of its sticking.

**Moulds:** After the ingots of each heat are stripped the empty moulds are stored in the mould yard until they are sufficiently cool to be drawn back to the open hearth for another charge, and during the wait they are washed inside with clay slurry, the water of which is quickly evaporated by the heat of the mould, leaving it covered with a thin coating of the clay. Any damaged moulds that cannot be used are charged as cold iron, as they are cast from a good grade of Bessemer pig iron. Many types and sizes of moulds are used. Heavy moulds chill the surface of the steel quickly and hasten the solidification, which always proceeds from the wall of the mould toward the middle of the ingot. Since steel contracts on solidifying, there is a cavity left directly under the top surface of the ingot, as the metal in this location is the last to solidify. This cavity, called the **pipe**, is responsible for the production of a great deal of scrap in rolling the steel. There are numerous methods to reduce the size of the pipe and to keep it as near the top as possible, but it cannot be entirely eliminated. The principle of most of the devices is to keep the top of the ingot molten longer than the bottom, so that the molten steel on top will flow into the cavity as fast as it forms and thus lessen the extent of the pipe. The Gathman type of mould depends upon uneven thickness of mould wall to effect the same result. By having the mould thin at the top and thick at the bottom, the thin top has a less chilling effect on the molten steel at the top, which, therefore, is the last to solidify. A similar method consists in lining a removable top of the mould with brick or clay, thus preventing rapid conduction and radiation. Some try to keep the steel at the top of the ingot fluid by a coke, a charcoal or a gas fire. Many other more complicated devices have been invented, also, but their use involves much additional expense. Besides, piping is regarded by many as a necessary evil, and the safest way to avoid it is to allow a proper discard from the top of the ingot, which discard is cut off at the blooming mill shears. Armor plate ingots are sometimes cast in specially constructed hard sand moulds. Ingots for this material are always bottom cast, two ladles being poured at the same time, which are followed frequently by a third, pouring directly into the mould. There are standard sinkheads for all armor plate ingots.

**The Charging Machine:** Of all the labor saving devices employed about the open hearth plant, none have brought a greater saving of money and time than the charging machine. Indeed, it may be looked upon as the most essential part of the equipment, for if the charging were done by hand, the time thus lost, especially in the case of the large furnaces, would be so great that this feature would appear as a serious drawback to the process. There are several types of these machines, but the ones most generally employed are of the low ground type. They consist of two main parts. First, there is the bottom truck made up of a very strong steel frame-work and mounted on flanged wheels which travel on a very wide gage track laid in front of the furnace. Next, there is the charging carriage, which moves over a track, laid on the frame of the truck, at right angles to the direction of motion of the truck itself. On this carriage is mounted a kind of lever, the long arm of which extends toward the furnace and is known as the charging bar. The charging bar is hollow to provide space and bearings for the locking bar, about which it can be made to revolve, and is shaped on the end to fit into the socket of the charging box. The charging bar is thus capable of giving eight different primary motions, or any number of resultants of these motions. In operating the machine, the charging boxes rest on buggies running on a narrow gage track between the machine and the furnace. First, the truck of the machine is moved so that the charging bar is directly opposite the charging box to be emptied, then the carriage is moved forward to bring into position the end of the charging bar, which is then dropped into the socket on the end of the charging box and locked in position by advancing the locking bar until its front end projects into a hole provided for the purpose in the socket of the box. Now, the machine is made to serve for a shifting engine, and, by moving the truck, the whole train of charging boxes may be moved along in front of the furnace, so that the box engaged is brought directly opposite the door. The charging bar is then raised, carrying the box with it, and by a forward motion of the carriage the box is passed into the furnace, where, by rotating the charging bar, the box is turned upside down and its contents deposited. By reversing these motions the box is then placed upon the buggy again. The charger will pick up and empty a box in less than a minute. As the capacity of the box is more than one ton, for even the lightest materials of the charge, it is possible to charge even the very large furnaces in less than an hour. Charging machines are always electrically operated.

**Charging Boxes:** The charging boxes are made of cast steel or of five-eighth inch boiler plate with cast steel ends. One end of the box is provided with a socket opening from the top so that the T section on the end of the charging machine peel, or arm, may readily be inserted and withdrawn from it. The boxes have a capacity of sixteen cubic feet or more, and into them all solid material for the furnace charge is placed. For transporting the boxes from place to place about the works, buggies are provided. These buggies are of standard or narrow gage type, are made of cast iron and accommodate three to four boxes each.

**Stock Yard:** There is usually one stock yard to each plant. In it are kept the stores of limestone, ore, cold pig and, sometimes, scrap, from which materials the cold charges for the furnaces are made up. The ore and limestone are loaded into the boxes from chutes or by grab buckets, depending upon the manner of storing; the cold pig from railroad cars or from a stock pile by means of a magnet; while the scrap is brought from the rolling mills ready loaded in the charging boxes, or if it is delivered in railroad cars, it is transferred to them by magnets. Soft ore is generally used to make up a charge on account of its lower cost, because there is no advantage in charging lump ore on the bottom, and it is not necessary to have as pure an ore as is the lump ore. After a charge is made up, the buggies are pushed over platform scales and weighed by the weighmaster, who records the weights in a stock book. The stockyard men take into account the amount of pig iron to be used and, to a certain extent, the carbon contents of the scrap charged and add to the charge what ore they think will be necessary. Reports giving the weights of all materials are made out in triplicate, one of which is sent to the melter, so that after it reaches the furnace front the melter-foreman or his first helper may vary the ore charge to suit their plans or ideas.

**Arrangement of the Plant:** The furnaces of the plant are always enclosed and covered by an immense steel building, and in the modern plant the furnaces are arranged end to end in a long row along the center of this building. That part of the floor of the building along the front, or charging side, of the furnace is called the charging floor. On this floor and next to the furnaces is laid a narrow gage track on which the solid materials are conveyed to the furnace for charging, while, back of the narrow gage track, there extends a very wide gage track, with a spread of about

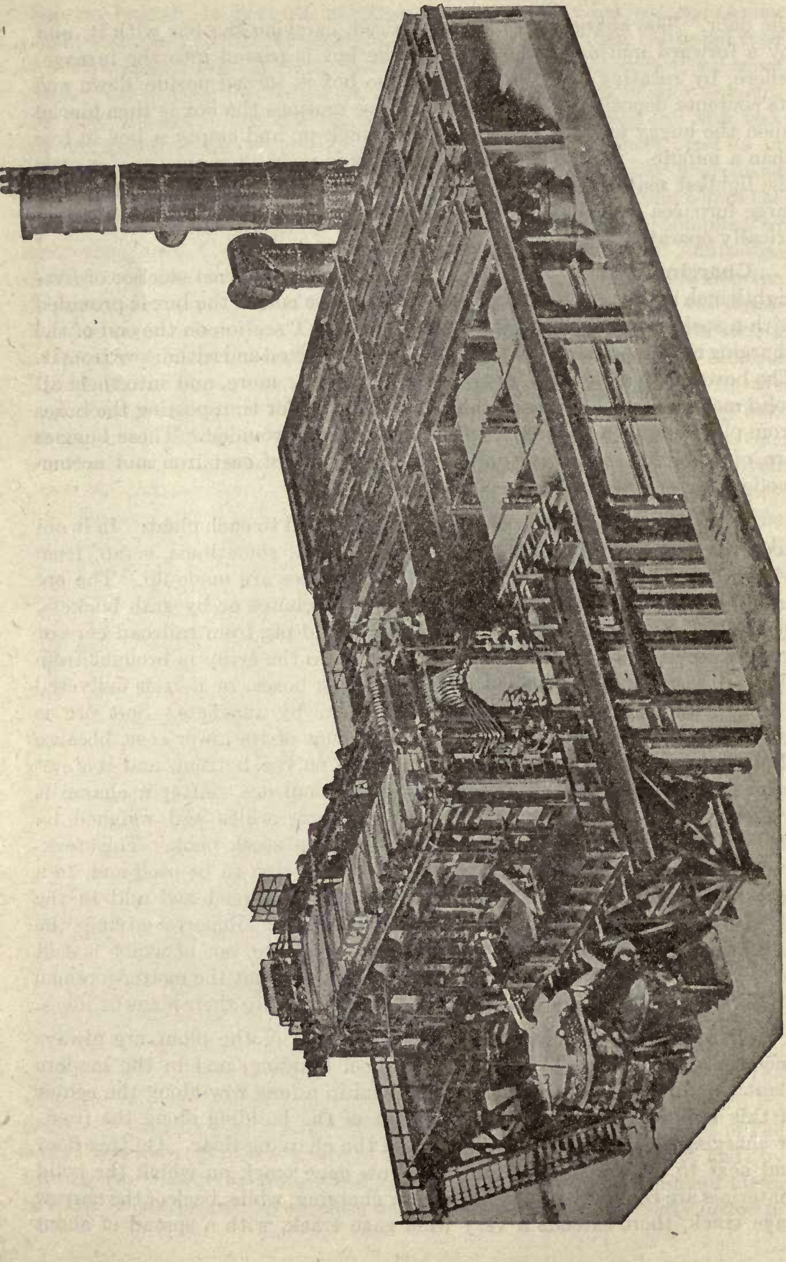


FIG. 25. Model of 100-Ton Producer Gas Fired Open Hearth Furnace. View from Tapping Side.

twenty feet, for the charging machines. The space above this floor and the furnaces is spanned by two or more electric overhead cranes. The remaining floor space of the building lying along the tapping side of the furnace is called the pouring floor, and is also spanned by electric cranes. These two floors may be on the same level, as in some of the older plants; but all the new plants are of the **two-level** type, that is, the pouring floor lies some twelve to eighteen feet below the level of the charging floor. The pouring platforms, six to eight feet wide and about eight feet high, are located along the outer edge of the pouring floor. The mixer and cupolas are often located at one end of the open hearth building, as this arrangement permits the transfer of the hot metal to be made with the cranes. However, in large plants this arrangement would be inconvenient, as it would interfere with the work of the cranes, so the hot metal is carried to the different furnaces on a track laid on the charging floor. With this arrangement the mixer may be located at any convenient point. When producer gas is used for fuel, the producer plant is built back of the open hearth plant, parallel to the charging floor. The calcining plant, stock yard, and mould yard are located at points as convenient to the open hearth house as possible. The stripper should be placed so that the steel is always advancing toward the soaking pits of the blooming mill, though this matter is but a question of convenience.

## SECTION III.

### CHIEF FEATURES OF BASIC OPEN HEARTH CONSTRUCTION.

**Parts of the Open Hearth Furnace and Their Arrangement:** An open hearth furnace consists of the furnace proper, containing the covered laboratory, hearth or bath, in which the charge is placed; ports for admitting the gas and air over the charge; regenerative chambers, containing checker brick for storing up heat from the products of combustion and imparting it to the cold gas and air; flues and uptakes, connecting the checker chambers with the furnace proper; slag pockets, which are located at the base of the uptakes; flues, leading from the air and gas supply (if producer gas is used) to the checker chambers, with connections to the stack; valves for regulating the direction of flow of gas, air and waste gases; and the stack itself. The furnace proper is located on the level of the charging floor and rests on a concrete foundation. The slag pockets, checker chambers, flues and valves are all located in a cellar, on a level about fifteen feet below the charging floor in houses of the one level type, or on the first floor level in the two level type. The checker chambers are not located under the furnace proper but under the charging floor in front of it, and the stack is placed a short distance beyond nearer the gas producers. The base of the stack flue sets on a level with the bottom of the checker chambers, but the stack proper begins at the charging floor level.

**The Furnace Proper:** The furnace, itself, is a rectangular brick structure, supported on the sides and ends by vertical steel buck-stays in the form of channels or slabs, four to five and one half inches thick and eleven inches wide, and bound together at their tops, both longitudinally and crosswise, by stays and tie rods. The most recently constructed furnaces have a capacity rated at 100 tons. Such a furnace is approximately eighty feet in length and twenty feet in width, outside dimensions over all. Ten sets of buck-stays on the front and rear sides, and four or six sets on the ends are required to furnish the requisite support against expansion of the brick work. The buck-stays are held in place by 12-inch channels placed at their tops. These channels extend entirely around the furnace, those along the sides being securely tied with bolts and clamps to those crossing the ends of the furnace. The front and rear buck-stays are united by tie-rods which are two and one-half inch steel rounds; the ends of these extend through the buck-stays and are threaded to receive nuts to hold them in place so that they can be tightened and loosened according to the expansion and contraction of the furnace. The foundation under the furnace proper is built of concrete, and is of such depth and shape as to bear the superimposed load with reasonable safety. It is usually in the form of two large piers, with an arched opening separating them. The furnace proper comprises the hearth, the side walls, and the roof.

**The Hearth** is constructed as follows: On top of the concrete foundation is placed a layer of three feet or more of second quality fire brick, and upon these is laid a two foot layer of first quality fire brick in which a number of 15 inch I-beams are placed to act as a bottom anchorage for the vertical buck-stays which surround the furnace; a nine inch layer of magnesite brick is then laid on top of the firebrick, and upon these bricks, a bottom is made up approximately ten and one-half inches thick with a mixture of burned magnesite, 75%, and ground basic slag, 25%, which is sintered into place. Dolomite may be substituted for the magnesite, but in this case the bottom must be much thicker than when magnesite is used. When complete, the hearth has the form of a shallow dish whose sides extend up to the level of the charging doors. In order to obtain this shape the succeeding courses of magnesite brick are stepped back, until the normal thickness of side wall, about thirteen and one-half inches, is reached. The exact hearth dimensions, inside, between fifteen and sixteen feet in width and about forty feet in length, are dependent upon the desired maximum capacity of the furnace and incidental features. The depth is such that the bath of molten metal will be from twenty to twenty-four inches deep The back wall of the hearth is pierced at its exact center for the **tapping hole,** which is about eight inches in diameter and is provided on the outside with a removable cast iron lip for receiving the end of the **steel spout,** the function of which is to conduct the molten steel from the furnace to the steel ladle at the time of tapping. The **slag hole** is placed about fifteen feet from the tap hole and near the upper edge of the hearth. It is surrounded with magnesite brick and is provided with an iron casting at its base for the attachment of the cinder spout.

**The Walls** are begun on the top course of magnesite brick that surrounds the upper edge, or brim, of the hearth. They are built of silica brick, are about thirteen and one-half inches thick and extend to a distance of about eight feet above the charging floor level. The back wall is built up solid except for the tapping hole and slag hole, but the front wall contains the arched doorways for charging. The doors are usually five in number, the middle one being in the middle of the furnace, and are so placed that their bases, or sills, are a few inches above the slag line. Each opening is provided usually with a water cooled cast steel frame, placed between two buck-stays to which it is fastened, and is closed by a water cooled, fire brick lined cast iron or steel door that may be lifted vertically either by hydraulic or electric power. A wicket, or peep hole, is placed on the center line near the bottom of each door.

**The Roof** over the hearth is made of silica brick, about twelve inches thick, and is arched from front to back only in the newer furnaces, but sometimes, also from end to end in older types. The roof is built independent of the walls, and rests on **skew back brick** set in water cooled skew back channels that are riveted or bolted to the buck-stays of the furnace.

**The Bulk Heads** which form the ends of the hearth below the ports were originally built of solid brick work and were a source of much trouble, as they burned out rapidly. These difficulties were all avoided by replacing much of this brick work with a large, hollow cast steel box with open ends to provide for air cooling. The inside surfaces of the bulk heads are made of magnesite brick.

**The Ports:** The air and gas ports at each end of the furnace are built at an angle to the bath, so that the flame is directed against the bath and away from the roof. In order to protect the roof and promote the mixing of the gas and air, the air enters above the gas. The bricks separating the two ports are protected by a water cooling system. Where natural gas is used, unless the furnace was constructed for producer gas, there is but one port at each end of the furnace, the gas entering on each side of either end of the furnace behind a bridge wall, which extends across the furnace in front of the well, or up-take, from the checkers. This wall is usually made of magnesite brick, though chrome brick is well suited for the purpose, and is about thirteen and one-half inches thick and nine inches high.

**The Up-and-Down-Takes** are the vertical flues which connect the air and gas ports with the **slag pockets** and the fan-like flues leading to their respective checker chambers. They are built of silica brick and are not water cooled. In producer gas fired furnaces there is a pair of up-and-down-takes for air at each end of the furnace, the two in each pair being at opposite sides of the furnace. The up-and-down-takes for the gas rise with their centers coincident with the center line of the furnace and may stand out with three walls exposed, designated as the **dog-box type,** or be built in between the air flues. For a 100-ton producer gas fired furnace these flues are each four feet by three feet, inside dimensions.

**Arrangement of Up-and-Down-Takes for Natural Gas, Coke Oven Gas, Powdered Coal and Tar:** The construction of the up-and-down-takes in a natural gas fired furnace is much simpler, as it is only necessary to have one up-take for the air at each end of the furnace. This up-take in modern furnaces is circular, with a diameter of about six and one half feet, and is therefore called the **well.** The air, as it rises, is deflected downward toward the bath by the port, which is arched from front to back but is straight, longitudinally, with a downward slope toward the hearth. This roof is usually about nine inches thick, except near the neck where it joins the roof of the furnace. Here it increases to twelve inches on account of this point being subjected to the greatest wear. The bridge wall previously described, which crosses the port adjacent to the up-take, causes the incoming air to roll down past the opening from the gas pipes, one of which enters at each side of the port. Thus, there are in all four pipes to a furnace. These gas pipes have a diameter of four inches. The main supply pipe usually passes over an entire row of furnaces. A branch line, provided with a meter, a valve, and a three way cock, leads to each furnace, where it again branches into the four inch pipes which enter the ports. For tar and powdered coal the same construction as for natural gas has been employed, because, so far, these substances have been used only as a substitute for the latter fuel when the supply became low. Both these substitutes are introduced into the furnace by inserting the nozzles of the burners through small openings in the brick work closing the ends of the furnace, one burner at each end of the furnace being required.

**Slag Pockets:** The slag pockets are chambers at the bottom of the up-and-down-take flues. Their functions are to serve as flues to conduct the gases to and from the checkers and to catch any solid matter carried over with the products of combustion, thereby preventing most of this slag material from reaching the checkers and clogging them up. The pockets are designed large enough so that only in extreme cases do they have to be cleaned out more than once every run. In the 100-ton producer gas fired furnace, they are about three feet six inches wide, and eight feet high. The two at each end of the furnace are separated by a three foot silica brick wall. The outside walls are two feet seven and one half inches thick for the air, and three feet for the gas side; the former have an inside lining of silica brick, set against first quality fire-brick, while the latter is made of silica brick only. The floor and roof are covered inside with silica brick, the latter being arched on a radius of half the width of the pockets. One end of each pocket merges into a short, fan-like flue, called a **neck,** which leads to the top of its regenerator chamber.

**Regenerators for Producer Gas:** The regenerators, of which there are two pairs to a furnace, are built out in front of the furnace and under the charging floor, about half below and half above the casting floor level. They are separated from the furnace by a distance of about four feet. Each pair is made up of one checker chamber for gas and one for

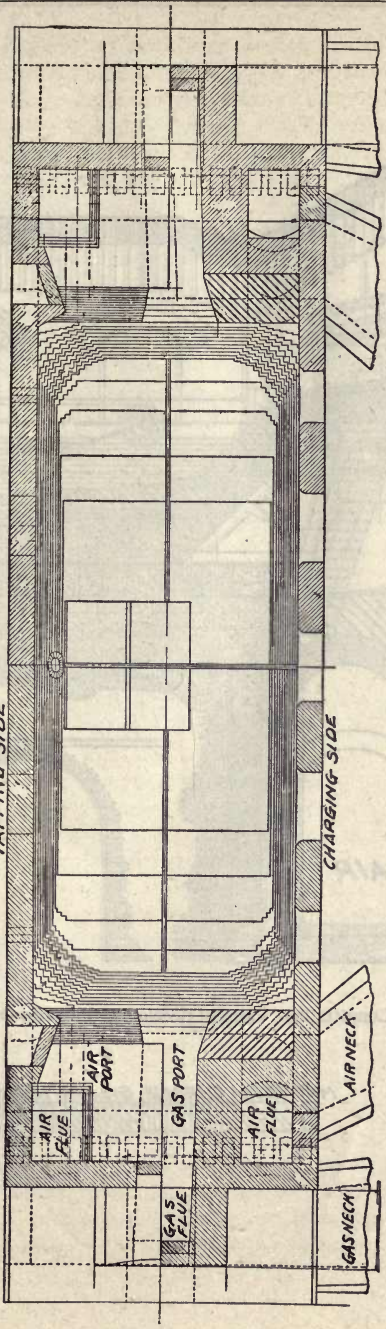


FIG. 27. Horizontal Section of 100-Ton Open Hearth Furnace at Level of the Gas Ports.

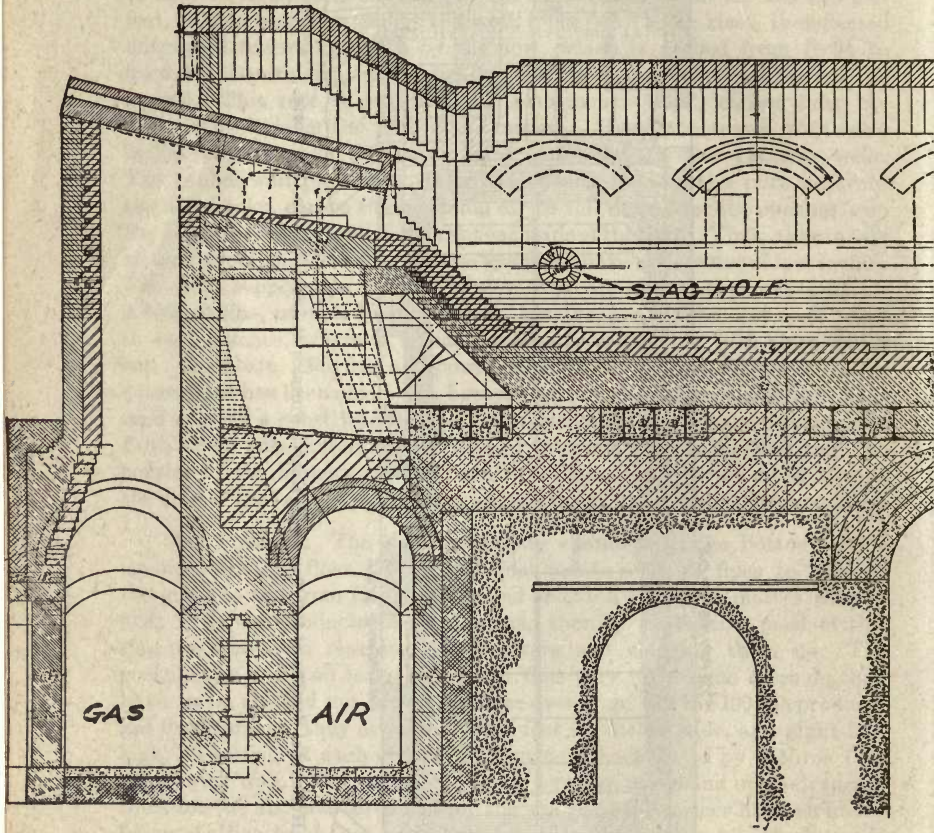
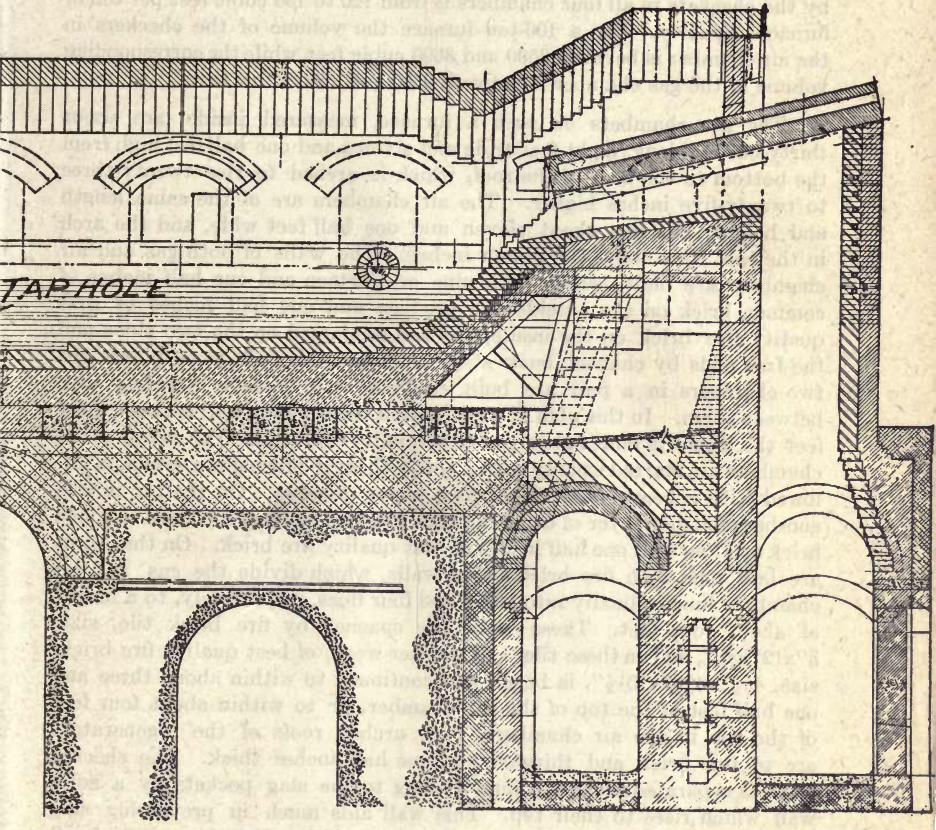
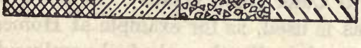


Fig. 26. Longitudinal Vertical Section of 100-Ton Open Hearth Furnace.



Showing Slag Pockets, Flues, Ports and Hearth.



air, arranged so that the outer wall of the gas chamber is nearly in line with the end of the furnace. The gas chamber is always smaller than the air chamber, because the larger volume of air is necessary to burn the gas and assist in the oxidation of the bath. The total space actually occupied by the checkers in all four chambers is from 120 to 150 cubic feet per ton of furnace capacity. For a 100-ton furnace the volume of the checkers in the air chamber is between 3500 and 3600 cubic feet while the corresponding volume in the gas chamber is between 2500 and 2600 cubic feet.

The gas chambers on such a furnace, measured inside, are about thirty-one feet long, eight feet wide and sixteen and one half feet high from the bottom to the base of the roof, which is arched to rise twenty-three to twenty-five inches higher. The air chambers are of the same length and height, but are about eleven and one half feet wide, and the arch in the roof rises about thirty-four inches. The walls of both gas and air chambers are built usually with nine or thirteen and one half inches of common brick on the outside and thirteen and one half inches of first quality fire brick on the inside, and are reinforced on the two sides and the free ends by channel buck stays and tie rods. At some plants the two chambers in a pair are built en bloc with a single dividing wall between them. In this plan of construction the dividing wall is about three feet thick and is built entirely of first quality fire brick. The floors of the chambers are started usually with a nine inch layer of concrete, which is followed with a heavy coat of tar as a water proofing. On the tar is laid another nine inch layer of concrete, then four and one half inches of common brick and four and one half inches of first quality fire brick. On this floor, are laid nine inch fire brick withe walls, which divide the gas and air chambers longitudinally into three and four flues, respectively, to a height of about four feet. These walls are spanned by fire brick tile, size, 3″x12″x31″, and on these tile, the checker work, of best quality fire brick size, 4½″x4½″x10½″, is begun and continued to within about three and one half feet of the top of the gas chamber, or to within about four feet of the top in the air chambers. The arched roofs of the regenerators are of fire brick and thirteen and one half inches thick. The checker work is separated from the flues leading to the slag pockets by a solid wall which rises to their top. This wall aids much in preventing slag and dust from being carried into the checkers. But in spite of all precautions, some dirt is carried over into the chambers, which causes them to become choked eventually, when the furnace must be closed down until the checkers are cleaned or replaced.

**Regenerators for Natural and Coke Oven Gases:** At some plants where natural gas or coke oven gas is used, as for example at Homestead and Clairton where natural gas was originally the only fuel employed, the gas chamber, in addition to the regular air chamber, is utilized to preheat the air. The original idea was to construct the regenerative chambers so that in case gas producers were built, the change in fuels would not necessitate a rebuilding of the furnace; but, now, the chambers for natural gas are all being constructed in this manner, because it was found that when two air checkers at each end of the furnace are employed, better results are obtained than when only one is used. Where one large checker is operated, the air and stack gases, instead of flowing to all parts of the chamber, tend to take a direct course through the center, thus markedly decreasing the efficiency of the chamber.

**Regenerators for Powdered Coal:** The use of powdered coal for fuel introduces a serious difficulty in the operation of the regenerators because of the large percentage of ash that is carried over into the chambers by the draught. This fume soon clogs the ordinary checkers to such an extent that they are no longer efficient. Two different types of regenerators, namely, the arched and columnar types, designed with the idea that they would permit the ash to be cleaned out of the chamber without tearing out the brick work, have been tried; but as the ash fuses upon the bricks, these schemes are impracticable and have consequently been abandoned in favor of the old style of construction. But instead of the usual checker brick a large tile, measuring about 24"x9"x4", has been substituted, which gives larger openings for the passage of the gases. This construction appears to be much more satisfactory than either of the others that have been mentioned.

**Flues and Valves:** While the openings into the slag pockets are at the top of the checker work, the openings for the ingress and egress of gases at the opposite end of the checker chamber are at the bottom. Here the small flues formed by the withe walls open into a large one which leads to the stack flue in the case of the air chambers, or, in the case of the gas chambers,to a three-way water sealed valve,one of the best types of which is represented by the Ahlen valve. Another branch of this valve leads to the stack and the third to the gas main. These valves, together with the dampers and mushroom valves in the flues from the air chambers, supply the means by which the reversals of the flame are made. In the modern furnaces, these valves and dampers are connected so that the reversal of the air and gas currents take place simultaneously. All the valves and dampers are controlled from the charging floor. Since natural gas, and also coke oven gas, cannot be preheated without decomposing them, the valve system in furnaces using these fuels, as well as those using powdered coal, is much simpler than for those using producer gas.

**The Stack:** The stack for each furnace must be of such size and height as to supply sufficient draught to the furnace. It is lined with first quality fire brick, and usually has an inside diameter of 5 feet and a height of from 140 to 160 feet above the charging floor. The shell is made of $\frac{3}{16}$ inch boiler plate. It usually rests on a concrete foundation, on the same level as the floor of the checker chambers, and at this level it has openings for flues from the gas and air chambers, as previously described. For controlling the draft a damper is placed in the main flue at its entrance to the stack. With new or clean checkers this damper partly closes the main flue, but as the checker becomes clogged, it is raised from time to time as required.

## SECTION IV.

### OPERATION OF A BASIC OPEN HEARTH—PURIFYING THE METAL.

**Furnace Attendants and Their Duties:** For the work on each furnace, three men, a first helper, a second helper and a cinder-pit-man, are needed, and besides these, there is a foreman, called a melter foreman, in charge of a number of furnaces. Ordinarily, the first helper has charge of the furnace except at the tapping of a heat. He informs the charging machine operator of the amount of ore the charge will require and how and where to place the various parts of the charge; he regulates the heating of the furnace; runs off the slag; directs any repairs necessary during the operation; and has charge of **working the heat**, that is, making the necessary additions of ore, pig, spar, etc. to prepare the steel for tapping. But when the heat is ready to tap, the melter foreman takes charge. The first helper, subject to the supervision of the melter, actually taps the heat, and, after doing so, he directs the repair of the bottom and helps make up the banks and clean up the steel spout. The second helper is next in charge; he keeps a supply of dolomite, feed ore, fluorspar, ferro-manganese and ferro-phosphorus on hand and places the solid recarburizing additions on the platform convenient to the ladle. He helps to work the heat, digs the plug out of the tapping hole when the heat is ready to tap, keeps the tapping hole open and clean while the furnace is being rabbled, and assists in making up the banks of the furnace preparatory to recharging. He also attends to the plugging of the tapping hole, relines the steel spout after each heat and cleans up around the furnace. The cinder-pit-man attends to the cleaning of the pits, from which the slag and metal must be removed after each heat. In addition, he assists in making bottom at his own furnace and all the others under his melting foreman. The melter, or foreman, usually has charge of a group of six or seven furnaces. He takes charge of any furnace in his group when any serious difficulty arises, and he always has charge of the tapping of the heat. He receives an order for the kind of steel desired from the steel distributor, so when the tapping time of a heat is near, he orders the recarburizer and moulds necessary, and takes charge of the furnace when the carbon is but a few points above the tapping point. He decides when the heat is ready, gives the order to tap, and directs the addition of the recarburizers. He gives the order for lifting the ladle when the steel is out of the furnace, superintends the teeming of the steel, and inspects the bottom of the furnace after the heat is out.

**Preparation of the Furnace for Its First Charge:** Starting a new furnace is an operation that requires a great deal of care in order to avoid injuring the brick work and to prevent explosions, especially when producer gas is used for fuel. The complete preparation of the furnace may be said to take place in four stages, known as **drying, heating, making bottom** and **washing.** The drying is begun very slowly with wood or gas fires, and requires about twenty-four hours, during which time all the connections to the stack on both ends of the furnace are left open. The temperature is then gradually increased for about another twenty hours. When the furnace has almost reached a red heat inside, the products of combustion are led off through only one set of checkers for three or four hours, then gas is turned on carefully and the real heating is begun, which requires about twenty-four hours more. During this time, the flame is reversed at intervals of about an hour at first, then more often, in order to heat up both sets of checkers evenly and uniformly. When a slag-melting temperature has been reached, finely ground magnesite is thrown into the furnace to cover the joints between the magnesite brick, and a little finely ground basic cinder is scattered on top of it. About twelve hours is required for these additions to fuse and make the bottom solid. The making of the bottom is then begun. For this purpose burned magnesite is much preferred, but as this substance is sometimes very expensive, calcined dolomite is employed as a substitute. With the former, the procedure is about as follows:—A mixture of burned magnesite, 75%, and basic cinder, 25%, both ground to pass a half inch screen, is scattered over the bottom and sides of the hearth to a depth of about a half inch, and allowed to sinter. At the end of about three hours, the gas is turned off, and another layer of the mixture is thrown in; and this procedure is repeated, at the same intervals of time, until the bottom and banks have been built up to the desired thickness of about eleven inches, which occupies about ten days in all. The tapping hole is next cut through from the outside, to terminate on the bottom, and is then filled up with burned dolomite, held in place by a cap of clay on the outside. The furnace is then ready for the wash heat. About twenty tons of basic cinder is charged and melted. This melt is rabbled up against the banks so that every part of the hearth is made solid, and is then tapped out. Burned dolomite is now piled on top of the banks as high as possible, when the furnace is ready to receive its first charge.

**Charging:** The first charge consists of limestone, scrap, and cold pig iron; neither ore nor hot metal are used on a new bottom until it shows it is not absorbing iron and is absolutely solid. **Trade heats,** of approximately half scrap and half hot metal are charged for the first half dozen heats, after which the percentage of hot metal is increased as rapidly as possible to the normal. The materials in the charges vary for different kinds of heats, but in general, a so-called Monell heat requires from 75% to 100% hot metal and a trade heat less than 75% hot metal. In each case, the remainder of the metallic part of the charge consists of scrap, while the ore and limestone are varied to suit the conditions. An example of each as used on a 100-ton funrace follows:

| Monell. | | Trade. | |
|---|---|---|---|
| Limestone.... | 20000 pounds. | Limestone.... | 17000 pounds. |
| Ore........... | 40000 pounds. | Ore........... | 10000 pounds. |
| Scrap......... | 45000 pounds. | Scrap......... | 95000 pounds. |
| Pig Iron...... | 165000 pounds. | Pig Iron...... | 115000 pounds. |

In place of ore, briquettes, made from blast furnace flue dust, or heating furnace cinder may be substituted. The charge, with the exception of the molten iron, is brought to the furnace in the charging boxes previously mentioned, and charged by machine. Hot metal is brought, either from the mixer or from the blast furnace direct, in ladles and is then poured into the furnace through a runner that is introduced at one of the doors for the purpose. Other additions in small quantities are thrown in by hand through the doors. At one plant, furnaces with removable tops are provided, in order to make it possible to charge very large pieces of scrap which would not pass through ordinary doors. At all plants advantage is taken during repairs to old furnaces to charge such large scrap through the top before the roof is put on. As to the grade of the materials in the charge, it is preferable to have an iron low in sulphur and silicon because the former element is only partly removed in the furnace, if at all, and the latter, upon being oxidized to silica, rapidly cuts away the banks. A manganese content between 1% and 2% is also desirable, as it assists somewhat in the removal of the sulphur. As there is almost a complete elimination of phosphorus in the process, the quantity of this element in the charge is not of great importance up to one per cent. As previously indicated, the pig iron, in order to save time and conserve heat, is charged in the molten state whenever possible.

**The Order of Charging the Raw Materials:** As to the order of charging, the limestone is always charged first for these reasons: If it were charged on top of the scrap, for example, it would act as an insulator and thus prolong the melting period; it would all go to make up a part of the first slag, which would be too thick and viscous to work well; it would be drawn off with this slag in the run offs, thus leaving very little lime in the furnace to hold the phosphorus in the latter stages of the refinement; and, finally, the benefits to be derived from the lime boil, to be described later, would be lost. Upon the limestone, will be charged the ore, or briquettes, which, if any is needed, will vary in amount according to the nature of the rest of the charge and the heating capacity of the furnace. In order to hasten oxidation, ore may also be added from time to time during the later stages of the process. The scrap is next charged, and if cold pig iron is used, it is charged with the scrap. The gas, which is usually but partly turned on during the charging is then turned on full, and the first or melting stage begins. If hot metal is to be charged, it is not added until the melting period is well advanced.

**Melting Down the Charge:** Heat is imparted to the charge partly through radiation from the incandescent particles in the flame. The fuel should, therefore, burn with a full long flame reaching almost from end to end of the furnace. But the flame should never extend through the ports and down-takes, as it would then rapidly fuse the brick of those flues and waste the fuel. For the same reason, the flame should be directed downward from the port and not be allowed to impinge on the roof. The light scrap and pig iron, if any is added to the solid charge, begin to melt first. During the melting much of these materials is oxidized, so that there is formed both molten metal and oxides, which trickle down over the scrap to the bottom. A slight amount of molten slag and metal is thus present, on the bottom of the furnace, before the hot metal, i. e., molten pig iron, is charged. Reversals of the flame should occur every fifteen to twenty minutes during this period, and care must be taken not to overheat the roof, for too high a temperature will cause the bricks in a new roof to spall, and those in an old one to fuse. Silica brick frequently **sweat,** that is, fuse slightly, but this condition does no harm and indicates a favorable temperature in the furnace. Care must be taken with the roof and checkers in a new furnace, especially, and the temperature must be kept relatively low for the first ten heats or more, after which time the gas may be gradually increased until the full working temperature is attained.

**The Addition of the Hot Metal:** The molten metal can usually be added in about two hours after the charging of the solid materials is begun. The exact time for adding this metal is governed by the temperature of the solid charge. Evidently this temperature should be above, or at least as high as, that of the melting point for pig iron. This statement does not imply that the scrap, which has a much higher melting point than pig iron, should be completely melted. Indeed, a delay in the addition of the molten metal until the scrap is all melted may be very undesirable, for not only would the scrap be excessively oxidized, but the high temperature combined with the excess oxides present would result in a too violent reaction, and much foaming of the bath and loss of metal due to the rapid generation and evolution of carbon monoxide would result.

**The Purification Periods:** The purification of the hot metal, after it is introduced into the furnace, is brought about through the oxidizing influence of the iron oxides and the fluxing properties of the limestone. While both oxidizing and fluxing reactions are actually taking place in the furnace at the same time, the action of the iron oxides must be considered as preceding that of the limestone, for the acid impurities must first be oxidized before they can be neutralized, or fluxed, by the bases. It is evident that the fluxing action may immediately succeed the oxidation, but the conditions set up by the manner of charging the limestone tends to retard its calcination and thus to separate the two actions. Now, the carbon monoxide generated by the action of the iron oxides upon the carbon of the pig iron is at first evolved in a manner quite different from that of the same gas formed later on in the process or of the carbon dioxide from the calcination of the limestone, and this difference is indicated by the way in which the bath is agitated. Hence, the furnacemen have fallen into the habit of speaking of the purification as taking place in stages, known as the **ore boil, the lime boil,** and the **working period.** The third is the stage that follows the complete calcination of the limestone. In order that the reader may understand what is implied by these terms, the changes that occur during the purification of the metal are discussed under these three headings.

**The Ore Boil:** Proper chemical testing will show that the purification of the molten iron begins immediately after it is charged into the furnace, and, with the exception of carbon, the oxidation of which is not completed till the heat is ready to tap, progresses very rapidly. So, in about two hours practically all of the silicon and the greater part of the manganese will have been oxidized, and the former, then in the form of silica, will have been neutralized, some with lime, but the greater portion with the oxides of iron and manganese, and will have become slag. Some of the sulphur, also, will have been oxidized, particularly if the sulphur content of the hot metal was high, but as the oxides of this element are volatile and the high temperature tends to decompose the sulphites and sulphates, only a part of the oxidized sulphur is retained by the slag, and the remainder is carried off with the products of combustion. A very small portion of this element finds its way into the slag as sulphides, probably as manganese sulphide. With the silicon and manganese, the phosphorus is also rapidly attacked by the iron oxide, which not only oxidizes it, but neutralizes the resulting oxides of this element. These iron phosphates, which are easily reduced, likewise pass into the slag, where the iron oxide is replaced with lime, thus forming the calcium phosphates, which are very stable compounds. During all this time the carbon is also being slowly oxidized. This action, which at first takes place near the surface of the metal, results in the evolution of carbon monoxide in the form of tiny bubbles, which become entangled in the viscous slag and cause it to foam. Consequently, the slag, thus permeated with little gas cells, occupies much more than its natural space in the furnace. Carbon dioxide is also evolved by the limestone, which begins to be calcined more and more rapidly as the temperature at the bottom rises; but as the gas resulting from the decomposition of the limestone escapes in relatively large bubbles, it causes very little of the foaming.

**The Run off:** When the slag level has been raised to a height a little above that of the bottom of the openings for the doors and is threatening to break through the dolomite dykes built up just inside these openings, the dolomite with which the slag hole is dammed is cleaned out of this opening, and the excess slag is allowed to flow through the cinder spout into the cinder pit or into a slag pot placed below to receive it. This tapping of slag is known as the **run-off.** The bases in this first slag are composed chiefly of iron and manganese oxides, the lime and magnesia being relatively low. It is not unusual for these slags to contain iron as oxide equivalent to 30% metallic iron, and as they constitute about 40% of the total slag formed in the process, they represent the source of greatest loss of metal for the entire process. Practically all of the iron contained in the run-off is in the ferrous condition.

**The Lime Boil:** The action of the ore and other iron oxides, formed by the oxidizing flame, upon the carbon will be somewhat violent for two hours or more, during which time the scrap will have been almost completely melted down. Gradually, however, as the carbon content decreases and the temperature of the bath rises, the ore boil subsides, or changes its character, and, the calcination of the limestone becoming more rapid, the lime boil is in the ascendency. The lime boil is characterized by a rising of the lime to the top of the bath and by a violent bubbling of the bath, caused by the rapid evolution of carbon dioxide gas from undecomposed limestone which still remains on the bottom, and also in part by the continued oxidation of carbon in the molten metal. These activities play important parts in the process. Thus, not only does the violent bubbling caused by the evolution of the carbon dioxide gas agitate the metal and slag, thus mixing them and exposing the metal to the oxidizing influence of the flame, but a part of the gas, at least, unites, directly or indirectly, with the carbon remaining in the iron to form carbon monoxide. Furthermore, by rising to the surface, the lime may replace iron and manganese oxides in the phosphates, sulphates and silicates present and thus become a part of the slag, while any excess lime is also taken up and goes to increase the basicity of the slag. This property of the slag makes it more capable of retaining both the phosphoric and silicic acids together and renders the former less liable to be reduced. During this period the flame in the furnace should be reversed more frequently (about every 15 minutes) in order that the temperature of the bath eventually will be well above the melting point of the decarbonized metal.

**The Working Period:** Since all the impurities except carbon have now been eliminated, the operations during this period aim at regulating the properties of slag, adjusting the carbon content of the steel, and raising the temperature of the bath to the point where the steel may be tapped from the furnace and cast into ingots before it begins to solidify. In order for the steel to be teemed without difficulty, this temperature should be at least 167° C. (300° F.) above its fusion point. Both the chemical and the physical properties of the slag play most important parts in the basic process. In order that it may protect the metal against contamination by sulphur from the flame, retain the impurities, especially phosphorus, and promote the elimination of the carbon, the slag must contain a large quantity of active oxidizing agents, except at the end of the period, and must be strongly basic at all times. But even with the chemical composition of the slag properly adjusted, its activity will depend upon the fluidity to a great extent. The reagents at the disposal of the operator for regulating these properties are iron oxide, limestone, dolomite and fluorspar. The iron oxide is usually in the form of lump ore, though heating furnace cinder formed on a magnesite bottom may be used.

**Methods of Working the Heat:** There are two general methods of working heats, and briefly described, they are as follows:

The first method is somewhat like the Bessemer, that is, the carbon content of all heats is reduced to a common point, about .10%, when the steel will be tapped and the per cent. of carbon will be raised to that desired by the addition of recarburizers. In the second method the carbon is caught on the way down, that is, the carbon content is reduced to a point slightly under that required, to allow for the carbon contained in various additions, and the bath of steel is then tapped. Medium and low carbon steels are usually worked by the first method, while high carbon steels may be worked by either.

**Testing for Carbon:** So toward the end of the lime boil, or earlier if it appears that the carbon content of the bath is dropping rapidly, the first helper will begin taking tests in order to follow the progress of the heat. These tests he takes by securing a small test-spoon full of the metal, which he pours into a small rectangular mould. As soon as the metal has solidified in the mould, it is removed by jarring the mould while in an inverted position; the test piece is nicked in the center, rapidly cooled with water, and then, while still warm enough to dry itself, it is broken with a heavy sledge hammer. From the fracture thus exposed, the carbon content, which determines how the heat is to be treated, can be very accurately estimated. In order that the temperature of the bath may be raised to a point sufficiently high for tapping by the time the carbon is reduced to the point aimed at, it is desirable that the carbon content of the bath at the end of the lime boil should be forty to fifty hundredths of a per cent. (40 to 50 points) higher than that desired at tapping.

**Control of Carbon and Temperature:** If, as occasionally happens, the carbon is nearly all removed while the bath is yet too cold to tap and pour successfully, it is difficult, on account of its inactivity, to bring the heat up to the proper tapping temperature without danger of burning, or over-oxidizing the steel and unduly increasing the wear on the roof of the furnace. A heat working under such conditions is known as a **sticker.** To prevent this over-oxidizing, **pigging up** is resorted to, that is, the carbon content is **held**, or kept constant, by adding pig iron, which also aids in raising the temperature by producing a little boil in the bath. Usually, however, there will be fifty to eighty points of carbon to be removed from the bath after the lime boil. Therefore, as soon as the first helper sees that the lime is about all up, he will first take a test, then see that all lumps of unfused matter, or **nigger heads**, are melted and that the slag is sufficiently fluid. To bring about the rapid melting of the unfused bodies and increase the fluidity of the slag, fluorspar sufficient for the purpose will be added. Then to hasten the elimination of the carbon, it may be necessary to **ore down**, that is, additions of ore or heating furnace cinder will be made from time to time as required to reduce the carbon content. After each addition of oxide has had time to act, a test is taken. During the last half hour, in some cases the last hour, the heat is in the furnace, no ore will be added. Some foremen erroneously believe that the elimination of carbon at this point may be hastened by stirring the bath with a long steel bar, a process known as **shaking down,** while others will merely allow the metal to lie in the hearth undisturbed. In the case of low carbon heats the flame will now be reversed in the furnace about every ten minutes in order to raise the temperature, and as soon as the tests show that the carbon is within three or four points of the desired content, the melter, or foreman, is notified. He takes additional tests for the carbon content and also for temperature, orders the recarburizers, inspects the furnace, ladle, etc., and completes the arrangements for tapping the heat.

**Judging the Temperature of the Bath:** For judging the temperature of the bath, two very simple tests are employed by the furnacemen. One of these tests consists of quickly inserting the end of a long steel bar or rod into the bath of metal and slowly moving it from side to side until the part immersed in the metal melts off. Then the bar is withdrawn, and from the appearance of the hot end the condition of the bath with respect to temperature may be judged. Thus, if the bath is too cold, this end of the rod will be pointed; if too hot, it will show nicks on the sides near the end; but if the temperature is right, the end of the rod will have melted off so as to leave a clean, square end. The second method depends upon the quite evident fact that the higher the temperature of a fluid the longer it will remain fluid in contact with cold surroundings. It is carried out simply by quickly withdrawnig a test-spoonful of the molten steel from the bath and at once pouring it, rather slowly, but at a fixed rate of flow, out of the spoon. The operator judges the temperature of the steel by the way it flows and by the extent and thickness of the skull it leaves in the spoon. By long practice with these methods the workmen become very expert in making these relative determinations of temperature.

**Tapping:** The furnace should be manipulated so that a tapping temperature is reached before the carbon content has been reduced to the tapping point, as otherwise some difficulty will be experienced with high carbon steels in holding the bath, if the carbon is to be caught on the way down, while with low carbon steels, it will be difficult to reach a tapping temperature or the metal will be over-oxidized, with the result that it will tend to be both hot short and cold short unless deoxidizers such as spiegel, ferromanganese, or pig iron, are added. Prolonging the life of the heat at this point in order to reduce the sulphur content is very bad practice for the double reason that the removal of the sulphur is uncertain and the cure is worse than the disease. The proper temperature for tapping low carbon heats is 1600° C., or a little higher, while for heats in which the carbon is caught on the way down, the tapping temperature may be about 100° C., lower. To accomplish the tapping, the second helper digs out from the rear the mud plug and most of the dolomite with which the tapping hole is closed, after which the hole is opened by driving outward the dolomite remaining in it by inserting a tapping rod through the wicket of the center door in the front of the furnace. The steel then flows through the hole out of the furnace and down the spout into the ladle. Since the tapping hole is on a level with the bottom of the hearth, the greater part of the steel is out of the furnace before any slag appears, and this fact permits of recarburization in the ladle. It is not advisable for the recarburizing materials to be allowed to come into contact with the slag, since some of the phosphoric acid in the slag may be reduced and the phosphorus re-enter the steel. The tapping spout and ladle are so placed as to direct the stream of molten metal a little to one side of the center of the ladle, as the swirling motion tends to mix and make more homogeneous the contents of the ladle.

## SECTION V.

### FINISHING THE HEAT—MAKING STEEL FROM THE PURIFIED METAL.

**Methods of Finishing the Steel:** The process of finishing the steel consists in making such additions as are required to produce the kind and grade of steel desired, and with few exceptions these additions are made immediately before and after tapping the heat. The methods of making the necessary additions to produce the various kinds and grades of steel differ somewhat, not only for the different grades but in different works making the same grades. For example, the ferro manganese and spiegel are preferably added to the steel in the ladle and in the molten state, but not all plants are at present equipped to melt these materials, and ferro manganese is still generally added in the solid form. For the plain steels the methods of making additions for carbon and manganese may be briefly stated in the following tabulated form.

#### High Carbon Steels. (C.60% to 1.30%)

**Method I.** Carbon is caught on the way down; ferro-manganese is added, and coal, if needed, in the steel ladle.

**Method II.** The steel is tapped with the carbon at .10%; molten spiegel mixture is added in the steel ladle.

**Method III.** The carbon in the bath is eliminated to .10%; sufficient molten pig iron is added in the furnace at the time of tapping to raise the carbon content almost to the point desired. Then ferro-manganese may be added to the ladle to make up the deficit in the carbon, and supply the manganese deficit left by the pig iron.

#### Medium Carbon Steels. (C. .30% to .70%)

**Method I.** The steel is tapped with a carbon content of .10%; molten spiegel mixture is added in the steel ladle.

**Method II.** The carbon in the bath is eliminated to .10%; molten pig iron is added in the furnace and ferro-manganese in the ladle as in III for high carbon steels.

#### Low Carbon Steels. (C. less than .40%)

**Method I.** For dead soft steels the carbon content is reduced as low as possible without danger of over-oxidizing the steel, and ferro-manganese is added in the steel ladle.

**Method II.** The carbon content is reduced to .10% and ferro-manganese is added alone, or ferro-manganese and coal are added in the steel ladle. In case a large quantity of ferro is required, some furnacemen prefer to add a part of it in the furnace just before the tapping hole is opened.

**Method III.** For finishing very low carbon steels neither molten spiegel nor molten pig iron are used on account of the difficulty of weighing and keeping molten small quantities of these materials. But in large furnaces, pig iron may be used, if the carbon content is more than .20%, as in Method II for medium carbon steels.

**Other Elements:** The additions for other elements will be made about as follows:—Copper is added in the solid form to the steel fifteen to twenty minutes before the heat is tapped. Sulphur is always added before the ferro additions. Ferro silicon is necessarily added in the steel ladle; while it is the common practice to add ferro vanadium by dropping it into the stream of molten metal in the runner, or spout, as it is flowing into the ladle. As nickel is chemically negative to iron, none is lost in the furnace, so nickel steels are made by charging nickel steel scrap, then adding pig nickel in sufficient amount to make up the deficiency, as shown by chemical analysis, about thirty or forty minutes before tapping. The same practice may be employed in the case of steel requiring copper and chromium, but a comparatively large part of the latter element is lost through oxidation in the furnace. Chromium is added in the form of ferro chromium.

**Some Features that Make the Finishing of the Steel Difficult:** It requires considerable experience to finish steel properly, for there are a number of circumstances that tend to complicate the operations. For example, the addition of ferro, on account of its carbon content, will always slightly raise the carbon content of the steel, though it is primarily added to increase the manganese. Similar conditions also prevail in the use of other ferro alloys and pig iron. Again, there is always a loss of the elements added, except in the case of copper and nickel, and this loss, different for each element, will vary with any one under different conditions. Hence, the efficiency of these substances is never 100%. Furthermore, it is seldom any of the elements can be obtained in pure form for this purpose, and the substance containing the element sought may vary in its content of that element. The various substances used, their efficiencies, and the amount of each element present in the bath at the tapping of a normal heat are indicated in the following table.

### Table 31. Data Relating to Materials Used in Finishing Steel.

| Material Added | Element Sought | Percentage of Element in Bath | Efficiency When Added in | |
|---|---|---|---|---|
| | | | Furnace | Ladle |
| Pig Nickel | Ni | .00 unless Ni. scrap used | 98% | Never |
| Ferro Chromium | Cr | .00 " Cr. " " | 80% | " |
| Pig Copper | Cu | .00 " Cu. " " | 99% | " |
| Stick Sulphur | S | .040 | Never | 66%—70% |
| Anthracite Slack | C | Any desired | " | 44%—50% |
| Pig Iron | C | " | 95% | Never |
| " | Mn | .10 to .20 | 50% | " |
| Ferro Manganese | Mn | .10 to .20 | 50% | 85%—90% |
| Spiegel | Mn | .10 to .20 | Never | 80%—90% |
| " | C | .10 to Any desired | " | 100% |
| Ferro Phosphorus | P | .010 | " | 75% |
| Ferro Silicon | Si | .00 | " | 65—70% |
| Ferro Vanadium | V | .00 unless V. scrap used | " | 90% |

In the following table will be found an analysis typical of each of these substances.

### Table 32. Representative Analyses of Materials Used in Finishing Steel.

| | Fe % | C % | Mn % | P % | S % | Si % | V % | Cr % | Ni % | Cu % |
|---|---|---|---|---|---|---|---|---|---|---|
| Ferro Manganese | 13.03 | 6.80 | 79.35 | .16 | ...... | .66 | ...... | ...... | ...... | ...... |
| " Phosphorus | 79.97 | 1.10 | .18 | 18.00 | .65 | .10 | ...... | ...... | ...... | ...... |
| " Silicon, Electric | 49.44 | .55 | .016 | .075 | .018 | 49.90 | ...... | ...... | ...... | ...... |
| " " Blast Fce | 87.465 | 1.52 | .42 | .080 | .015 | 10.50 | ...... | ...... | ...... | ...... |
| " Chrome | 22.05 | 6.36 | .35 | .003 | .79 | .48 | ...... | 69.96 | ...... | ...... |
| " Vanadium | 42.65 | 1.58 | 6.25 | .010 | 1.06 | 10.49 | 37.96 | ...... | ...... | ...... |
| Spiegel | 75.68 | 4.39 | 19.13 | .053 | .028 | .72 | ...... | ...... | ...... | ...... |
| Pig Nickel | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | 97.00 | ...... |
| Pig Copper | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | 99.00 |
| Stick Sulphur | ...... | ...... | ...... | ...... | 100.00 | ...... | ...... | ...... | ...... | ...... |
| Pig Iron | 94.00 | 3.80 | 1.00 | .17 | .030 | 1.00 | ...... | ...... | ...... | ...... |

Given the weight and composition of the metal in the bath, the desired composition of the finished steel, and the composition and efficiencies of the substances to be added, the calculation of the amounts of the various additions is a simple problem in arithemetic.

**Teeming:** As soon as the stream from the furnace no longer contains any steel, the spout, or runner, is removed, and the steel ladle is lifted by the crane and carried to the pouring platform, where the steel is teemed into the ingot moulds ready to receive it. Teeming is not to be confused with pouring. While the latter logically refers to the way the metal is let out of the ladle, usage has made pouring synonymous with casting, which refers to the manner of introducing the metal into the ingot mould. Thus, if the metal is introduced into the mould through its top, the resulting ingot is said to have been top poured or top cast; but if through its bottom by means of runners, the ingot is said to have been bottom poured or bottom cast. Teeming and top pouring are accomplished in the following manner: The ladle is placed with its nozzle over the center and about a foot from the top of the first mould in the mould train, when the stopper is raised and the steel flows through the nozzle into the mould below. In teeming the heats, care must be taken that neither the stream of metal nor any part thereof be allowed to strike the sides of the moulds, for these splashes of metal will adhere to the mould, which quickly chills them, and, being coated on their surfaces with a film of oxide, they may cause ingot defects which later appear as slivers in the rolled steel. As the first mould is filled, the stream is stopped, and by means of a hydraulic pusher the train is moved forward so as to bring the next mould under the nozzle of the ladle. At some plants the teeming is done from an overhead crane, which moves the ladle from mould to mould. After the ladle has been emptied of steel, the slag remaining in it is dumped into cinder cars and ultimately conveyed to the cinder yard. In the meantime, the mould train is hauled to the stripper. On soft steel and special heats, unless there is a high percentage of manganese or silicon present, aluminum is thrown into the moulds, about two ounces to each ton, in order to further deoxidize and quiet the steel. Aluminum is especially effective in overcoming wildness because of its strong tendency to combine with oxygen. Of this small amount added practically none remains in the metal, so that this aluminum exerts no influence as an alloy in the steel.

**Sampling:** The sampling of the heat for chemical analysis is accomplished when the heat is half teemed by slackening the stream from the ladle, whilst a spoon of suitable size is held under the nozzle and filled with the molten metal, which is immediately poured into a test mould specially designed for the purpose. The test mould may be of either one of two types, which careful and extensive experiments have shown to give test pieces most uniform in composition and most free from blow holes. One of these types is a split mould that gives a test piece having a section 1½ inches square and a length of nearly 5 inches, with a flared opening about 2 inches deep to facilitate pouring. The other type is a small cup shaped mould that gives a test piece 3¾ inches in diameter at the top and 2½ inches at the bottom with a depth of 2¾ inches. Upon being taken from the mould, the test piece is immediately stamped with its heat number, and is then delivered to the chemical laboratory for analysis. Experiments have shown that a sample taken in this way most nearly represents the average composition of the heat.

## SECTION VI.

### KEEPING THE FURNACE IN REPAIR.

**Preparation of the Furnace for the Next Charge:** After the runner is lifted and thus detached from the furnace, the cinder and any steel that remains in the furnace flow out of the tapping hole into the cinder pit.

The second helper must keep the tapping-hole open until everything that can be removed from the furnace has flowed out. Fluorspar is usually thrown in on the slag left to be sure that it flows out and does not build up on the bottom of the furnace. Often, holes will be found in the bottom, due to the intrusion of steel below the surface, which, boiling there, brings up part of the basic material forming the bottom. Slag and steel are found in these holes after tapping and must be rabbled out, so that the bottom can be properly repaired. After all the steel and slag are removed from these holes, they are filled up with dolomite. The gas is left on to keep the slag and steel fluid during this process; but is shut off as soon as the repairs to the bottom have been completed. Proceeding to the next step, the second helper and cinder-pit man remove the steel that has chilled in the tapping hole, rake out and free the hole of iron and close it up with dolomite. A plug of clay is used to seal up the outside of the hole and hold the dolomite in place. The banks, which have been cut by the slag from the heat just out, are repaired by throwing burned dolomite on them (3000 to 4000 lbs. is used after each heat in a 100-ton furnace); and the furnace is then ready for charging again.

**Furnace Troubles:** In the operation of a furnace, troubles of a very serious nature may occur at any time, unless the furnace is watched closely, and carefully handled. These troubles present so many possibilities and are so varied that space will permit of little more than an enumeration of some of the more serious ones here. Thus, the tap-hole may break out prematurely if it is not properly tamped and capped, or it may become hopelessly clogged if it is not properly cleaned after each heat. Sometimes, sections of the bottom become detached and rise, due to the buoyant force of the metal, and when this occurs the heat must be tapped at once, and no more heats may be charged until the damaged bottom is repaired. The ports require constant attention to prevent them from building up or melting down, and thus changing the angle of the flame, which would then tend to over-heat some part of the furnace and would be rendered less effective in heating the bath. Leaks may occur in the walls of the up-and-down-takes, which result in the gas being burnt in part before it reaches the hearth. The walls and roof often wear out long before the rest of the furnace needs repairing. Roofs usually last for about 300 heats. The roof can be repaired in a few hours, and a cave-in of the roof is of a serious nature only when it falls in near the end of a heat. The most disastrous mishap that can occur to a furnace is a break-out. Breakouts may be caused by several things. A hole near a bank may not have been noticed or may have been insufficiently repaired, in which case the steel works down into it and gradually makes it deeper, until, finally, the metal finds its way through the wall and out of the furnace. Sometimes, owing to a thin spot on the banks or to slag having reached above them and worked down into them, the slag gradually cuts its way out through the walls, in which case it is usually followed by steel, as the hole soon becomes low enough to reach the bath. Such mishaps are also known as break-outs and are always of a serious nature. Once a break-out occurs, the tapping hole should be opened immediately, and as much as possible of the steel gotten into the ladle or cinder pit. The spread of cinder and metal upon the floor where the break-out has occurred can be limited usually by throwing dolomite around it. Finally, after about 600 or 700 heats, the checker work has become so badly clogged and the brick work is so eaten away, that it becomes necessary to close down the furnace for general repairs, during which the greater part of the brick work may be torn out and rebuilt.

**Repair Materials:** It is evdent that, for making up the bottom and for doing the repair work about a furnace, much depends upon the materials employed. Great care must always be exercised to see that they are of the right chemical composition, and best suited for the work in hand, as, otherwise, the best of workmanship in making the repairs will go for naught. Therefore, a few remarks in this connection should be of interest.

**Dolomite** is found in local deposits similar to those of limestone. Like the latter it varies in composition through quite wide ranges, but that suitable for open hearth work will have, after being calcined, approximately the composition shown by the following chemical analysis: Silica, $SiO_2$, 1.66%; Iron Oxide, $Fe_2O_3$, .94%; Alumina, $Al_2O_3$, 1.24%; Lime, CaO, 50.01%; Magnesia, MgO, 35.26%.

**Magnesite:** The magnesite used before the European war was imported from Madelein and Budapest, Austria, and was brought to the mill already burned and ground. It was used on the furnace bottom, banks and ports, and in repair work. An average analysis of thirty-eight cars of the imported material is as follows:—

| $SiO_2$ | Fe | Mn | $Al_2O_3$ | CaO | MgO | Ig.Loss |
|---|---|---|---|---|---|---|
| 2.07% | 6.00% | .37% | 1.63% | 3.81% | 84.11% | .52% |

Since the outbreak of the war, however, deposits of this material in California and Washington have been opened, and this domestic supply promises to replace permanently the imported material. This magnesite is purer than the imported, and for that reason it does not sinter or bond so readily, but by mixing a little of the proper fluxing material with it, this drawback has been easily overcome.

**Chrome Ore:** Chrome ore is still imported, as the limited deposits so far discovered in the United States and Canada are of an inferior grade. It is received in the form of small lumps. It is ground and mixed, in a wet pan, with one-half magnesite, and is used in repair work where a neutral substance is required, such as in patching flues, tapping holes, ports, etc. An analysis of an average sample of a satisfactory grade of this ore gave these results:

| $SiO_2$ | FeO | MnO | $Al_2O_3$ | MgO | $Cr_2O_3$ | Ig. Loss |
|---|---|---|---|---|---|---|
| 9.02% | 13.50% | .80% | 10.82% | 19.89% | 42.66% | 2.92% |

Besides these materials, some ganister may be employed at some of the works, while all plants will use large quantities of loam and of fire clay for lining furance spouts and ladles, for making up stoppers, and for other repair work of minor importance.

## SECTION VII.

### CHEMISTRY OF THE BASIC PROCESS.

**Some of the Principles and Conditions Involved:** Having followed the procedure of making steel by this process, the reader should be interested in a discussion of a subject, which to the metallurgist, at least, represents the most interesting and profitable part of the study, namely, the chemistry of the process. In beginning this study it should be recalled that the purification of pig iron, which is the first of the two main steps in making steel, includes the elimination from the metal of the four elements, silicon, manganese, phosphorus and carbon, and that the principle by which this elimination is effected is that of oxidation. In basic open hearth processes, the elimination of sulphur may also take place to a greater or less extent, depending upon the amount present, but is never to be considered seriously as a principal objective. It now remains to be pointed out that this oxidation, when brought about indirectly, that is, through the interaction of these elements with oxygen bearing compounds, as is the case in this process, involves two other principles as well. These are the principles of reduction and neutralization, for it is manifestly impossible under these conditions that one substance can be oxidized without another's being reduced, and it develops, as will be shown later, that this interaction is made possible through the immediate neutralization of the oxidized substances. While these principles and the reactions by which the purification is brought about are, when considered separately, very simple and can be easily understood, they are somewhat difficult to follow in the actual working of the furnace, because they are here occurring simultaneously and, therefore, tend to mask each other in the effects they produce. For this reason it is best to consider the subject, first, from the standpoint of the chemical properties of the elements affected and of the oxygen compounds of these elements under the conditions of the basic open hearth process.

**Properties of Iron and Its Oxides:** One of the most marked of the chemical properties of metallic iron is its tendency to combine with oxygen. Even at ordinary temperatures this tendency is very marked, as is seen from the ease and quickness with which it combines with oxygen and water to form the familiar compounds known commonly as iron rust. These compounds are but the hydrated sesqui-oxide, or per-oxide, of iron containing varying amounts of combined water, as represented by the formula $Fe_2O_3 \cdot xH_2O$. This tendency of iron and oxygen becomes stronger as the temperature rises, so that at a temperature ranging from 800° to 900°, or higher, the combination becomes very rapid, and a compound quite different from those composing rust is formed. It is commonly known as **Scale,** and is represented by the formula $Fe_3O_4$, or $FeO \cdot Fe_2O_3$. These facts help to explain why iron is seldom found in nature uncombined, and the two compounds, represented by the formulas given above, together with the carbonate of iron, constitute the valuable part of all the ores of iron. The ore used in all our furnaces is the red hematite, which for the purpose of this discussion, may be considered as being composed of the sesqui-oxide, $Fe_2O_3$, and gangue. Besides free oxygen, certain compounds may, at high temperature, serve as sources of supply of oxygen to iron. Among these are carbon dioxide and water vapor, which constitute the chief products of combustion in any case of burning a fuel in the presence of an excess of oxygen, such as normally exists in an open hearth furnace. The heating of free iron to these high temperatures in contact with either free oxygen or steam always results in the formation of $Fe_3O_4$, according to the following reactions:—$3Fe+2O_2=Fe_3O_4$, $3Fe+4H_2O=Fe_3O_4+4H_2$. But at a temperature of 1000°C. or more, with iron in contact with carbon dioxide, another and less common oxide, FeO is formed, thus $Fe+CO_2=FeO+CO$. Ferrous oxide, FeO, and ferroso-ferric oxide, $Fe_3O_4$, may be formed in the furnace in other ways, also, one of which is by the progressive reduction of $Fe_2O_3$. If $Fe_2O_3$ be heated to a high temperature it loses oxygen and is converted into $Fe_3O_4$. This change takes place at temperatures between 1100° and 1200° C., some 500 degrees below the maximum temperatures of the open hearth. If FeO be formed under conditions even only slightly oxidizing, it passes into $Fe_3O_4$. Another difference in the properties of these oxides, which is of great importance in considering the chemistry of the open hearth, is seen in their power to neutralize acids. Thus, while both $Fe_2O_3$ and FeO exhibit very marked basic properties and combine rapidly with acid oxides, $Fe_3O_4$ cannot be induced to form corresponding salts at the temperatures that prevail in the open hearth. Pure scale, $Fe_3O_4$, fuses at about 1450° C., a temperature easily attainable in the open hearth, and it dissolves readily in either iron or calcium silicates. Ferrous oxide, FeO, is soluble in both the molten iron and the slag, and though the amount that remains dissolved in the metal when solid is small, being seldom present to an extent greater than .315% the equivalent of .07% oxygen, its effects are very harmful, as it produces both red and cold shortness in the metal. With metallic manganese it gives the following reaction: $FeO+Mn=Fe+MnO$. MnO is not soluble in the molten metal, which fact assists in accounting for the efficiency of manganese as a deoxidizing agent.

**The Importance of Ferrous Oxide, FeO, in the Part Played by the Oxides of Iron in the Process:** From what has been said concerning the properties of the three oxides of iron, it is evident that ferrous oxide, FeO.

is the principal, perhaps the only, direct oxidizing agent in the open hearth process. Although iron sesquioxide, $Fe_2O_3$, may be charged into the furnace, much of this oxide is transformed by the heat into ferroso-ferric oxide, $Fe_3O_4$, before it has an opportunity to become active. Besides, since the impurities are held in solution by the metal, either the oxidizing agent must dissolve in the metal, a condition that is not true for either $Fe_3O_4$ or $Fe_2O_3$, or the oxidation of the impurities must occur at the surface of contact between metal and slag. That conditions in the open hearth during the melting period tend to form an abundant supply of ferrous oxide can be shown by an analysis of the first slag formed, as is illustrated by the following analyses of samples of this slag taken just before the introduction of the hot metal.

**Table 33. Analysis of First Slag Formed in Open Hearth Heats**

| | $SiO_2$ % | FeO % | $Fe_2O_3$ % | MnO % | $P_2O_5$ % | $Al_2O_3$ % | CaO % | MgO % | S (S+$SO_3$ % |
|---|---|---|---|---|---|---|---|---|---|
| Slag from Fce., No. 9......... | 8.54 | 61.05 | 11.10 | 2.31 | .26 | 1.98 | 9.13 | 5.48 | .16 |
| Slag from Fce., No. 15......... | 1.00 | 78.24 | 15.31 | .81 | .14 | .37 | 2.70 | 1.12 | .25 |

Concerning the neutralizing powers of these oxides, FeO must also act as the initial base, as will be shown later, but in the slag $Fe_2O_3$ is also capable of acting as a base. It is important to emphasize these facts here because of their influence on the chemical action of the other elements eliminated during the purification period, for their action depends on the conditions, which it is, therefore, essential to define. Briefly, the chief of these conditions is that at the time of introducing the hot metal there is present in the furnace a slag that is very rich in ferrous oxide.

**Properties of Silicon and Its Oxide, Silica:** Silicon forms but one compound with oxygen under the conditions prevailing in the open hearth, and this compound is silica, $SiO_2$. The tendency of silicon to combine with oxygen is even stronger than that of iron, due to the greater heat of formation of its oxide, so that it is capable of reducing any of the oxides of the latter, and upon this fact depends the elimination of this element from the molten metal. As to which of the oxides of iron is the active agent in the oxidation of silicon, there can be little doubt but that ferrous oxide, FeO, is the principal one that suffers direct reduction by the silicon, for, as already indicated, the silicon, either as an alloy or a compound of iron, is distributed throughout the mass of molten metal, and it is necessary that either the oxidizing agent also dissolve in the liquid or the silicon diffuse to the surface of the metal in order that the molecules may be brought into that intimate contact required to effect a reaction. The oxidation of the silicon, then, is represented by the following reaction: $Si+2FeO=SiO_2+2Fe$. Silicon, however, is a very strong acid, so that if this reaction occurs, the silica will immediately combine with ferrous oxide to form a bisilicate, a tri-silicate or some still more acid salt, depending upon the relative amount of base available. Since this oxidation takes place with only a limited supply of ferrous oxide present, it may be assumed that the salt requiring the least base, such as the tri-silicate, would be formed. If so, the reaction would be as follows: $3\ SiO_2+2FeO=(FeO)_2\cdot(SiO_2)_3$. If the bisilicate is formed, the reaction would be represented thus: $SiO_2+FeO=FeO\cdot SiO_2$. Since the neutralizing action must always instantly follow the oxidation, it is perhaps best to represent the change by a single reaction, which can be done by combining the first two, thus: $3Si+8FeO=(FeO)_2\cdot(SiO_2)_3+6Fe$. The ferrous silicate is in the fluid state, for its fusion point is below that of the metal. It is of lower density than the iron, and, therefore, rises to the surface, where it temporarily forms a part of the slag. On the way to the slag it may undergo a change as noted later under manganese. Once in the slag, this ferrous silicate is capable of undergoing many changes. The first of these changes is probably due to the ability of the silica to take on additional base. Having been formed in a region where there is only a limited supply of base, the silica could not be neutralized to the extent it is capable. But now, having diffused into the slag, where there is abundance of bases, this trisilicate may become a monosilicate with either a monoxide or a sesquioxide base. The formation of the monosilicate with the monoxide base, FeO, may be represented thus: $(FeO)_2\cdot(SiO_2)_3+4\ FeO=3(FeO)_2\cdot SiO_2$, The ferrous oxide thus combined cannot act as an oxidizer and, therefore, becomes inactive. However, it may be made available through the action of lime and magnesia. Both these bases are capable of replacing ferrous oxide in the manner indicated by the following reactions:—

$$(FeO)_2\cdot SiO_2+\left\{\begin{matrix}2\ CaO\\2\ MgO\end{matrix}\right.=\left\{\begin{matrix}(CaO)_2\cdot SiO_2\\(MgO)_2\cdot SiO_2\end{matrix}\right.+2\ FeO.$$

The ferrous oxide thus liberated is now subject to reduction, and available to the bath for further use. The sources of supply of lime and magnesia are the stone charged into the furnace and the lining of the furnace itself. These alkaline earth silicates constitute the major portion of all the final slags formed in the process, but these slags are never free of iron. for they hold its oxides in solution.

**Properties of Manganese and Its Oxides:** While manganese combines with oxygen in several different proportions to form an equal number of different oxides, under the conditions that exist in the basic open hearth only one of these oxides is formed, namely, the manganous oxide, or protoxide of manganese, MnO. Like silicon, the manganese in the charge, being alloyed with iron, must be oxidized largely through the agency of ferrous oxide. But as silicon is capable of reducing manganese oxide, there appears little chance of oxidizing the latter until the former element has been largely eliminated from the bath. However, there is much evidence to show that at least a part of the manganese finds its way into the slag long before all the silicon has been oxidized. This fact is explained by the assumption that manganese is capable of replacing iron in the silicates of iron, thus: $FeO \cdot SiO_2 + Mn = MnO \cdot SiO_2 + Fe$. or $(FeO)_2 \cdot (SiO_2)_3 + 2Mn = (MnO)_2 \cdot (SiO_2)_3 + 2\,Fe$. With this idea in mind, it is easy to conceive the simultaneous elimination of both these elements, in which elimination the ferrous oxide plays the part of oxidizing agent, only, and manganese fulfills the office of the base for the neutralization of the silica. Such a change, involving the simultaneous oxidation of silicon and manganese, is represented by the following reaction: $3\,FeO + Si + Mn = MnO \cdot SiO_2 + 3Fe$. When this silicate of manganese reaches the slag, it is subject to the same changes as are the corresponding iron oxide silicates, the manganese oxide being eventually set free by lime and magnesia. This free oxide of manganese, being insoluble in the metal, remains in the slag as such as long as the latter is rich in iron oxides; but if the slag should be depleted of its oxides, then manganous oxide is liable to reduction, in which event the resulting metallic manganese returns to the bath. Another property of manganese, though it is of little importance in ordinary open hearth operations, may be mentioned. It refers to the ability of manganese to replace iron in combination with sulphur. Thus, all the sulphur contained in the pig iron or steel scrap going into the furnace may be considered as being combined with this element and in the form of manganese sulphide. This substance is slightly soluble in the slag as well as in the metal, and this fact accounts for the presence of small amounts of sulphide found in open hearth slags. On the surface of the slag, in contact with an oxidizing flame, manganese sulphide is subject to oxidation according to this reaction: $2\,MnS + 3O_2 = 2\,MnO + 2\,SO_2$. The sulphur dioxide, $SO_2$, thus formed is a gas and may escape from the furnace with the products of combustion. However, it is evident that the quantity of sulphur removed in this way must be very small.

**Sulphur and Its Oxides:** Owing to the peculiar properties of sulphur and its oxides, they are subject to a number of conflicting influences, under the conditions of the open hearth process, that render the removal of this element very uncertain. As an element, sulphur combines directly with iron to form iron sulphide and is easily oxidized to form oxides, $SO_2$ and $SO_3$, both of which are gaseous acid anhydrides, and, when neutralized, form sulphites and sulphates, respectively. At temperatures far below the lowest working temperature of the open hearth, the sulphites and sulphates of the heavier metals, like iron, for example, decompose to form either the sulphide or the oxide of the metal and sulphur dioxide. At temperatures relatively low for furnace operations, like that of the puddling furnace, both manganese and iron sulphides are readily oxidized by the higher oxides of these elements, such as $Fe_2O_3$, forming oxides of the metals and $SO_2$ which escapes, as a gas, from the furnace. At the higher temperatures of the open hearth there are a number of factors that operate against the elimination of the sulphur in this way, among which may be mentioned an increased tendency of iron to combine with sulphur, an increase in the reducing power of the molten iron, the fact that CO gas is capable of reducing $SO_2$, and the probability that there is little $Fe_2O_3$ available to do the work. $Fe_3O_4$ may replace $Fe_2O_3$ in the oxidation, but it is very improbable that FeO is capable of producing the same result. Unlike the sulphates of the heavy metals, the sulphates of the alkaline earths, such as calcium sulphate, are not decomposed by heat alone, at least not by any temperature attainable in the open hearth. Therefore, once the sulphur is oxidized and thus combined with lime, there is some chance of its being held by the slag. However, iron is capable of decomposing the sulphate of lime, thus, $CaSO_4 + 4\ Fe = FeS + CaO + 3\ FeO$, in which case the iron sulphide dissolves in the iron. As evidence that such a reaction may take place, several instances may be cited in which steel has been ruined, for the order it was intended, through charging old boiler tubes, containing much boiler scale, with the scrap. The presence of oxides in the slag tend to hold this reaction in check, so that it takes place to an appreciable degree only when the slag is burdened with an excessive amount of this sulphate, and even then it can occur only at the surfaces of contact between metal and slag.

**Sulphur From the Fuel:** Another source from which sulphur may be imparted to the metal is the fuel. That fuel carrying compounds of sulphur may be responsible for a portion of the sulphur content of steel is a well known fact, but through what reactions the transfer is brought about does not appear to have been satisfactorily explained. Now, it has been established by J. B. Ferguson, writing in the Journal of the American Chemical Society, November, 1918, that "CO and$SO_2$ react between 1000°C. and 1200°C. to form $CO_2$ and sulphur vapor and traces of carbon oxysulfide in mixtures rich in CO." In the early stages of an open hearth heat, just after the addition of the molten pig of the charge, these conditions as to temperature and presence of CO gas prevail at the surface of the charge, and any sulphur vapor that may be formed as above will readily be taken up by the exposed molten or solid metal of the charge, forming iron sulfide. If there is taken into account the action of manganese toward sulphur, there are, then, two agencies that act feebly to eliminate sulphur from the metal, and two that are active, also feebly, in returning it, or of introducing it. The stability of the calcium sulphate, however, acts as a guard against the introduction of the element, except under some such unusual condition as that noted above.

**Phosphorus and Its Oxides:** This element is very easily oxidized, when in the free state, by oxygen alone, and forms several oxides, of which only one, phosphorus pentoxide, $P_2O_5$, need be considered here, because it is the only one formed under the conditions prevailing in the open hearth. Like sulphur, phosphorus occurs in the metal as a definite compound, iron phosphide, $Fe_3P$, and like silica, the oxide, $P_2O_5$, is an acid, which must be neutralized as soon as it is formed. The reaction by which it is removed from the metal is, therefore, probably most nearly correctly represented by the following expression: $2\ Fe_3P+8\ FeO=(FeO)_3 \cdot P_2O_5+11\ Fe$. Silica has the power of replacing $P_2O_5$ in the ferrous phosphate, thus exposing the latter oxide to reduction, so that phosphorus is never permanently removed from the metal until the silicon has been practically all eliminated. This power of silica also accounts in part for the fact that phosphorus is not eliminated by any of the acid processes for making steel, for the proportion of this compound in the slag effectually prevents the formation of the phosphate. In the basic process the abundance of bases present in the slag is more than sufficient to satisfy the silica, so that the ferrous phosphate is not only permitted to form, but on reaching the slag it is converted into a much more stable calcium phosphate, probably the tri-calcium phosphate, $(CaO)_3 \cdot P_2O_5$. Even this salt is, relatively speaking, easily reduced. Phosphorus, therefore, is held by the slag only so long as the latter is maintained strongly basic and at least moderately oxidizing.

**Carbon and Its Oxides:** Owing to the peculiar chemical and physical properties of carbon and its oxides, the elimination of this element gives rise to phenomena distinctively different from those of the elements just reviewed. In that review it was pointed out that the oxidation of those elements gives compounds which are liquids under the conditions of the open hearth, that is, they are slag forming elements. But the oxidation of the carbon, which is represented by the reactions $C+FeO=CO+Fe$ and $Fe_3C+FeO=CO+4\ Fe$, gives rise to the gas carbon monoxide, and, owing to the conditions under which it takes place, produces the phenomenon known as the ore boil. Thus, since the carbon, either as a compound or as an element, is dissolved in the metal, and the iron oxides, in the slag, the region of greatest activity, at the beginning of the oxidation, is located near the surface of contact between the two liquids. The generation of the carbon monoxide here gives rise to innumerable tiny bubbles of the gas, which immediately rise into the slag; but owing to the small size of the former and the viscosity of the latter, their immediate escape is hindered, so that they find their way to the surface very slowly. They thus collect in the slag, increasing its volume and imparting to it the appearance of foam. In the course of time, the highly oxidizing condition of the bath has disappeared with the consequent lowering of the carbon content, and both oxide and carbon are so reduced in amount that the oxidation no longer takes place rapidly and near the surface of the metal; so the slag loses the foamy appearance. Indeed, as the silicon, manganese, phosphorus and part of the carbon have been oxidized, the bath of metal is becoming depleted of its reducing agents, so that more and more ferrous oxide penetrates or is dissolved by the metal, which fact, together with the decomposition of the limestone, gives rise to the formation of large bodies, or bubbles, of carbon monoxide deep down in or near the bottom of the layer of metal. These bubbles rise through the metal rapidly, so that when they strike the slag, it is not given time to part, but is lifted into the atmosphere of the furnace and thrown to one side.

**The Action of the Limestone:** It is interesting to note to what extent the decomposition of the limestone on the bottom of the furnace may contribute to this action and to the elimination of the carbon. The reaction representing this decomposition is $CaCO_3=CaO+CO_2$. Now, the carbon dioxide gas is no sooner set free than it is attacked by iron, thus: $CO_2+Fe=FeO+CO$. The FeO is then available for the oxidation of the carbon in the metal, thus: $FeO+C=Fe+CO$. By combining these two reactions it will be observed that, from each and every volume of carbon dioxide, $CO_2$, liberated, two volumes of carbon monoxide, CO, result. The CO derived from the decomposition of the limestone, as well as that from the action of dissolved FeO, escapes to the surface as just described. Any ore that might have remained at the bottom of the furnace up to this period of the carbon elimination would also contribute to the violence of this action. At the surface of the slag the carbon monoxide discharged by the bath may burn to carbon dioxide, which escapes with the products of combustion from the flame. The boiling of the bath thus plays a very important part in the process. When the slag is thrown aside by the bubbles of gas, the metal is exposed to the action of the flame, and though this exposure is but momentary in each instance, the large number of such exposures result in the formation of a considerable quantity of ferrous oxide in this way. But the greatest benefits are derived from the agitation of the bath. It is easily seen how this agitation must result in a mixing of the slag and metal, thus increasing the area of the reacting surfaces, while the stirring effect on the metal itself should not be overlooked. Thus, the metal lying near the bottom, which is the coldest and most impure, is brought upward to be heated and exposed to the oxidizing influences, so that both the temperature and composition of the bath are kept more uniform than they could otherwise be maintained.

**Effect of Carbon Elimination on Slag Composition:** In conclusion, it should be pointed out that the effect of the carbon elimination upon the slag is to reduce its content of iron oxides. By proper regulation of the conditions this reduction of the oxides in the slag may be brought down to the point where the total iron content of the slag will be about 10% of its weight, of which iron about 7/10, or 70%, will be in the ferrous condition. The advantages of adding ore to the charge, as may now be readily seen, are to increase the speed of the purification and to decrease the waste of metal, which is more expensive than ore.

**The Order of Elimination** of the elements just reviewed, with the exception of sulphur, is the same as the order in which they have been discussed, namely, silicon and manganese, phosphorus, and lastly carbon. Some reasons why the first three elements are eliminated in this order have been mentioned under their respective headings, but nothing has been mentioned that would appear to cause carbon, which is capable, under proper conditions, of reducing the compounds of all these elements, to be the last element oxidized in the open hearth. The explanation for this difference in the chemical properties of carbon is connected with the fact that its reducing power increases as the temperature rises. Again, chemical action, when it occurs independently of external influences, always takes place in the direction that will liberate the most energy, as was pointed out in Chapters I and VII. The oxidation of silicon, manganese, and phosphorus and the neutralization of the resulting oxides are exothermic reactions, whereas the carbon reaction is endothermic. The elimination of the four impurities thus takes place in accordance with the amounts of heat evolved or absorbed. As an example of these laws, let the elimination of silicon and carbon be compared. These reactions with the heat, or energy, values involved, are as indicated in the following expressions:

$$
\begin{array}{l}
(1)\ \mathrm{Si+2\ Fe\ O=\ Si\ O_2+2Fe(+64600\ cal.)} \\
\qquad -2(65700)\ +196000=64600 \\
(2)\ \mathrm{C+FeO=C\ O+Fe\ (-36540\ cal.)} \\
\qquad -65700+29160=-36540
\end{array}
$$

Reaction (1) shows that in the oxidation of one gram of silicon approximately 2307 cals. (64,600÷28=2,307) of heat are evolved, while in the oxidation of one gram carbon, as shown by reaction (2) 3,045 cal. of heat are absorbed. If now the reduction of silica and carbon monoxide by carbon and silicon, respectively, be compared as in reaction (3) and (4), it will be seen that, whereas carbon absorbs heat in reducing silica, silicon reducing CO, liberates heat. (3) $SiO_2$+C=2 CO+Si(—137640 cal.) (4) 2 CO+Si=
—196000 +2x29160 —2x29160
$SiO_2$+C(+137640 cal.) It is evident, then, that the oxidation of the carbon
+196000

cannot be complete until the silicon has been eliminated. At high temperatures, such as may prevail in parts of the blast furnace or in the electric furnace, for example, the heat absorbed in reaction (3) is supplied from external sources, which addition of energy causes the carbon to act as a reducing agent toward the silica. What has been said with respect to silicon also holds true in the case of manganese and phosphorus. In the basic open hearth the temperature rises gradually, so that carbon has no opportunity to act as a reducing agent toward oxides of these elements.

**Factors Opposing this Order of Elimination:** What has been written above should not be taken to mean that each element is completely and successively eliminated in the order mentioned, for there are other laws, such as the law of mass action, for example, that operate to bring about the elimination of these elements simultaneously. The oxidation of the carbon, for example, evidently begins shortly after the hot metal has been added to the charge, and certainly before the manganese and phosphorus have been entirely disposed of. What is implied is that the elimination of each element in the order named is successively in the ascendency until eventually only the carbon, in part, remains to be oxidized. When this element has been practically all removed, the bath of metal no longer contains reducing agents and is subject to over-oxidation by absorption of ferrous oxide, FeO, up to the point of saturation in equilibrium with the slag. This fact explains why it is undesirable to make ore additions to the slag just previous to tapping, and also why the heat, unless deoxidizing agents are added to the bath, should not be held in the furnace for more than a few minutes after the carbon content has been lowered to .10%, which figure is within about .03% of the minimum carbon content for this process.

**Resumé:** All that should now be required in order that the chemistry of this process may be fixed clearly in mind, is a rapid review of the subject matter included under the heading of Operation of the Furnace, which will now appear in a new light. To begin this review, picture a furnace in the course of operation which has received its charge of solid materials for, say, a Monell heat. The first effect on this charge will be an increase of temperature. The limestone, ore and the lining of the furnace all being basic in character, will remain inactive at first, and continue so until they will have absorbed sufficient heat to raise their temperature to the point where decomposition begins. For limestone this temperature is about 850° C., while the ore will not give up its oxygen until its temperature is near the fusion point, about 1400° C., unless it comes in contact with reducing agents. The absorption of heat by the ore and stone is hindered by the scrap charged upon them. This material, being a good conductor of heat and exposed to the flame, absorbs heat very rapidly, and as soon as the temperature rises above the thermo-critical range, oxidation of the iron begins, this giving rise to the formation of scale. The melting point of this scale is so near that of the metal, that it may remain on the surface until the metal itself begins to melt. It is understood, of course, that the impurities contained in the scrap will suffer oxidation with the iron. These fluids will trickle down over the colder material beneath and will eventually reach the ore on the bottom of the furnace. Here, together with additional oxide derived from the ore and some silica, lime, etc., collected from various sources, this molten scale will go to make up the first slag. This slag, poor in silica, but exceedingly rich in iron oxides, especially ferrous oxide, and containing some lime also, is well constituted for the work it has to do; and with the addition of the hot metal, the purification may begin at once. Thus, the silicon, manganese and phosphorus will have been practically eliminated from the metal within two hours after the molten metal is charged. The extent and character of the purification of the metal at the time of the run off with the resulting change in the composition of the slag are indicated in the following table of analyses.

### Table 34. Analyses of Hot Metal and Slag Before Charging and at Time of First Run-off.

| | | ANALYSIS OF METAL. Per cent. of | | | | | PARTIAL ANALYSIS OF SLAG. Per cent. of | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Heat No. | | C | Mn | P | S | Si | $SiO_2$ | FeO | $Fe_2O_3$ | MnO | CaO | MgO | $P_2O_5$ | $SO_3$ | S |
| 1 | Pig Iron Before Charging.......... | 3.85 | 1.55 | .198 | .035 | 1.04 | 4.72 | 66.67 | not det'md | 1.30 | 18.00 | 2.00 | .78 | .... | .... |
| 1 | At Time of Run Off.. | 2.39 | .05 | .022 | .040 | .04 | 19.19 | 32.86 | 5.22 | 12.97 | 18.38 | 6.11 | 1.11 | .... | .... |
| 2 | “ “ “ “ “ .. | 2.41 | .02 | .053 | .060 | .... | 25.18 | 17.39 | 4.07 | 13.16 | 17.88 | 12.18 | ...... | .090 | .029 |
| 3 | “ “ “ “ “ .. | 2.45 | .02 | .068 | .049 | .... | 23.68 | 26.33 | 7.10 | 13.54 | 12.22 | 10.14 | ...... | .090 | .027 |
| 4 | “ “ “ “ “ .. | 2.80 | .01 | .015 | .043 | .... | 15.74 | 45.16 | 7.50 | 6.19 | 11.34 | 5.23 | ...... | .165 | .037 |
| 5 | Briquettes Instead of Ore Used.......... | 3.74 | .01 | .043 | .037 | .... | 19.30 | 42.59 | 5.91 | 6.84 | 12.41 | 3.84 | ...... | .182 | .063 |

From this point the reader should be able to continue this review through the oxidation of the carbon unaided, and in doing so, he will have fixed in mind the chemistry of the process much more firmly than if he but read the inadequately expressed thoughts of another. As a further aid, what is said in Chapter V concerning final open hearth slags should be referred to.

# CHAPTER IX.

## MANUFACTURE OF STEEL IN ELECTRIC FURNACES.

### SECTION I.

### INTRODUCTORY.

**The Plan of Study:** To understand the process of manufacturing steel by means of the electric furnace requires some knowledge of electrical phenomena. To the question as to what electricity is, no very satisfactory definition can be given. The modern idea is, that it is the fundamental of which all matter is composed, because there is evidence to indicate that electrons are but corpuscles of negative electricity, which, together with nuclei of positive electricity, go to form atoms. That it is either a form of energy or an agent for transmitting energy is evident, and the various phenomena attending it may be due to the production of strained conditions in the Ether, somewhat similar to the effect of heat upon water in the generation of steam. However, the question is of no importance except to distinguish the thing from the phenomena produced by it, which are of great importance. To those who have not been able to devote much time or study to the subject, these phenomena appear as deep mysteries and are difficult to understand. This study may, therefore, be appropriately introduced by a brief explanation, presented in as simple a manner as possible, of such of the phenomena and laws of electricity as apply to the subject of steel manufacture by this method. To be of the greatest help to those unfamiliar with electricity, it is necessary to begin with the fundamentals and build up such a structure as the limits of space and time will permit.

**Force, Work, Energy and Potential:** In the industrial world the fundamental or prime factor is work. It is defined as the operation of overcoming resistance through space, or as the production of effects upon bodies. That which is the immediate cause of these effects is **force,** which is more accurately defined as that which causes, or tends to cause, a change in the motion of a body, in either velocity or direction. Thus, a column may exert a powerful force in supporting part of a building, because it tends to change the direction of motion the overburden would have if free to fall; but it does no work, because no effect is produced. Force is measured by the product of the mass of the body it acts upon and the acceleration (rate of change of motion) it produces. In the centimeter-gram-second (C. G. S.) system the absolute unit of measurement is the **dyne,** which is the force required to produce an acceleration of one centimeter per. sec. per. sec. in a mass of one gram. On the foot-pound-second (F. P. S.) system, the unit is the pound, which is the force exerted by gravity on a definite mass of matter. A similar unit on the centimeter-gram-second system is the kilogram, which is the force exerted by gravity on a mass of one kilogram. That which imparts to a body the ability to do work is energy. Both are, therefore, measured by the same unit. In the foot-pound-second system this unit is the foot-pound, or the work done by a force of one pound acting through a distance of one foot. In the centimeter-gram-second system a large unit is called the kilogram-meter, while a small unit, one dyne acting through a distance of one centimeter, is called the **erg.** The **joule,** equal to 10,000,000 ergs, is a more practical unit. Thus, if a weight of 10 lbs. is lifted against gravity to a distance of 5 ft., 50 foot-pounds of work has been done on that body, and 50 foot-pounds of energy was expended, and the same amount of energy is stored up in the body raised in the form of potential energy, which imparts to this body the ability to do work. In practice the body lifted would be said to have its potential raised, or a difference in potential has been effected between this position of the body and (the same body in) its former position.

**Power:** It will be noticed that work is independent of time. The time rate of doing work is called power. In the foot-pound-second system the unit is the horse power, (h. p.), which equals 33,000 foot-pounds in one minute or 550 foot-pounds in one second. It is based on experiments in which it was found that the work an average draft horse can perform continually without over-exertion is equivalent to lifting a weight of 150 pounds vertically while travelling at the rate of 2.5 miles per hour. In the centimeter-gram-second system the unit is the **watt,** which is that power that will do one joule of work in one second. The large unit equals 1000 watts and is called kilowatt. This unit is employed in electrical work. 1 kilowatt= 1.34 h. p., or 1 h. p.,=746 watts=.746 kilowatts. Since energy is conserved, power can be supplied only by creating a difference in potential.

**Transmission of Energy:** In the mechanical world it is often desirable, for economical reasons, to create this potential difference at some central point, known as the power station, from which the power may be distributed by proper means to various other points and applied as required. For the transmission of energy there are four agencies, namely, gases, such as steam; fluids, such as water; electricity; and the Ether. In certain respects the characteristics exhibited by any one of these agencies in use is similar to each of the others. In the first case the difference in potential is maintained by making use of the potential, or chemical energy, of fuels to generate steam, which may be conducted through pipes to impart motion to engines and do work upon matter, or to give up its energy as heat. Similarly, water may be made to transmit energy by causing it to flow through pipes from high levels to lower ones. Somewhat analogous to the flow of the water, is the passage of the electric current along a wire. In each case means must be taken to maintain the flow by keeping up a difference in potential. In the case of water, a pump could be inserted in a circuit for returning the water to the higher level as rapidly as it flows downward. In practice a pump would be impracticable, but the sun accomplishes the same thing by vaporizing water so that it rises into the atmosphere to fall again as rain, and thus complete the circuit. In electric circuits this difference in potential is maintained by means of the electric battery, the static machine, or the dynamo, the last of which will be briefly described later. The close similarity between these two cases will be readily observed by a study of the following table of analogues, in which the water is assumed to be flowing through a horizontal pipe at the point of examination:

**Table 35. Hydraulic—Electric Analogues.**

| Functions of the Currents | | Hydraulic Units | Electromagnetic Units |
|---|---|---|---|
| **Hydraulic** | **Electric** | | |
| Pressure | E. M. F. or Voltage | Pressure per sq. in. or Head in feet | Volt. |
| Quantity | | Pound | Coulomb. |
| Rate of flow | Amperage | Pounds per second | Coulombs per sec. or Amperes. |
| Friction | Resistance to conduction | Loss in Head,<br>No unit | Ohm. |
| Work | Electrical Energy | Foot-pounds | Joule. |
| Rate of Work | Wattage | Horse-power or watt | Watt or Volt—Ampere. |

One important point of difference between the transmission of water and electric current is evident; namely, that whereas water passes through a hollow tube, electrifications pass along solid bodies, usually wires. It is also common knowledge that electrifications will pass along some substances very easily and only with difficulty, or not at all, along others. No substance is so good a conductor as not to offer some resistance to the transfer. Substances that offer little resistance are called conductors; those in which the resistance is great, non-conductors or insulators. In the following table, the substances named are arranged in the order of their conductivities:

**Table 36. Relative Conductivity of Various Substances.**

**Conductors**
Metals
Graphite
Acids
Salt water
Linen
Cotton
Dry wood
Paper
Silk
India rubber
Porcelain
Air
Glass
Sealing-wax
Rubber
Vulcanite
**Insulators**

**Electromotive Force (E. M. F.):** While a definition of the various electrical units at this time would be out of place, occasion should be made to explain electrical pressures. Just as hydraulic pressure might be called water-moving force, so pressure produced electrically is called electromotive force (e. m. f.). As indicated above, the unit of measurement for electromotive force is the volt, which is also the unit for measuring difference in potential. In practice electromotive force and difference in potential are different things. Electromotive force refers to the total electrical pressure existing in a circuit, whereas difference in potential is merely the difference in electrical pressure between two points on the circuit.

## SECTION II.

### THE DEVELOPMENT OF ELECTROMOTIVE FORCES—OR "GENERATION OF CURRENT."[1]

**Methods for Setting up Electric Currents:** As already indicated the difference in potential between two points, which is necessary to produce an electric current, may be created by different methods, of which the most common and useful are the following: 1. By friction, as in the electrophorus, or electrostatic machine. 2. By chemical action, such as that which takes place in the electric battery, or voltaic cell. 3. By electromagnetic induction, as in the dynamo. In all these cases, energy must be expended to produce the difference in potential, and the points of different potential must be connected by a conductor. Electrostatic machines, while they produce a high electromotive force, generate only a small quantity of electricity in a given time. Current produced in this way has, therefore, a very limited use. In the voltaic cell these conditions of current are reversed, the amperage being high and the voltage low. The dynamo can be made to give current high in both voltage and amperage. It is, therefore, the most useful of all electrical machines, and is the source from which the current required by the electric steel furnace is obtained. This being the case, a discussion of the principles involved in the working of this machine should be both interesting and instructive. To an observer not familiar with the subjects of magnetism and electricity, the dynamo appears as a machine for changing motion into electrical energy, and, in a way, this idea is correct. But the generation of the current is not due to motion alone. Other phenomena, known as magnetism and induction, are involved, and to understand the generation of the current these must be studied first.

**Magnetism:** The attractive force of magnets upon iron is well known. Upon investigation, it is found that every magnet possesses two poles, designated as North and South, N. and S., or + and —, from which lines of force issue, and that these lines of force protrude into the space surrounding the magnet and extend from pole to pole. In studying the action of one magnet upon another, the following laws are observed: 1. Like magnetic

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[1] For a fuller study of the generation, transmission and ultilization of the electric current see the standard text books on Physics, also Practical Electricity by Terrel Croft and Applied Electricity for Practical Men by Arthur J. Rowland. Published by McGraw-Hill Book Company, Inc., New York.

poles repel one another; while unlike poles attract one another. 2. Lines of force having the same direction, i. e., issuing from like poles, repel each other; those of opposite direction attract. All these facts are illustrated in the accompanying figures, which are diagrams made from photographs of actual conditions.

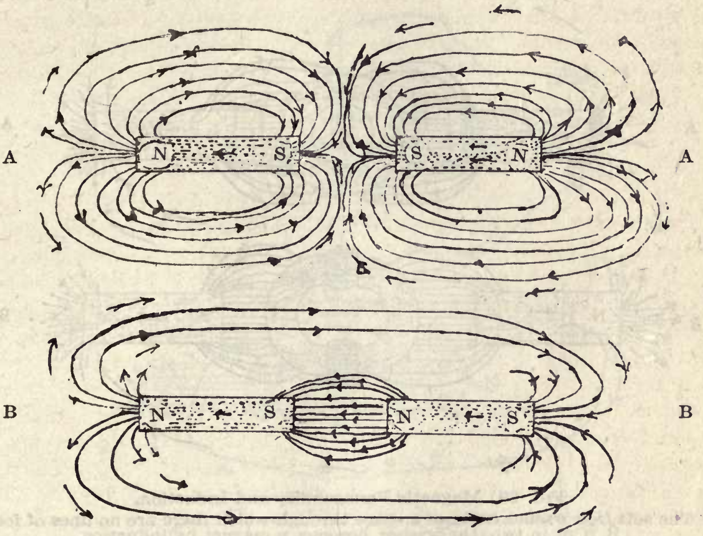


Fig. 28. Diagrams of Sections through the space surrounding magnets showing lines of force between like (A) and unlike (B) poles. Anyone may study these lines of force for himself by securing two bar magnets, some iron filings, and a piece of paper. The paper is laid upon the magnets and the filings are sprinkled upon it. The filings are thus magnetized and arrange themselves in lines or curves corresponding to the lines of force.

**Magnets and Magnetic Substances:** Magnets may be natural or artificial. Most magnets are artificial and may consist of straight bars or rods as shown in the figure, or be curved, as is the case with horse shoe magnets. These magnets may be either permanent or temporary. Permanent magnets are made of hard steel and retain their magnetism indefinitely, whereas temporary magnets are made of soft steel and are magnets only so long as they are under the influence of a magnetizing force. The space surrounding the magnet through which lines of force pass is called the magnetic field, and the number of lines is referred to as the magnetic flux. Substances that are attracted by a magnet or are magnetized when placed in a magnetic field are called magnetic substances. While it can be shown that most substances are affected by magnetism, iron, its alloys, and one oxide, $Fe_3O_4$, are the only substances available for use. These lines of force cannot be insulated, for they pass through all substances, but by the use of a permeable substance, like very soft steel or iron, they may be deflected from their course and concentrated in the mass of iron as shown in A of Fig. 29.

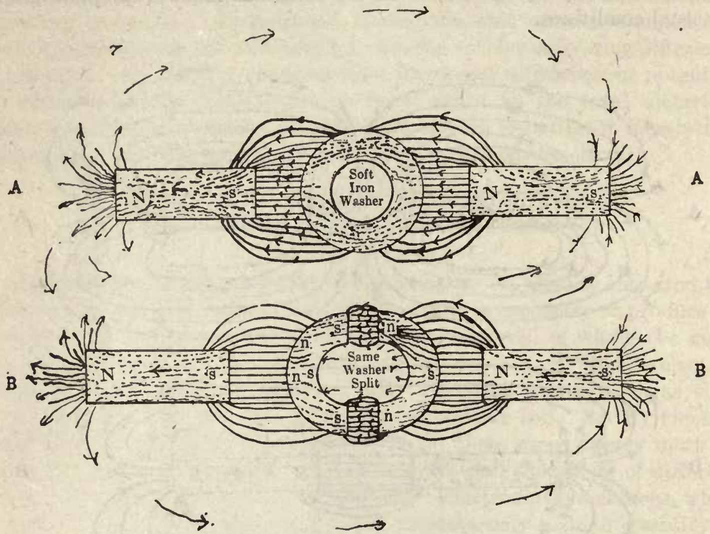


Fig. 29. Magnetic Permeability and Induction.
A. The soft iron washer encloses a space through which there are no lines of force.
B. Cut in two, the washer becomes a magnet by induction.

**Magnetic Fields and Electric Currents:** These magnetic lines of force are closely associated with the electric current, for it is easily shown that every current bearing conductor is surrounded by a magnetic field, the lines of force in which form circles concentric with the conductor. These lines of force have a definite direction as in the case of ordinary magnets, and this direction bears a fixed relation to the direction of the current, as shown in A of Fig. 30. This fact is made use of in producing the electromagnet, by coiling the conductor, properly insulated, about a core of soft iron, as shown in C of Fig. 30. Such a coil is known as a helix or solenoid, and has poles similar to magnets. The various relations between flow of current, lines of force, and poles of the helix are shown in the figure. The wide application of these facts cannot be discussed here, except in so far as they have to do with the development of an electromotive force, or, as this is more commonly referred to, the generation of the electric current. In connection with the generation of currents, this question might arise: If a current produces a magnetic field about a conductor, will the production of a magnetic field about a conductor result in a current? This question is now to be answered by a brief study of electromagnetic induction.

**Electromagnetic Induction:** The easiest way of bringing about such a condition as noted in the preceding paragraph is described in the following experiment: If a coil of many turns of fine copper wire is connected to a delicate galvanometer and one end of a bar magnet is thrust into it, the galvanometer needle will be deflected, showing that a current is set up in the coil As long as the magnet remains stationary, no current will pass. Upon suddenly withdrawing the magnet, however, a current will again pass, but the direction of this second current is opposite to that of the first. If these operations be repeated with the other pole of the magnet, similar currents will be induced, but in directions opposite to those obtained when the first pole is used. Instead of moving the magnet, the coil can be moved with a like result, and in place of the magnet a solenoid can be substituted. In the last case it may not be necessary to move either the solenoid or the

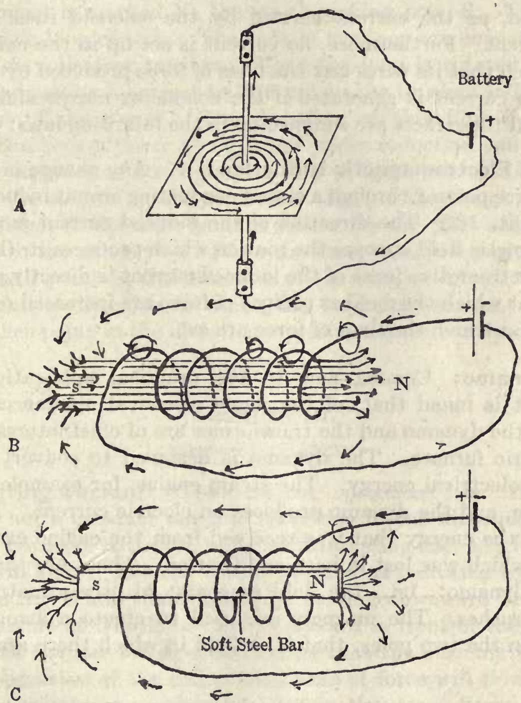


Fig. 30. Magnetic Fields About Current Bearing Conductors.
A. Lines of force about a wire carrying a direct current.
B, Lines of force in the current bearing helix.
C. The Electro-magnet. The lines of force pass into the soft steel bar, which becomes a magnet by induction.

coil, as current can be set up in the coil by breaking the circuit or otherwise interrupting the current in the solenoid. From these facts it would seem that the sole cause of the current is the change in magnetic flux. Further study of these phenomena reveals the fact that the current induced is affected by the speed with which the magnet may be inserted and withdrawn, and the number of wires in the coil. In the case of the solenoid a third factor is introduced, as the current carried by the solenoid itself affects the induced current. Furthermore, no current is set up in the coil unless the motion is such that its wires **cut** the lines of force produced by the exciting elements: no current is generated if the conductor moves **along** the lines of force. All these facts are summed up in the following laws:

**Laws of Electromagnetic Induction:** 1. Any change in the number of lines of force passing through a closed conducting circuit induces a current in that circuit. (2) The direction of the induced current is always such that its magnetic field opposes the motion which produces it (Lenz's law). (3) The electromotive force of the induced current is directly proportional to the rate at which the number of lines of force are increased or decreased, or, the rate at which the lines of force are cut.

**The Dynamo:** Coming now to the practical application of these principles, it is found that, of the many electrical appliances depending upon them, the dynamo and the transformer are of chief interest in a study of the electric furnace. The dynamo is designed to convert mechanical energy into electrical energy. The steam engine, for example, does work on a dynamo, and the dynamo produces an electric current. This current contains all the energy that was received from the engine except a small percentage which was lost in heat and friction. There are three essential parts of a dynamo: 1st., the field magnets; 2d., the armature; 3d., the collecting brushes. The magnets are used to create a strong magnetic field between the two poles, that is, a field in which there are many lines of force.

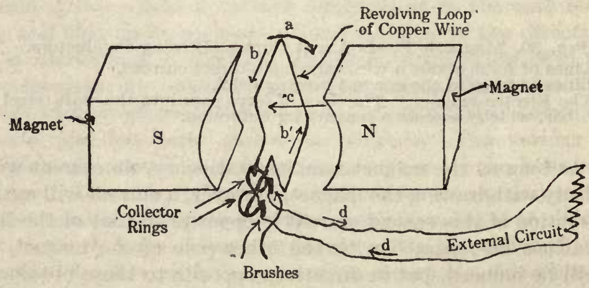


Fig. 31. Diagram Illustrating Essential Parts and Principle of the Dynamo. a. Direction in which loop revolves. b and b′. Direction of current through loop. c. Direction of lines of force. d and d′. Direction of current in external part of the circuit.

Hence, in all large dynamos electromagnets are used. The armature consists of coils of wire wrapped around a soft iron core; it is mounted so as to rotate in the magnetic field and cut lines of force. The current is thus generated in the manner described under induction. The essential parts of a dynamo are shown in the diagram of Fig. 31, which illustrates the arrangement for a drum wound armature. The north-seeking pole of the field magnet is marked N; the south-seeking pole, S. The armature is here a single loop of wire. The ends of the loop are connected to rings which rest on collecting brushes. When the loop is rotated, it cuts the lines of force, causing a current to flow out to the brushes and through the external part of the circuit. The direction of this flow bears a fixed relation to the lines of force as explained under induction and as shown in the figure. In practice the following rule is employed to determine the direction of the current in the armature. Extend the thumb, first finger, and middle finger of the right hand in such a manner that each will be at right angles to the other two. Place the hand in such a position that the first finger will point in the direction of the lines of force (N. to S.) and the thumb in the direction in which the conductor moves. The middle finger will then point in the direction in which the current flows.

## SECTION III.

### KINDS OF CURRENT.

**Alternating Current:** The current produced in the dynamo armature is not a constant one and travelling in one direction, such as is obtained by means of batteries, but is an alternating one, as a further study of Fig. 31 will show. Let the coil be rotated as indicated by the curved arrow above it. While the side at b is moving downward in front of the pole N., the side at b′ will be moving upward in front of the pole S. An application of the law for direction shows that the currents thus induced by the two branches of the coil cutting lines of force will flow in opposite directions in relation to each other, but in the same direction from end to end around the coil. This current continues as long as **b** and **b′** are moving in the same direction across the lines of force—that is, during one-half of one complete rotation. Then, as the rotation continues, the sides of the coil cut the lines in an opposite direction, and the current is completely reversed. Each time the coil is turned half way around, the direction of the current is changed. Each end of the coil is attached to a ring. The rings are attached to the axis of the coil and rotate with it. Brushes slide upon the rings and conduct the current out upon the line of the external circuit. The line current is thus changed in direction twice during each complete rotation of the coil or armature. Each change in direction is called an alternation. Two alternations constitute a cycle—that is, a circle or series of changes which will be repeated in the next cycle. The time required for one cycle is the period. The number of cycles in one second is the frequency. The frequency is one-half the number of alternations in one second. In modern forms of alternators the frequency is seldom more than 60 nor less than 25 cycles per second. To produce 60 cycles in a second with a machine like that shown in Fig. 31, the armature would have to make 3600 rotations in one minute. To avoid such high speed, a number of pole pieces are arranged in a circle around the armature, making what is called a multipolar machine. These poles are wound so that north and south-seeking poles alternate in position. A cycle is then produced in the circuit by the passage of any two adjacent poles. If there are ten poles, there are five cycles during one rotation of the armature. A current of 25 cycles per second would mean 50 alternations per second or 3000 per minute; on a two pole machine it would require 1500 r. p. m.; on a 10 pole, 300 r. p. m. The latter is about as low a speed as a machine can be operated upon economically. These are some of the reasons why it is not practical to operate alternators on cycles over 60 nor under 25.

**Graphic Representation of Alternating Current:** The surges of the current are approximately harmonic, hence the electromotive force may be represented by the sine curve, as shown in Fig. 32. This figure shows one complete wave or cycle, as taking place in ½ second of time, and going from zero through a positive maximum and back to zero, where it continues to a negative maximum to return again to zero, thus completing a cycle. The different stages of vibration represented in the graph are spoken of as phases. Thus b and b′ are in the same phase, but b and h′ are in opposite phases, etc.

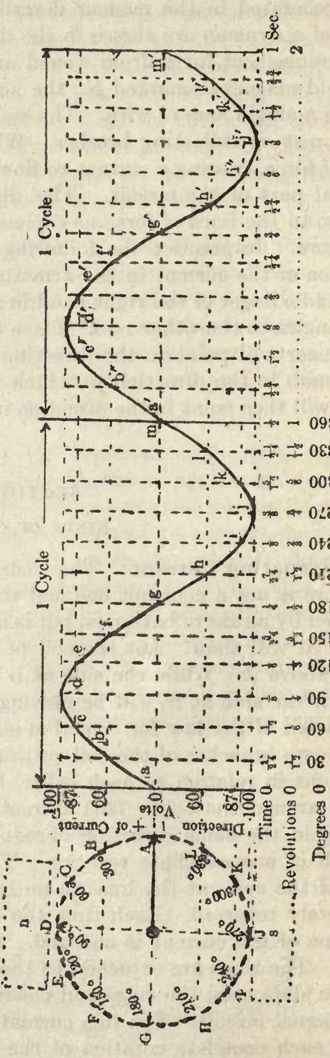


FIG. 32. Diagram illustrating the sine curve used to represent the flucating voltage and amperage of an alternating electric current. This particular curve is for voltage. The curve for the amperage would be similar, but unless the resistance is one, the numerical values would be different.

**Direct Currents:** While all dynamos produce alternating current in the armature, this current may be changed to a direct one by means of a commutator properly connected to the armature. How this is done can be understood by a study of the accompanying figure.

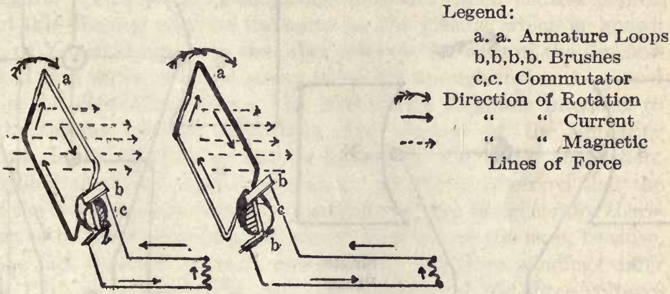


Fig. 33. Diagram Illustrating how Current is Rectified by means of a Commutator

For reasons to be given later, direct currents are not used in furnaces for refining iron and steel.

**Polyphase Currents:** In order to increase the efficiency and output of alternators, recourse is had to polyphase current. These currents are the result of attempts to put to economic use the interpolar space, or surface of armature core, which is only partly filled in by conductors in single phase machines. In any given machine of this kind, which involves certain given mechanical and magnetic losses, approximately only half of this space is utilized. This waste of space and consequent inefficiency can be removed by utilizing the space devoted to the core of the coil for the winding of other coils, and thus form a second armature of an equal number of coils overlapping the former and utilizing the same magnetic field. In this second armature the phase of the current would be a quarter period, 90 degrees, ahead or behind that of the first, and so would require four wires to carry the currents to and from the generator. The output of the machine, however, has been doubled. Further attempts to increase output have resulted in electrical engineers going even further and constructing triple armatures, in which the phase of the currents generated differ by equal intervals of 1/6 of a period, or 60 degrees. But this scheme then leads to considerable elaboration, if the circuits be totally independent with six conductors, and very little advantage could be shown to exist over the two-phase with four lines. However, in cases where it is possible to arrange that the demand in the different circuits be approximately equal and evenly distributed, the three phase system can be worked out to great advantage by using only three conductors. By referring to the accompanying diagrams (Figs. 34 and 35) it will be seen that, at any moment whatever, the sum of the electromotive forces in the three circuits is zero. In other words, the electromotive force on one line is always equal to that on the other two, and opposite in kind. Thus, at any instant one of the three wires is to be looked upon as the return wire for the other two.

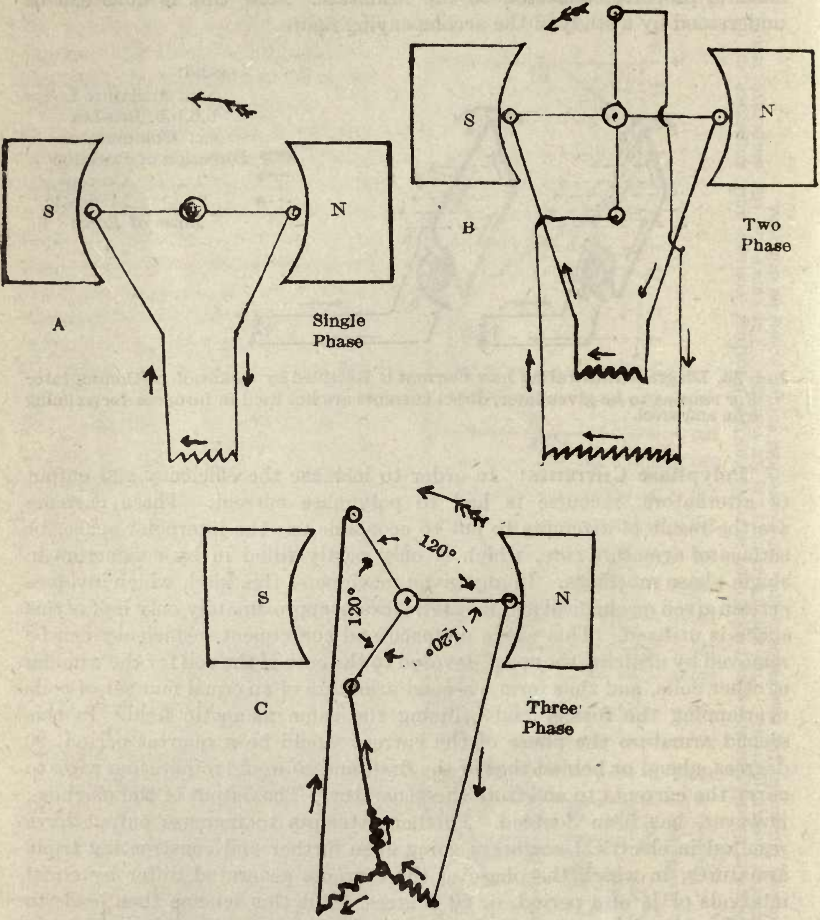
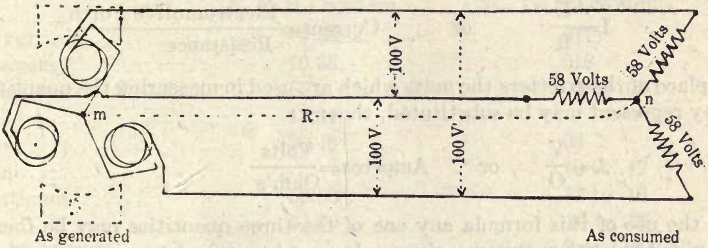
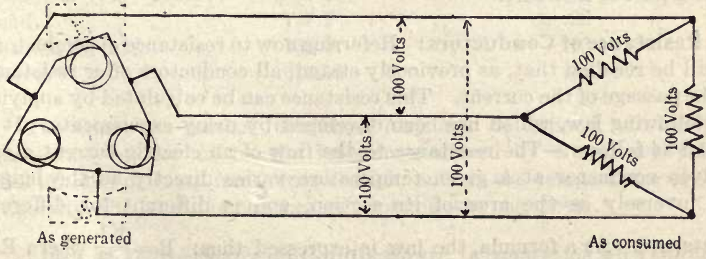


Fig. 34. Diagrams Illustrating The Methods of Generating the Three Kinds of Alternating Current.

**The Two Schemes of Wiring for Three Phase Current:** The coils of the three phase current alternator, as well as those of the apparatus that is to consume the power, may be connected in two different ways with each other as shown in the following diagrams. In these diagrams the three phase generator is considered as a compound machine made up of three separate machines. In such a machine, the separate units may be wired independently as shown in Fig. 35A. Instead of three return wires, one common return wire may be employed, as shown by the dotted line R in the figure. But it is found that, with balanced loads on each system, R is a neutral line, that is, no current flows through it; consequently, it is omitted as in the figure. The points m and n are therefore called neutral points. The form of this diagram suggests the name for the scheme, which is known as the star, or Y, connection. In the other schemes the coils of the dynamo are connected in a series, and the power is led off through mains connected to points in the connecting lines. Fig. 35B shows diagrams intended to illustrate the scheme for this connection. On account of the similarity to the Greek letter Δ, this scheme is known as the delta connection. It is also called the V and mesh connections. It will be observed that the windings of the delta connection form a closed circuit, and the generator therefore appears to be short circuited. However, such is not the case, because, owing to the fact that the currents generated by the three windings differ in phase by 120°, as shown in Fig. 34C, the resultant of the three voltages is at every instant zero, hence no current can flow by way of the short circuit. With this plan of connections the load may be balanced or unbalanced as each coil or set of windings supplies its own load.



**A. Diagram of Star (or Y) Connections.**



**B. Diagram of Delta (Mesh or V) Connections.**

**Fig. 35 Diagrams Illustrating the Two Methods of Winding and Wiring for Three-Phase Currents.**

These connections are of importance in understanding how the power of 3-phase currents is transmitted. They also affect the voltage employed, the relations being as shown in the preceding diagrams. The Duquesne furnace, for example, operates on 104 volts with star connections and 180 volts with the delta. This care in explaining three phase current has been taken, because it is the most common kind of current and is used in the Heroult furnace, the details of which will be explained later.

## SECTION IV.

### TRANSMISSION OF THE CURRENT.

**Ohm's Law:** With this brief explanation of the generation of the current, it will be well to turn next to the problem connected with its transmission. Here, also, it is necessary to begin with the simplest essentials. The most fundamental idea in this connection can be briefly stated in the form of a law, known as **Ohm's law.** This law states that the strength of current passing along a conductor varies directly as the electromotive force, or drop in potential, and inversely as the resistance. This law is generally put in the form of a formula, thus:

$$I=\frac{E}{R} \quad \text{or} \quad \text{Current}=\frac{\text{Electromotive Force}}{\text{Resistance}}$$

In place of these letters the units which are used in measuring the quantities they represent may be substituted, thus:

$$A=\frac{V}{O} \quad \text{or} \quad \text{Amperes}=\frac{\text{Volts}}{\text{Ohm's}}$$

By the use of this formula any one of the three quantities may be found, provided the other two are given. It may be applied to an entire circuit or to a part of a circuit.

**Resistance of Conductors:** Referring now to resistance of conductors, it will be recalled that, as previously stated, all conductors offer resistance to the passage of the current. This resistance can be calculated by applying the following law, which has been developed by many experiments. It is stated as follows:—The resistance to the flow of an electric current along a given conductor at a given temperature varies directly as the length and inversely as the area of its section, and is different for different substances. As a formula, the law is expressed thus: $R=\frac{Kl}{d^2}$ where R= resistance, l=length, $d^2$=square of the diameter, which is directly proportioned to the area, or the area itself, and K=specific resistance of the substance. In the foot-pound-second system, l=length in feet, and d= diameter in **mils,** or thousandths of an inch. A **circular mil** is the area of a circle one **mil** in diameter. So if the diameter of a wire is expressed in mils, $d^2$=the area in circular mils. The **circular mil** is not to be confused with the **square mil** which is the area of a square having sides 1/1000 inch long. The area of a circle in square mils, the diameter of which is expressed in mils $=\frac{\pi d^2}{4}$. In this connection the following formulas may be found of assistance:

1. sq. mils=cir. mils×0.7854 2. cir. mils$=\frac{\text{sq. in.}}{.0000007854}$

In wire, a length of one foot and a diameter of one mil constitutes a **mil-foot.** The specific resistance of any substance is the resistance of one mil-foot. In the following table are the specific resistances of a few substances, determined for this system, at 60° F. In the metric system, l=meters, $d^2$=sq. millemeters, and, of course, K has a numerical value different from that by the foot-pound-second system, as shown in the table.

**Table 37. Specific Resistance of Various Substances.**

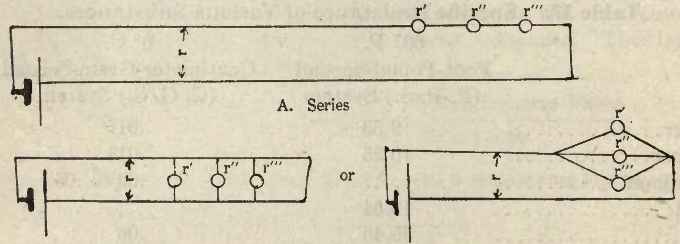
| | 60° F.<br>Foot-Pound-Second<br>(F. P. S.) System | 0° C.<br>Centimeter-Gram-Second<br>(C. G. S.) System |
|---|---|---|
| Silver................ | 9.53 | .017 |
| Copper............... | 10.35 | .018 |
| Aluminum............ | ...... | .03 to .05 |
| Gold................ | 13.34 | ........ |
| Zinc................. | 36.46 | .06 |
| Iron................. | ...... | .10 to .12 |
| Platinum............ | 58.00 | .12 to .16 |
| Steel................ | 63.00 | .10 to .25 |
| Molten Steel.......... | ...... | 1.66 to 2.2 at 1700° C. |
| Nickel............... | ...... | .15 |
| Lead................ | 127.2 | .22 |
| German Silver........ | 135.0 | .15 to .36 |
| Mercury.............. | 616.16 | .94073 |

The Ohm, the unit of resistance, may now be defined. It has been established by law to be the resistance offered by a mercury column 1.063 m. long of 1. sq. mm. cross section, and at the temperature of 0° C. Originally, the length of the mercury column was one meter.

**Effect of Temperature on Conductors:** In connection with the effect of temperature upon conductors, it should be noted that there are two classes of substances, known as conductors of the first class and conductors of the second class. In conductors of the first class, which includes all the metals, the resistance increases with a rise in temperature, hence their conductivities decrease. This is shown in the case of steel, which at 15° C.

has a specific resistance of only .10 to .12, whereas at 1700° the specific resistance of the molten metal is about 1.66. In the case of carbon and conductors of the second class, these relations are reversed, so that they become better and better conductors as their temperatures rise. As all the refractory materials that go into the construction of furnaces belong to this class, this matter must be carefully considered in building electric furnaces.

**Resistance in Series and Parallel.** In the preceding paragraph, only single substances were considered in the circuit. In the actual distribution and use of power, it is generally necessary to divide circuits, in which divisions different materials or machines will also make up a part of the circuit. This division and connections can be made in two ways, namely, series and parallel, as shown in the following diagram illustrating two methods of light wiring.



A. Series

B. Parallel

**Fig. 36. Diagram Illustrating Different Methods of Wiring.**

In Fig. 36 A, the resistance of the line is r and of each of the lamps it is r', then the whole resistance, R, is the sum of these four, or

$$R=r+r'+r''+r''' \text{ or } R=r+3r'.$$

Resistance of conductors connected in parallel is not found so simply. It is deducted from the law of conductivities, which states that the conductivity of a combination of conductors is equal to the sum of the conductivities of the conductors singly. Now, it is self evident that the conductivity is represented by $\frac{1.}{R}$ The resistance in the parallel connections above would then be found by solving the following:

$$\frac{1}{R}=\frac{1}{r}+\frac{1}{r'}+\frac{1}{r''}+\frac{1}{r'''}$$

This matter is of importance in dealing with electric furnaces, as shown in the following schematic diagram of the wiring of Heroult and Girod furnaces, which marks the chief difference between these two furnaces.

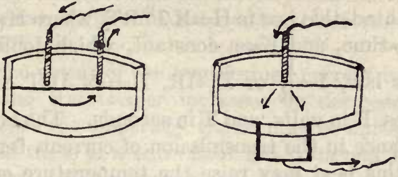


**Fig. 37.** Wiring Diagrams for Heroult and Girod Electric Steel Furnaces.

These diagrams show the Heroult furnace, on the left, to be connected in series and the Girod in parallel.

**Currents Through Divided Circuits:** If the different parts of parallel connected conductors have equal resistance, then equal currents will flow through these parts, as is evident from Ohm's law, thus,

$$I=\frac{E}{R} \qquad I'=\frac{E}{R'}$$

As the current is always delivered at a constant voltage, E is the same in both cases; hence, if $R=R'$, $I=I'$. If the resistances are not the same, then I would not equal $I'$. The current flowing in each conductor, however, can be found from the following law: Currents which flow parallel to each other vary inversely as the resistance of the parallel connected conductors.

**Self-induction, Impedance, Power Factor:** In dealing with alternating currents, Ohm's law does not hold, for the alternations cause **self-inductance** in the conductor, that is, they generate currents opposite in direction, or kind, to that of the main current; and this inductance also offers resistance to the current in addition to that offered by the conductor. The sum of these two forces opposing the passage of the current is called **impedance.** If impedance be substituted for resistance, then Ohm's law holds for alternating currents, also. Again, any self-induction in the circuit causes a difference in the phase between the electromotive force (voltage) and the current (amperage), so that the latter either forges ahead of or lags behind the former, and the two do not reach their maxima and minima together. Consequently, their product at these points, which represents the energy available for consumption, is less than the total energy supplied. The ratio, expressed in per cent., between the useful voltage, or that which is required to overcome the resistance of the conductors and to produce the heat or do any other work desired, and the actual voltage required is called the **power factor.**

**Heat Developed in Conductors:** Since all conductors offer resistance to the flow of the current, work is done in overcoming this resistance. In doing this work part of the electrical energy is converted into heat energy, just as work is done and heat developed in overcoming friction. This heat can be calculated by means of Joule's law, who found from many experiments that the heat developed by a current flowing through a conductor is directly proportional to the time, to the resistance, and to the square of the current. Mathematically stated, this law is $H=K\ I^2\ RT$, where H=heat, I=current, R=resistance, T=time, and K=a constant, which Joule found to be .24. Since from Ohm's law, $I=\frac{E}{R}$ or $E=IR$, $H=.24\ IET$ colories, when I is measured in ampres, E in volts, and T in seconds. The heat thus developed is of much importance in the transmission of current, for if the current be sufficiently large this heat may raise the temperature enough to burn off the insulation, or even to melt the wire. This heating can be overcome in two ways. In the first method, the diameter of the conductors could be increased, which would decrease the resistance and increase the carrying capacity. That this method has its limits is evident, due to the immense weight of wire required in some cases where large current (amperage) is required, as is the case with electric furnaces. The second method is applicable to alternating current only and illustrates both the adaptability of the electric current in general and one advantage of alternating current in particular. From Joule's law it is evident that a current of large voltage may be carried on a given wire provided the density, i. e., amperage per circular mil or square millimeter be kept low. Since power=amperes × volts, or for alternating current Power=amperes × volts × power factor, this can be done without reduction in power. But since the furnace requires a current of low voltage and high amperage, such a current could not be used unless means be taken to change this high-voltage-low-amperage current into one of low voltage and high amperage. How this is done can be learned from the following description of the transformer.

**The Stationary Transformer:** In this instrument the desired transformation is effected by electro-magnetic induction already discussed. Of course, then, only those currents which are started and stopped or increased and decreased in rapid succession, or those in which the direction of the current is changed many times in a second, can be transformed. Such current is furnished by the alternator. In structure the transformer consists of two coils of wire side by side with a core composed of many sheets of soft iron, or a special silicon steel, packed together. The coils must not have any metallic connection with any part of the instrument. The first coil, that through which the main current flows, is called the primary. The second coil, or that in which the current is induced, is called the secondary.

**Kinds of Stationary Transformers:** Transformers are of two kinds—step-up and step-down. The step-up transformer increases the voltage and decreases the amperage. The step-down produces the opposite effect. The change depends on the relative number of turns of wire in the primary and secondary coils. If, for example, there are 100 turns in the primary and 1000 turns in the secondary, the voltage will be increased 10 times and the amperage decreased 10 times. This is then a step-up transformer. A step-down transformer would reverse these conditions throughout. If there are the same number of turns in both coils, the current will not be changed except as it may be affected by the transformer efficiency, which should be about 98%.

In regard to the power of the transformed current it will be seen that, since, whenever the transformer increases or decreases the voltage, it decreases or increases the amperage, the number of watts will be a constant quantity. Suppose there is a current of 100 volts and 10 amperes flowing through the primary. The power is then 1000 watts. If the transformer raises the pressure to 500 volts, the strength of the current will fall to 2 amperes, but the power of the current is still 1000 watts. A good transformer gives out nearly all the energy that is put into it. A small percentage, varying from 2% to 5% of the voltage, is converted into heat. Usually this heat is prevented from collecting by immersing the coils in cylindrical tanks of oil so constructed as to form a circulating system through pipes extending externally from the top to the bottom of the cylinder. These pipes act like a hot water radiator and serve to keep the whole bath and its contents cool. The oil also serves as an insulator. For steel furnaces three phase 25 cycle current is stepped down from 6600 volts to 104 on the star connection or 180 on the delta, the latter of which is seldom used on molten charges.

## SECTION V.

### THE UTILIZATION OF THE CURRENT IN ELECTRIC FURNACES.[1]

**Effects Produced by Electric Current:** The heating and magnetic effects of electric currents have already been touched upon in connection with generators, conductors and transformers. In order to understand how the electric current is utilized in electric furnaces it is necessary to study these and other effects from a slightly different standpoint; namely, their effect upon the metallic charge in the furnace itself. In this connection it may be truly said that there is but one other effect produced by the electric current, and this effect is that of bringing about chemical action. To the question as to what chemical action is caused by the current in the bath of steel, the correct answer is: There is none. As this answer is not in accord with chemical effects produced by currents in other metallurgical operations, an explanation may be necessary.

**Chemical Action Produced by the Electric Current:** As pointed out in Chapter I, electrolysis is brought about when electric currents are passed through liquids under certain conditions, some well known examples being the dissociation of water and the electrolytic separation of aluminum. In these instances, however, it will be observed that these chemical changes occur only when direct current flows through the electrolytes. If alter-

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[1] For a full discussion of electric furnaces See The Electric Furnace by Alfred Stansfield, Published by McGraw-Hill Book Co., Inc., New York, Electric Furnaces in Iron and Steel Industry, by C. H. Vom Baur, published by John Wiley & Sons, New York, and Electric Furnaces for Making Iron and Steel by Dorsey A. Lyon and Robert M. Keeney Bureau of Mines Bulletin 67.

nating current is used, then the direction of the current is constantly changing, and no action, such as noted above, can take place. Furthermore, such action would be harmful in carrying out the electro-thermal process for steel. While it might be possible with direct current to purify the metal by removing the impurities as sulphides, silicides, and phosphides, there would be no way of controlling the process so as to prevent the reduction of lime, alumina and other oxides, the elements from which would then find their way into the metallic bath. This reduction would result in a more impure product than the raw material. Designers of electric furnaces for the iron industry will, then, use alternating current exclusively and strive in every way to prevent any electrolytic action that might result in electrolysis.

**Electrical Units of Measurements:** The subject of electrolysis offers an opportunity to define another of the primary units used in electrical measurements. The ohm has already been defined in studying resistance. It now remains to explain how the value of the ampere is fixed. If a current be made, by means of suitable electrodes, to pass through a solution of silver nitrate, metallic silver will be deposited upon the cathode, or positive pole, and the amount of silver thus deposited in a given time will be proportional to the strength of the current. This fact has been made the basis for fixing the value of the ampere. The legal definition reads as follows:—The **ampere** is that current which when passed through a 15% neutral solution of silver nitrate will deposit .001118 grams of silver in one second. **The volt** is then legally defined as the e. m. f. which will cause a current of one ampere to flow through a resistance of one ohm. In fixing the value of these units, it was arranged so that the power possessed by a current of one ampere under a pressure of one volt is just equal to one watt. Hence the power of the current in watts equals the product of the amperage and voltage, or $W = V \times A$. The **watt-hour** is the energy expended in one hour when the current is one ampere and the voltage, or pressure, one volt. Hence, 60 watts used for one min. or one watt used for 60 min. will give one watt hour. A **kilo-watt-hour**=1000 watt hours.

**The Magnetic Influence of the Current** can be of but slight importance to the metallurgist. To the designer of induction furnaces they are of double importance. On account of a certain motor effect which they produce in the molten metal, these forces cause what is known as the pinch effect which will often break the circuit. In arc furnaces this motor effect is present in the immediate vicinity of the electrodes causing a slight motion of the bath.

**Heating the Bath:** It is to be understood, then, that the only use to which the current is applied in the manufacture of steel is for the generation of heat. It may be well, therefore, to consider briefly the heating possibilities of the current in connection with its practical application to this purpose. A little thought shows that these possibilities are only three in number, and may be called heating by direct resistance, heating by indirect resistance, and heating by means of radiation from an arc or arcs. A brief discussion of the three methods, which is also made to serve as a means of describing the principles of the many makes of furnaces, follows:—

**Heating by Direct Resistance:** In the method of heating by direct resistance, the necessary heat to keep the bath molten is produced by making use of the resistance of the iron itself. In some respects this method would appear to offer some advantages. 1. Since heating is effected by the passage of the current through the liquid metal, the heat would be uniformly distributed throughout the mass. 2. Since the heat generated is proportional to the square of the current, the amount of heat could be regulated by changing the resistance of the furnace. 3. Very low voltage currents could be used. But the disadvantages outweigh the advantages, as will be realized better if they are set along side the advantages, thus: 1. As the specific resistance of iron is low, the high temperature required could be obtained only by the use of very high amperage, which would require exceedingly heavy connections. 2. This draw-back could be overcome by increasing the length of the bath and decreasing the cross sectonal area; but such an arrangement has been found impracticable on account of the large area the bath then covers, which results in great heat losses and precludes the easy change of slags and handling of the metal. Hence, all early attempts to employ direct resistance for heating proved failures. The problem was, however, eventually solved by the invention of the type of furnace known as the induction furnace. In these furnaces the bath is made to form the closed secondary circuit of a transformer. This secondary can then consist of but one coil, as shown in the following diagram illustrating the principle of the induction furnace as invented by Colby and Ferranti and later improved and adapted to the manufacture of steel by Kjellin.

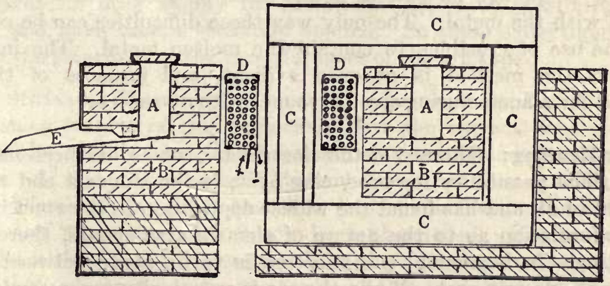

FIG. 38. Diagram Illustrating Principle of Induction Furnaces. Vertical Section of Kjellin Furnace.

The furnace includes a magnetic circuit, C, formed of the usual laminated sheet iron, as in a transformer core. Electric energy is supplied to a primary coil, D, while the secondary circuit is formed by the ring of metal under treatment, contained in the annular cavity, A, forming the crucible. Now, when energy, in the form of alternating current is supplied to the primary coil, D, it creates a varying magnetic flux in the laminated iron core, which in turn induces a current in the closed secondary circuit consisting of metal in crucible A. The current density in the secondary bears a fixed ratio to the number of turns in the primary coil D, so that it is possible by a suitable variation in impressed voltage to subject the metal to an extremely heavy current density, the heat being thus produced in accordance with Joule's law simultaneously throughout the entire mass of the metallic bath. Because of the limited contact area between slag and metal, this type of furnace does not readily lend itself to refining processes, if the form shown in the figure be adhered to. However, this form was later changed so as to give a central hearth of considerable size. Those who have designed furnaces with the object of improving the Kjellin type are Frick, Hiorth, Harden, Greene, and others. On account of the low specific resistance of iron, it is difficult to reach high temperatures in these furnaces. They are, therefore, not well adapted for desulphurizing operations in which sulphur is removed as sulphide.

**Indirect Resistance Heating** offers a second possibility. Instead of depending upon the resistance of the bath alone to furnish the heat required, some other conductor having a high resistance might be built into the furnace in such a way that the heat generated in it would be absorbed by the material to be heated. This is the principle employed in many laboratory furnaces and in large furnaces for manufacturing carborundum. But in applying the method to the manufacture of steel several insurmountable difficulties are presented. 1. The resister can not be composed of carbon and in contact with the metal, on account of the absorption of this element by iron. 2. If a suitable resister of another material could be found, it could not be placed in the bath, because it would then be in parallel with the metal. The only way these difficulties can be overcome is by the use of crucibles to contain the molten metal. The impracticability of this method is at once evident, and furnaces of this type designed for manufacturing steel have met with no success.

**Arc Heating:** The use of the electric arc, which has been mentioned as the third possibility for producing heat, is the simplest and the most practical of all and has found the widest application in the steel industry. Some information as to the nature of electric arcs should, therefore, be interesting. In beginning, a distinction is to be made between electric sparks and electric arcs. While the air is practically a non-conductor, it is possible to create such a high difference in potential between two given points as to cause a current to jump the gap and establish equilibrium. Such conditions occur in electrical storms, and lightning is an example of electric sparks. In arcs the current also passes through the air, but it will be observed that a much smaller voltage is required to form an arc than is needed to cause sparks. The most common example of the arc is the arc lamp. Here the arc is made between two carbon electrodes, but in order to strike an arc it is necessary to bring the electrodes into contact, after which a gap may be gradually produced and the arc still maintained. If the gap becomes too wide, however, the arc will break, hence means of regulating the distance between the electrodes must be provided. Evidently the air is not the conductor in arcs as in sparks. All these phenomena are explained by assuming that some of the electrode material is vaporized by the heat of the arc, and that these vapors serve as a conductor of the current. Some idea of the intensity of the heat of this arc, which gives the highest temperatures yet attained, is to be had from the fact that carbon vaporizes at about 3500° C.

**Methods of Applying the Arc in Arc Furnaces:** Furnaces of this type, then, depend almost wholly upon this high temperature of the electric arc for the heat required by iron and steel baths. The following diagrams will illustrate the three possible methods of applying the arc and heating the bath.

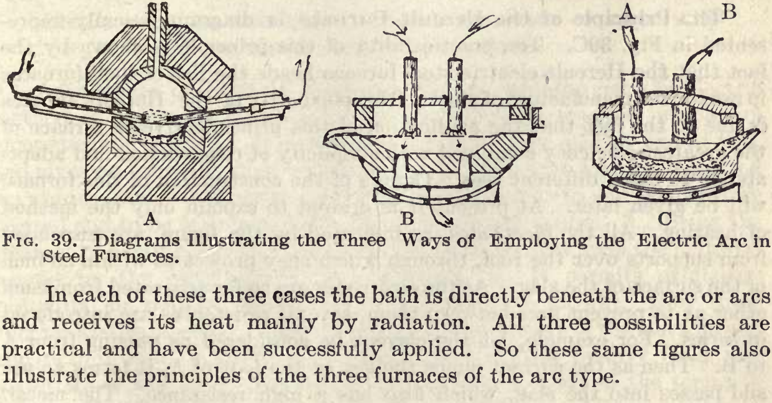

Fig. 39. Diagrams Illustrating the Three Ways of Employing the Electric Arc in Steel Furnaces.

In each of these three cases the bath is directly beneath the arc or arcs and receives its heat mainly by radiation. All three possibilities are practical and have been successfully applied. So these same figures also illustrate the principles of the three furnaces of the arc type.

**The Stassano Furnace** is represented in principle by Fig. 39A. The distinguishing feature of this furnace is that the current does not pass through the metal or slag, the heating being accomplished entirely by radiation. At first, Stassano built his furnaces so that they could be rocked or rotated in order to agitate the bath, but as this feature did not prove to be of any advantage, it has now been abandoned. His furnaces are now of the tilting type. In practice three phase current is generally used, and the three electrodes enter the furnace at an angle through the walls. This plan has the effect of placing a limit to the size of the furnace, and so few of these furnaces with a capacity greater than two tons have been built. From an electrical standpoint, the furnace possesses the important advantage of uniform power consumption, thus avoiding harmful fluxuations in current.

**Girod Furnaces:** The furnace scheme shown in Fig. 39B has been developed by several inventors. It was first successfully introduced by Girod for the purpose of manufacturing ferro-alloys. As shown in the figure the electrodes are inserted in both the top and the bottom of the furnace, thereby connecting electrodes, slag and molten metal in series. Heat is thus produced in three ways, theoretically at least. By means of an arc at the top, the greater portion of the heat is generated. After forming the arc, the current, in its downward courses, must pass through the layer of slag which, through the heat of the arc above, becomes a conductor of the second class, after which the current is conducted by the molten metal to the electrodes at the bottom. In furnaces using a single phase current, these bottom electrodes are four or six in number and are equally spaced about the periphery of the hearth. In the three-phase furnaces there are four upper electrodes, two of which must be in parallel, and sixteen bottom electrodes. In all cases the bottom electrodes are made of steel and are water cooled. Other designers of this type of furnace are Keller, Grönwall, Nathusius, Stobie and Soderburg.

**The Principle of the Heroult Furnace** is diagrammatically represented in Fig. 39C. The practicability of this principle is shown by the fact that the Heroult electric steel furnace heads the list of such furnaces in use for the manufacture of steel. This popularity of the Heroult furnace is due to the fact that the application of this principle gives a furnace of the greatest efficiency combined with simplicity of construction and adaptability to many different uses. Details of the construction of this furnace will be given later. At present it is desired to explain only the method of heating. All the electrodes, as indicated by the figure, are suspended from supports over the roof, through which they project to within an inch of the surface of the slag. As the electrodes are so far separated from each other as to prevent arcs between them, several resistances are introduced in series. For example, let the current be considered as passing from A to B. Then as the current jumps the gap at the foot of A, it forms an arc and passes into the slag, which also has a high resistance. The metal, having a much lower resistance, then acts as a conductor for the current to the region directly beneath the foot of electrode B, where the current must again pass through the layer of slag and form a second arc as it jumps the gap between slag and electrodes. It is evident that practically all the heat is formed by the arcs above the slag, **which acts as a shield to the metal** and protects it both from the carbon vapors thrown off from the foot of the electrode and from the exceedingly high temperature at this point. Portions of this heat is next imparted to the metal through the slag, where it may be distributed to all parts of the bath by conduction and convection. The distribution of the heat is thought to be aided by a slight motor effect produced by the current upon the metallic bath. Furnaces of this type using single phase and three phase current are in use. The only change necessary to be made for three-phase current is the insertion of a third electrode. In the development of these furnaces Heroult stands almost alone, though slight modifications have been introduced by Chaplet and Anderson.

**Some General Conclusions:** From what has been said, the following facts are evident: 1. That the only part the electric current plays in the manufacture of steel is in the production of heat. 2. That for producing this heat there are really but two methods available, which has resulted in two successful types of furnaces, namely, the induction type and the arc type. 3. That from a strictly metallurgical point of view no one of these types represents any marked advantage over the other, in their present high state of development. This statement has no relation to claims of the inventors to mechanical and electrical points of excellence in their respective apparatus. What advantage electric heating has over other methods of heating is now to be discussed.

## SECTION VI.

### GENERAL FEATURES PERTAINING TO THE METALLURGY OF STEEL MADE BY ELECTRO-THERMAL PROCESSES.

**Advantages of Electric Heating:** To the metallurgist the electric method of heating is an ideal one for the following reasons, which are characteristic of it: 1. It makes heat available very quickly and at will, and gives an unusually high temperature. 2. The heat may be regulated very nicely, which fact permits a charge to be brought to any temperature desired and to be maintained steadily at that temperature. 3. Being the cleanest of heating agents, it exerts no deleterious effect upon the material heated by the evolution of harmful gases. 4. It permits **oxidizing. reducing** or **neutral** operations to be carried on at will. How these characteristics of electric heating work to the advantage of the metallurgist and permit him to obtain a product of the highest quality from raw materials of any grade will be understood from a study of the topics to follow. In this connection the chemical possibilities are of first importance.

**Refining Procedure:** The first effect of the characteristics noted above is to bring the whole operation of refining metal under complete control. The electric furnace is to the metallurgist what the casserole and crucible are to the chemist. The bath, then, represents a mixture of compounds and elements, any one of which may be removed at will by the use of the proper reagents. The condition may be illustrated by assuming a furnace is to be charged with the crudest of raw materials, cold pig iron, and then showing how each impurity is removed. A study of the practice of many plants shows that the following procedure would be carried out: After the furnace has received its metallic charge, an oxidizing flux of lime and iron ore will be added. A part of this flux may be charged ahead of the metal, exactly as in the case of the basic open hearth. After the charge has been melted down, the furnace will be tilted slightly and the slag which has formed will be carefully raked off. This addition of flux and removal of slag will be repeated as often as may be necessary. A cleansing flux of lime alone will then be added and raked off. During this period the temperature should be kept low, because phosphorus is not readily oxidized at high temperatures in the presence of carbon. The bath will then be covered with a flux consisting of about 5 parts lime, 1 part sand or other form of silica, 1 part fluorspar, and ¼ part of carbon in some convenient form, such as coke, coke carbon, old electrode, etc. The furnace will then be tightly closed, and the temperature raised. In the case of induction furnaces, it will be found necessary after about two hours to introduce small portions of ferro silicon, silico-aluminum, or silico-spiegel. These alloys act energetically as deoxidizers and form a fluid slag which rises to the surface. In the Heroult furnace carbon is the only deoxidizer used. After the steel shall have been thoroughly deoxidized, any carburizing material or alloys will be added to bring the steel to the desired composition. When all such material will have been melted, and sufficient time will have elapsed to permit them to mix with the bath, the molten steel will be poured as a finished ingot product. This process divides itself into three distinct periods, namely, an oxidizing period, a reducing period, and a finishing period, a combination of conditions impossible of attainment in any other process. The action brought about during each of these periods, and the reasons for using the reagents employed may now be discussed.

**The Oxidizing Period:** It is evident that the action of the oxidizing flux must result in the removal of silicon, manganese and phosphorus in a manner similar to that of the basic process. The important distinction between open hearths and electric furnaces should be noted here. It is this: All the oxygen introduced into the electric furnace must be in the solid form as observed above, and the amount can be easily controlled, whereas the air admitted to open hearths furnishes an unlimited amount of oxygen that cannot be controlled. Therefore, since these three elements are easily oxidized at low temperatures before the carbon, the reaction may be stopped and the bath held at almost any carbon content desired. With respect to phosphorus, it has been suggested that this element may be removed as phosphide by means of some metal, as calcium. While this scheme is theoretically possible, it is still impracticable, for it is a difficult thing to find a metal that would not alloy with iron in preference to combining with phosphorus, or whose phosphides would not so alloy. Quite frequently, traces of phosphorus are found in the reducing slags, but this method of eliminating phosphorus, though often attempted, has not been made successful beyond the removal of very small amounts and at great expense. Hence, the only sure way of removing this element is to oxidize it to phosphoric acid, neutralize with lime, and rake off the resulting slag. In refining purer materials than pig iron, where the removal of silicon and manganese would not be required, the oxidizing slag is called the dephosphorizing slag. Considerable sulphur is removed during this period in the electric furnace, especially where an ore high in manganese is used, whereas in the basic furnace, its removal is a very uncertain quantity.

**The Reducing Period:** This is the period in which the electric furnace exhibits its great superiority over other modes of refining iron. During the period, the bath is almost completely deoxidized by means of carbon alone, and the removal of sulphur is positive and can be made almost complete. Its entire removal seems to be impracticable, as a content of less than .010% is obtained only after prolonged and expensive treatment. The flux added is, therefore, called either the desulphurizing or deoxidizing flux.

**Oxygen:** Oxygen occurs in steel principally as FeO, as has been stated in previous chapters, in which its harmful effects were also dwelt upon. Its removal may be represented by the following equation in which M may represent a great number of suitable elements:

$$FeO+M=MO+Fe.$$

The deoxidation may be brought about in the induction furnace only by means of the special deoxidizers previously noted, whereas in the Heroult furnace carbon alone may be employed. The use of carbon alone has been objected to because it was argued that the use of this element would give the oxide, CO, which is a gas, and the formation of this gas in the metal is objectionable. That steel at high temperature either combines with or dissolves this gas is fairly well established, for by experiment it has been shown that a given steel has a higher melting point in an atmosphere such as nitrogen than it has in an atmosphere of carbon monoxide. There is also good reason to believe that this gas is again liberated at certain temperatures on cooling. If this be true, then deoxidizing with carbon may give opportunity for formation of blow holes and other defects in the ingots. Some metal, then, whose oxide is a solid that will easily come to the surface as slag is to be preferred for this purpose. This metal must not be volatile at high temperatures and must dissolve or alloy with the iron. The metals that best meet these requirements are the ferro-alloys of manganese, silicon, vanadium, titanium, and metallic aluminum. For many reasons manganese, silicon and aluminum have proved the most satisfactory deoxidizers. How the carbon, acting through one or more of these elements, may be used to accomplish the deoxidation without injury to the steel is well illustrated by the practice at Duquesne, to be described later.

**Removal of Sulphur:** According to the statements of authorities upon the subject, sulphur may be removed in five ways: (1) As calcium sulphide, formed by the action of lime and carbon on ferrous sulphide at the high temperature of the arc furnace; (2) As calcium sulphide from the reaction of lime, ferrous sulphide, and calcium carbide at the higher temperatures of the arc furnaces; (3) As calcium sulphide through the reaction of lime, ferrous sulphide, and silicon at the lower slag temperatures of the induction furnace; (4) As calcium sulphide through the reaction of calcium fluoride, ferrous sulphide, and silicon; (5) As iron sulphide from the action of ferrous oxide on calcium sulphide. The reactions illustrating the removal of sulphur in electric furnaces are as follows:

(1) $FeS+CaO+C=Fe+CaS+CO$. Occurs in arc furnaces only.

(2) $3\ FeS+2\ CaO+CaC_2=3\ Fe+3\ CaS+2\ CO$. in arc furnaces only.

(3) $2FeS+2CaO+Si=2Fe+2CaS+SiO_2$.—Used with induction furnaces.

(4) $2CaF_2+2FeS+Si=2CaS+SiF_4+2Fe$. May occur in either induction or arc furnaces.

(5) $FeS+CaO \rightleftharpoons CaS+FeO$. May occur in arc furnaces.

An inspection of these reactions shows that certain requirements must be met before the elimination of sulphur can be brought about. Thus, in all cases a highly basic slag is essential, and in no case can desulphurization be effected before deoxidation of the metal and slag has been accomplished. The importance of the presence of elementary carbon or silicon is evident, and both these elements tend to react with iron or manganese oxides rather than with sulphides and lime. Furthermore, reaction (5) is reversible, acting from right to left in the presence of very slight oxidizing influences. Because of the relation in concentration maintained between oxides in the metal and oxides in the slag, both deoxidation and desulphurization of the metal may be brought about by additions of carbon to the slag, if the temperature is sufficiently high. In arc furnaces this method is employed almost exclusively; but induction furnaces, owing to their lower temperatures, require that desulphurization be effected by the use of silicon as shown in reaction (3) and (4), both of which take place at much lower temperatures than (1) and (2). In the arc furnace complete deoxidation of metal and slag is recognized by the presence of calcium carbide in the slag.

**The Finishing Period:** With the dephosphorization and subsequent deoxidation of the bath, the contents of the furnace may be brought to a neutral or slightly reducing state, when the final additions may be made for finishing the steel to specifications. In order to save time it is a common practice to make some additions before the desulphurizing period commences, especially if the additions are to be made in large quantities, which would chill the bath if added all at one time. As the conditions are reducing or neutral, loss of alloying elements is reduced to a minimum, and the composition of the steel can be controlled with precision. The ability to finish the steel in the furnace gives the electric process another advantage over any of the older processes, also, as this practice tends to produce greater uniformity in the steel.

**Some Comparisons:** When deoxidation of the bath is complete the contents of the electric furnace represents the nearest approach to perfect chemical equilibrium that has yet been attained in other large metallurgical operations. In the converter and the open hearth the metals are subjected to the action of air and gas; in the crucible the metal takes up carbon and silicon; but in the electric furnace, the action of the metal on the basic lining being very slight, there is no exchange of elements between metal and slag, if traces of phosphorus be excepted.[1] Of course, if the dephosphorizing slag of the oxidizing period has not been completely removed before deoxidization begins, some of the phosphorus compounds in this slag, as well as some in the new slag, will be reduced. However, with careful watching, this gathering-up of phosphorus by the metal may be entirely avoided. As to the relative merits of the various types of electric furnaces, the results obtained are about equal. However, it is evident that arc furnaces are well suited for reducing processes, while induction furnaces lend themselves most readily to oxidizing purposes.

**Fluxing Materials** used in the electric furnace should be as pure as possible and free from injurious amounts of sulphur or phosphorus. The lime and fluorspar should not contain more than small amounts of magnesia, as it makes the slag less fusible, which fact is of great importance when the high basicity of the slags is considered. For recarburizing, a material low in volatile matter, phosphorus, and ash should be used. At Duquesne, anthracite coal is chiefly employed.

**General Manufacturing Practice:** As indicated previously, the electric furnace may be used to refine pig iron direct. But as the major portion of the refining may be accomplished much more cheaply by one of the older methods, direct refining is not economically practiced at present. Two courses of procedure, therefore, remain. In the one, cold scrap iron and steel of any grade as to quality is remelted and refined to produce steel of high quality, while in the other the electric furnace is made part of a duplexing process, whereby it is used in conjunction with one of the older methods of refining to produce superrefined plain steels or alloy steels. This second plan is the one used by the U. S. Steel Corporation. At the South Chicago Works, the electric furnace is used in conjunction with Bessemer converters and tilting basic open hearth furnaces, and may be used in the finishing stage of either a duplex or a triplex process; but in either case the steel finished in the electric furnace is taken from the open hearth. At Duquesne the duplexing is in connection with basic open hearths only, and to furnish a concrete example of the construction and workings of the electric furnace this plant will be described.

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Lyon and Keeney, Electric Furnaces for making Iron and Steel. Bureau of Mines Bulletin 67, Page 125.

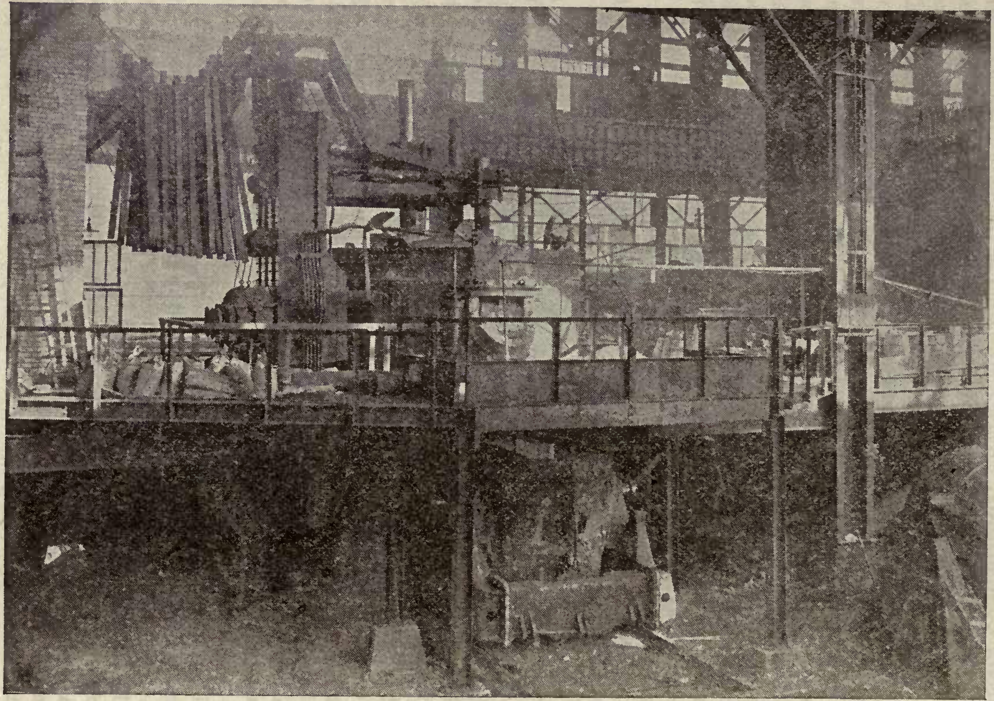


Fig. 40. Heroult Electric Furnace. General View—from pouring side.

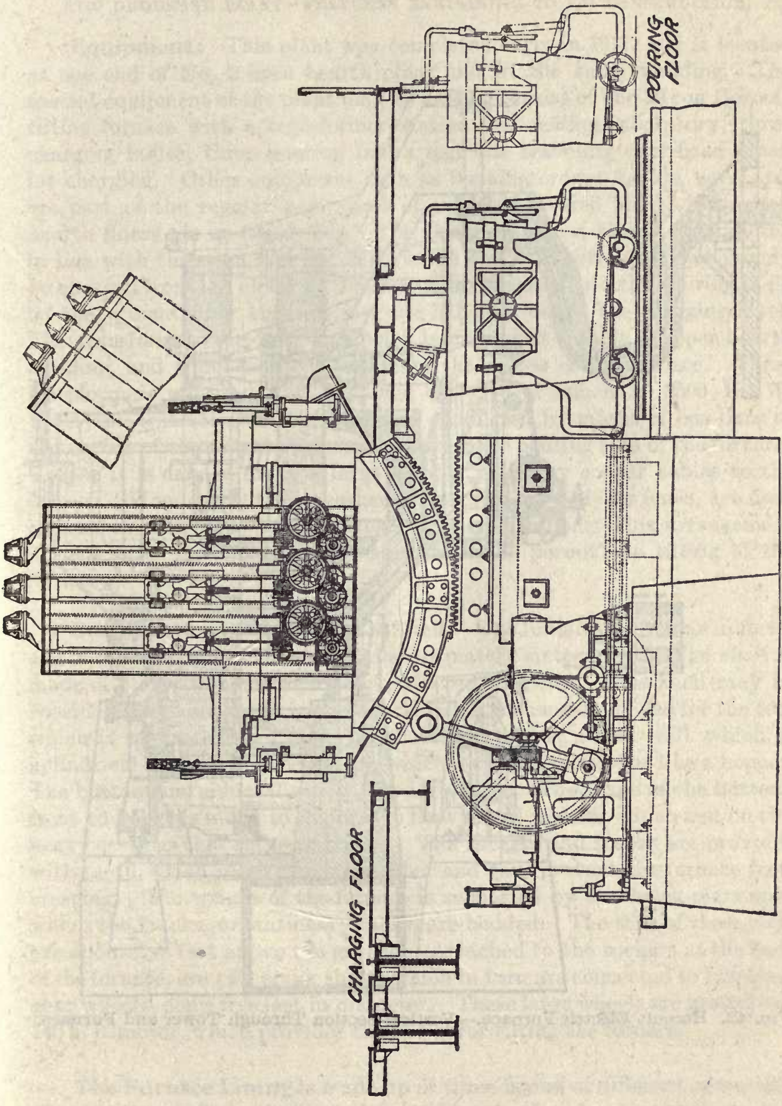


FIG. 41. Heroult Electric Furnace.—Drawing from Tower Side.

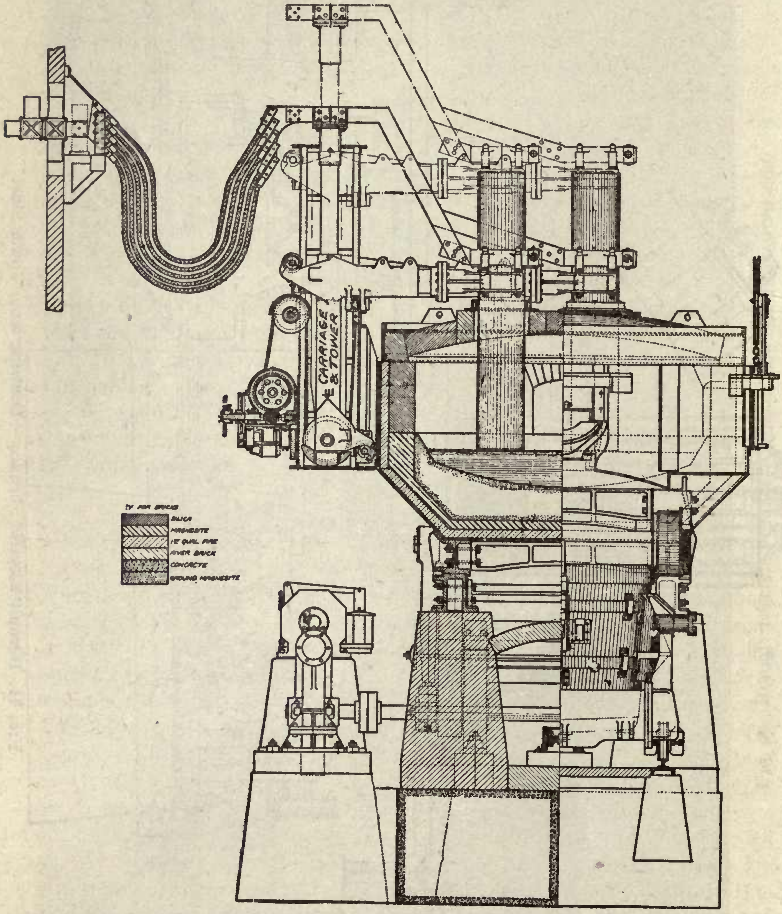


**Fig. 42.** Heroult Electric Furnace.—Vertical Section Through Tower and Furnace.

## SECTION VII.

### THE DUQUESNE PLANT—FEATURES PERTAINING TO ITS CONSTRUCTION.

**Equipment:** This plant was completed early in 1917, and is located at one end of No. 2 open hearth plant and in the same building. The special equipment of the plant may be said to consist of one 20-ton Heroult tilting furnace with a transformer station and testing laboratory, three charging ladles, three pouring ladles and one traveling over-head crane for charging. Other equipment such as teeming cranes, molds, cars, etc. are part of the regular equipment of the open hearth plant. The open hearth floors are on two levels. The electric furnace, therefore, standing in line with the open hearths, is elevated and so constructed that it may be charged from the charging floor level, and tapped into the pouring ladle on the ground floor thirteen and one half feet below the charging level. The transformer station is in a brick building just outside the open hearth building, and about eighteen feet from the center of the furnace. Three transformers are used, the combined capacity of which is 3500 K. W. From the transformers the current is conducted by means of bus bars to the corner of the transformer house nearest the pouring side of the furnace. Thence it is carried along a large number of heavy copper cables to the furnace. Wood bars, tied together like sections of a picket fence, are used to insulate the three lines of cables from each other. This arrangement furnishes the flexible connections necessary to permit the tilting of the furnace.

**Construction of the Furnace Shell:** The furnace is circular in form, and has an outside diameter of approximately sixteen feet. The shell is made of plate steel one inch thick, riveted together. This shell may be considered as being made in these three parts: a channelled band for the top, which is removable and made up of riveted plates; a side wall which is cylindrical in shape; and a bottom, which is shaped somewhat like a hopper. The bottom and side walls are riveted together. The shape of the bottom, front to back, is made to conform to heavy steel rockers, which rest on two heavy castings that serve as tracks. The rockers and tracks are provided with teeth, which mesh into each other and thus prevent the furnace from creeping. The weight of the furnace is supported by two brick piers upon which the tracks, or stationary racks, are bedded. The tops of these piers are about five feet above the ground. Attached to the rockers at the back of the furnace, are two crank shafts which in turn are connected to two large gear wheels, some five feet in diameter. These large wheels are geared to a 140 h. p. motor, which provides the power for tilting the furnace.

**The Furnace Lining** is made up of three layers of different materials. Next to the shell, in the bottom and sides, is placed a four and one half inch layer of fire brick laid edgewise, and upon this is laid a continuous bottom and side wall of magnesite brick. The bottom course is nine

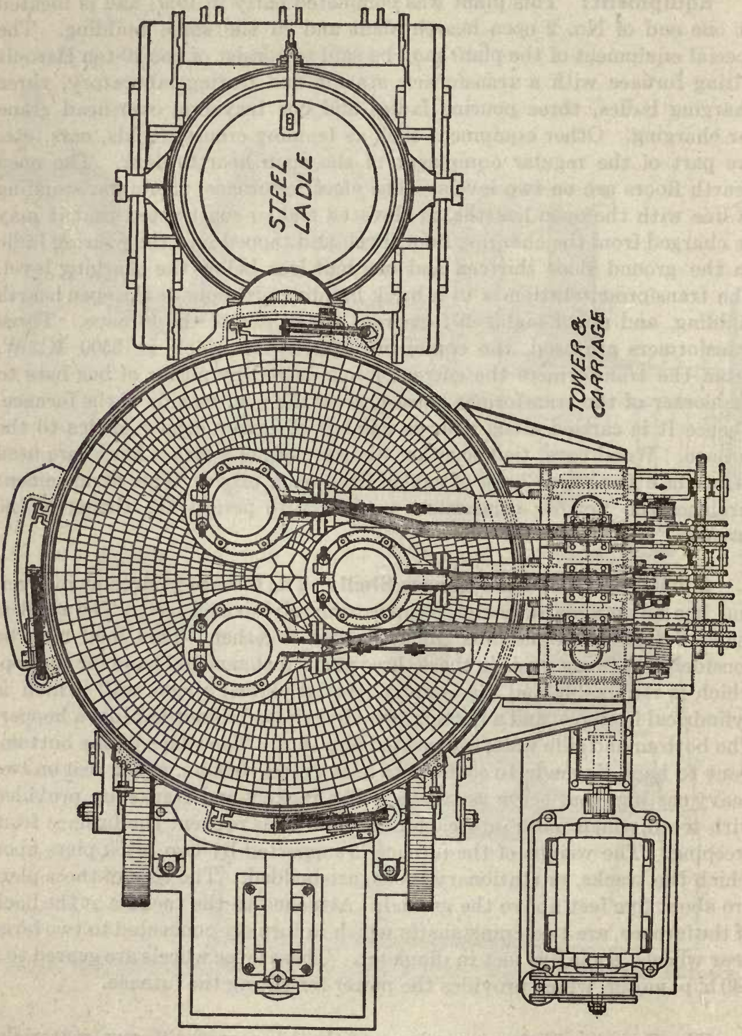


FIG. 43. Heroult Electric Furnace.—Perspective Drawing from Top.

inches thick, while the side wall is thirteen and one half inches in thickness. Upon the bottom brick is then sintered a layer, about thirteen inches thick, of dead burned magnesite, which is banked on the sides to a safe distance above the slag line.

**The Roof** is slightly dome-shaped, twelve inches in thickness, and made of silica brick set in on end. The first course next the channelled band is made up of large skew-back brick. Thus, the roof is made self-supporting. As a roof lasts for forty to seventy heats only, two extras are held in reserve, ready to be placed in case a roof fails unexpectedly. In the roof, three openings are made for the electrodes. Each opening corresponds to one vertex of a equilateral triangle, each side of which is about six feet long, and the center of which is the center of the roof. When in place, the roof sets so that one vertex points toward the vertical guides for the electrodes, which are on the side of the furnace next the transformers. While in use, the top is bolted to four brackets on the shell to prevent the top from slipping when the furnace is tilted.

**Controlling the Electrodes:** Through the three openings, noted above, the electrodes extend into the furnace for a distance of about four feet. In order to make the electrodes adjustable, they are attached to horizontal arms that project out over the furnace from heavy vertical rods arranged to move up and down within vertical guides. At the top of these rods and properly insulated from them, the cables that carry the current from the transformer house to the furnace are bolted and welded to bus bars which lead to the electrode holders. Thus, the same motion is imparted to both the electrode holders and the bus bars. Each of these rods is supported and moved by means of a cable attached to its base and leading over a small drum geared to a small electric motor. These motors act through automatic regulators, which serve to keep the end of the electrode at the proper arcing distance from the bath. By reversing a switch on the switch board, these motors may be operated independently of the regulator. Furthermore, the lifting device is provided with a hand wheel, so as to be operated like a common windlass, whereby the electrodes may be regulated by hand.

**The Electrode Holders** are made in two parts, both of which are in the form of a two pronged fork. The upper part is of copper and makes the connection between the electrodes and the bus bars, which are securely bolted to it. The electrodes are held between the two prongs, and since the distance between these prongs is about twenty-four inches, contact blocks must be used for electrodes less than twenty-four inches in diameter. A right-and-left screw bolt connects the ends of the two prongs, which enables the holder to be opened and closed at will and permits the electrode to be securely clamped in place. By this arrangement, electrodes of any size up to twenty-four inches diameter may be used. The lower part is made of steel and acts as a support for the upper part. These two parts, carefully insulated from each other, are held together by means of

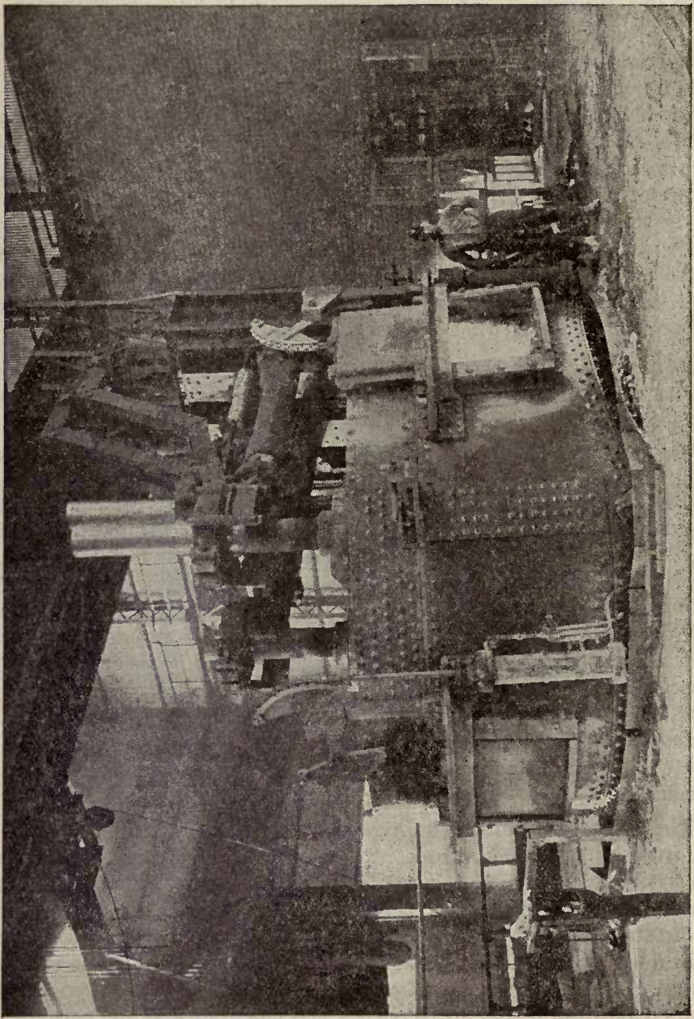


FIG. 44. Heroult Electric Furnace. General View—Furnace Ready to Charge.

insulated bolts. Finally, this lower part is fastened to the horizontal arm, previously mentioned, by an insulated flange joint. The upper prongs are water cooled.

**The Electrodes** used at the plant may be of graphite, twelve inches in diameter, or of amorphous carbon, twenty-four inches in diameter, and are received in sections six feet long. By means of threaded holes in the ends of the electrodes and headless screws of the same material to fit, these pieces may be joined together so as to give a continuous feed of electrodes to the furnace. In this way the great waste of electrodes from unused ends is avoided. These threaded holes also serve a useful purpose in removing the electrodes and changing them in the holders. As the carbons are constantly burning away, this change is frequently necessary. Since the electrodes are rather heavy—a six foot length of graphite electrode weighs 426 lbs.—the use of the crane is made necessary. By means of a linked pin of steel, threaded to fit the hole, the electrodes can easily be handled with the crane hook. Experience seems to indicate that graphite electrodes are best for molten charges but that amorphous electrodes are very well suited for use in melting cold charges. A water cooled copper ring encircles each electrode at its entrance into the furnace.

**Furnace Openings:** Besides the holes in the roof for the three electrodes, the furnace has three openings in the side wall, all located within an arc of 180° on the circumference. One is the tapping hole, a small opening through which the steel is poured into the steel ladle. This opening is provided with a spout, so constructed as to act as a slag skimmer when the furnace is tapped. Opposite the tapping hole is the charging door, through which the molten metal from the open hearth is charged, while half way between these two openings is located a second charging door, which can be used only for charging solid materials by hand. Both these charging holes are closed with neat fitting brick lined doors, which are lifted by means of compressed air cylinders in much the same way as open hearth doors.

## SECTION VIII.

### OPERATION OF THE FURNACE.

**Practice at Duquesne Plant:** The Duquesne furnace is used to make plain steels of any carbon content and many different alloy steels. For all the steels made in the furnace the raw material charged is finished basic open hearth steel, hence the refining in the electric furnace consists of deoxidizing and desulphurizing only. Unless the specifications on the basic steel should coincide with those for the electric, which is seldom the case, additions are made to the charge either in the transfer ladle or in the furnace. No additions of any kind are made in the pouring ladle or at the time of tapping, as is the common practice in making open hearth steel. A good example is furnished in the case of carbon. When it is necessary to raise the per cent. of this element, as is the case on orders calling for a higher per cent. than that of the open hearth heat, the amount required above that supplied by other additions is added, in the form of anthracite coal, to the steel in the transfer ladle, in the furnace, or a part in both. Additions of other elements are, as a rule, added after deoxidation of the metal is well advanced or completed. This ability to finish the heat in the furnace is a decided advantage in favor of the electric process, as a more homogeneous product is thus obtained.

**Charging:** Omitting the mechanical and electrical features, the operation of the furnace, in general, is carried out as follows:—Approximately twenty tons of a suitable open hearth heat is teemed from the steel ladle into the charging ladle, for the electric furnace. This charge is then conveyed by a dinkey, over a narrow gauge track, to the furnace, into which it is poured through a portable spout. During the pouring, a test for chemical analysis is taken, and upon the results of this analysis is based the approximate amount of carbon and manganese to be added. An increase of three to five points in the manganese content of the steel usually occurs during the deoxidizing period, and must be allowed for. If a medium or high carbon heat is being made from a low carbon open hearth heat, requiring the addition of a large amount of carbon, the greater portion of this element is added in the form of anthracite coal, which is thrown into the furnace as the heat is being charged. This procedure is necessary to insure that the coal will be absorbed by the steel.

**Deoxidizing:** As soon as the charging has been completed, the electrodes are adjusted, and the current is turned on. Since the charge usually freezes over on top, especially in the case of low carbon steels, nothing further is done until this solidified layer is completely melted. As soon as the bath is in a state of complete fusion, the first slag mixture, consisting approximately of four parts lime and one part fluorspar or one part clean sand for low carbon heats, is added; for high carbon heats, the mixture may contain about one-third part coke dust. Soon after this addition, the second sample for chemical analysis is taken to determine the per cent. of carbon and manganese in the bath, and while these determinations are being made further additions of the first slag mixture takes place. Samples of the slag taken at this time are usually brown in color and contain varying amounts of manganese oxide, which fact shows that the iron oxide in the steel is being reduced by the manganese present. A decided brown color can be taken to indicate that the deoxidation of the steel is well advanced. A second slag mixture composed of suitable proportions of lime, fluor spar, sand and coke dust is now added. Soon after the addition of this mixture the slag becomes less vitrious, shows a tendency to slake, and begins to fade in color. If the heating be continued long enough, with proper additions of the carbonaceous flux, samples of the slag will slake when cold and become gray, or even white, in color. Such behavior of the slag indicates that the deoxidation of the bath of metal and slag has been completed. This condition is also determined by means of the water test. If at this time a small sample of the slag while hot be immersed in a little water, the odor of hydrogen sulphide can usually be detected, and, if deoxidation is complete, the smell of acetylene gas can also be detected.

**Finishing the Heats:** During the deoxidation of the bath the results of the second chemical analysis have been reported, and if the per cents. of carbon and manganese are satisfactory, any alloys that may be required by the order are added as soon as the slag condition will permit. If the carbon content should be too low, it is raised to the required point by the addition of a proper weight of cold, very low phosphorus pig iron. The bath is chilled somewhat by the addition of the alloys, especially if they are added in large amounts, and about three-quarters of an hour is required to heat the bath up to the tapping temperature. Besides, in order to give the alloys time to mix with the steel, no additions are made for thirty minutes before tapping except in the case of 50% ferro silicon, which is added ten to fifteen minutes before tapping to avoid losses of the element.

**Tapping and Teeming:** When enough time has elapsed to melt all the alloys or other additions, slaking and water tests are made on the slag, and if these indicate a satisfactory condition of the slag, the heat is tapped. In tapping the heats, care is taken to prevent slag from running into the steel ladle with the metal. The special skimmer with which the tapping hole is provided for this purpose has already been mentioned. The steel is teemed very carefully, being usually box poured. In this method of teeming the stream of molten metal from the ladle flows into the middle of a box made in three compartments. From the middle compartment the steel overflows into the two end ones, which are provided with nozzles. This arrangement permits these nozzles to be carefully centered over two ingot moulds before the pouring is begun. Special care is taken in preparing the ingot moulds, so as to prevent ingot defects due to bad moulds. The steel is allowed to stand two hours in the moulds, so as to insure that solidification is complete before it is stripped.

**Scrap Heats:** Besides the refining of molten open hearth steel, which has just been described, the furnace is occasionally used to make steel from scrap. When using scrap, two methods may be followed. Thus, the charge may consist of cold scrap or be made up of scrap and molten steel. When scrap alone is used, it must be small, and the coarser material is charged first with the finest on the top. Even then the power fluctuations are great, and some difficulty is experienced in melting the scrap. These difficulties are over-come for the most part by starting the furnace on a short charge of molten steel and then adding the scrap to this charge. This latter method is the one employed most often at this plant. After the melting period the procedure is then the same as that already described for molten charges. An examination of the following tables will give a more concrete idea of the method of handling the different kinds of steel made in the electric furnace.

### Table 38. Showing History of a Heat of Low Carbon Plain Steel Made in the Electric Furnace.

Analysis of molten charge—steel as finished at open hearth: C.=.09%; Mn.=.38%; P.=.014%; S=.043%.

Order: C. .10/.15%; Mn.=.30/.50%; P. under .035%; S. under .040%; Si. under .04%.

| Time | Additions |
|---|---|
| 8:10 | Charge, 46700 lbs. Test. C.=.06%; Mn.=.33%; P.=.010%; S.=.038%. |
| 8:35 | Power on. |
| 9:35 | 1st slag mixture. Lime, 500 lbs., fluor spar, 150 lbs. |
| 9:50 | 485 lbs. pig iron added. |
| 10:00 | ½ second slag mixture, Lime, 750 Lbs., fluor spar, 125 lbs., coke dust, 100 lbs; sand, 100 lbs. |
| 10:05 | Sample for chemical analysis. |
| 10:20 | 104 lbs. ferro manganese added cold. (Laboratory report shows C.=.08%; Mn.=.19%.) |
| 10:30 | Chemical analysis, C.=.10%; Mn.=.32%. |
| 10:45 | 50 lbs. Ferro manganese added cold. |
| 10:50 | 300 lbs. pig iron added cold. |
| 10:55 | ½ second slag mixture. |
| 11:00 | ¼ third slag mixture—Lime, 100 lbs.; fluor spar, 30 lbs.; coke dust, 75 lbs. |
| 11:30 | ¼ third slag mixture. |
| 11:40 | ¼ third slag mixture. |
| 11:45 | ¼ third slag mixture. |
| 12:00 | 20 lbs. coke dust. |
| 12:30 | 30 lbs. coke dust. |
| 12:35 | 50 lbs. ferro manganese added cold. |
| 12:50 | Heat tapped. |

Final analysis: C.=.12%; Mn.=.35%; P.=.007%; S.=.035%; Si.=.01%.

### Table 39. A Heat of High Carbon Plain Steel.

Molten charge—Steel as finished at open hearth—C.=.19%; Mn.=.28%; P.=.016%; S.=.041%;

Order: C.=.95/1.05%; Mn.=.20/.35%; P.=under.030%; S.=under.030%; Si.=.10/.25%.

| Time | Additions |
|---|---|
| 3:20 | 150 lbs. Anthracite Coal added to ladle. |
| 3:30 | Charge, 52400 lbs. Test: C.=.29%; Mn.=.23%; P.=.012%; S.=.042%. |
| | 660 lbs. Coal added in furnace as heat is being charged. |
| 3:35 | 155 lbs. coal added. |
| 3:40 | Power on. |
| 5:35 | ½ first slag mixture. Lime, 1200 lbs.; fluor spar, 200 lbs.; coke dust, 100 lbs; sand, 100 lbs. |
| 6:15 | Chemical Analysis front door, —C.=.85%; Mn.=.29%.<br>side door, —C.=.85%; Mn.=.28%. |
| 6:15 | ¼ first slag mixture. |
| 6:30 | ⅛ first slag mixture. |
| 6:40 | 1/16 first slag mixture. |
| 6:50 | 1/16 first slag mixture. |
| 7:00 | ⅓ second slag mixture. Lime, 100 lbs.; fluor spar, 25 lbs.; coke dust, 75 lbs. |
| 7:05 | 1700 lbs. pig iron. |
| 7:10 | ⅓ second slag mixture. |
| 7:15 | ⅓ second slag mixture. |
| 7:20 | 175 lbs. 50% ferro silicon. |
| 7:40 | Power off, and heat tapped. |

Final analysis, C.=.97%; Mn.=.29%; P.=.007%; S.=.016%; Si.=.19%.

### Table 40. A Low Carbon Alloy Heat.

Molten Charge as finished at Open Hearth, C.=.09%; Mn.=.34%; P.=.015%; S.=.034%.

Order: C.=.12/.20%; Mn.=.40/.70%; P.=under .040;% S.=under .040%; Si.=under .20%; Cr.=.40/.80%; Ni.=1.00/1.75%.

| Time | Additions |
|---|---|
| 10:55 | Charge, 50800 lbs. Test, C.=.08%; Mn.=.29%; P.=.010%; S.=.042%. |
| 11:15 | Power on. |
| 12:00 | First slag mixture. Lime, 500 lbs.; fluor spar, 150 lbs.; |
| 12:30 | ¾ second slag mixture. Lime, 750 lbs.; fluor spar, 125 lbs.; coke dust, 100 lbs; sand, 100 lbs. |
| 12:45 | Chemical Analysis front door, C.=.08%; Mn.=.24%.<br>side door, C.=.08%; Mn.=.22%. |
| 12:50 | 200 lbs. ferro manganese; Mn.=78%. |
| 12:55 | 446 lbs. ferro chrome; Cr.=70%. |
| 1:00 | 730 lbs. nickel; Ni.=99%. |
| 1:30 | ½ third slag mixture—Lime, 50 lbs.; coke dust, 75 lbs. |
| 1:45 | ½ third slag mixture. |
| 1:50 | 30 lbs. ferro manganese and 60 lbs. 50% ferro silicon. |
| 2:00 | Heat tapped. |

Final Analysis, C.=.20%; Mn.=.51%; P.=.009%; S.=.028%; Si.=.03%; Cr.=.54%; Ni.=1.28%.

### Table 41. A High Carbon Alloy Heat.

Molten charge—Steel as finished at open hearth—C.=.20%; Mn.=.35%; P.=.010%; S.=.035%.

Order: C.=.95/1.05%; Mn.=.35/.50%; P.=under .030%; S.=under .030%; Si.=under .03%; Cr.=1.35/1.65%; V.=over .18%.

| Time | Additions |
|---|---|
| 11:48 | 150 lbs. anthracite coal added in transfer ladle. |
| 11:50 | Charge, 54500 lbs. Test, C.=.07%; Mn.=.34%; P.=.006%; S.=.040%. |
| 12:05 | Power on. |
| 12:50 | ¾ first slag mixture—Lime, 1300 lbs.; fluor spar, 160 lbs; sand, 125 lbs. |
| 1:20 | Chemical analysis $\begin{cases}\text{Front door, C.=.89\%; Mn.=.34\%.}\\ \text{Side door, C.=.90\%; Mn.=.35\%.}\end{cases}$ |
| 1:25 | ¼ slag mixture. |
| 1:35 | ⅙ second slag mixture. Lime, 150 lbs.; coke dust, 150 lbs. |
| 2:00 | 1180 lbs. ferro chrome, Cr.=70%. |
| 2:10 to 2:40 | Remainder of second slag mixture added at intervals of ten minutes. |
| 2:55 | 353 lbs. ferro vanadium. V.=35% |
| 3:05 | 60 lbs., 50% ferro silicon. |
| 3:30 | Heat tapped. |

Final analysis, C.=.99%; Mn.=.35%; P.=.006%; S.=.017%; Si.=.07%; Cr.=1.44%; V.=.22%.

## SECTION IX.

### THE CHEMISTRY OF THE PROCESS.

**Deoxidation of the Bath:** The tracing of the chemical changes that take place in the process employed at this plant furnishes an interesting study. Since the charge is finished open hearth steel containing the usual amount of manganese, it is to be expected that this element would play a most important part in the deoxidation of the steel. The fact, plainly shown by the preceding records, that the manganese is usually several points lower in the charging test than in the open hearth steel is proof of its deoxidizing action, which would be expected to continue in the furnace. The removal of oxygen, then, is represented by the following reaction: $FeO+Mn=MnO+Fe$. The MnO, being less soluble in the molten metal than FeO, rises to the surface and becomes a part of the slag. This action is identical with that in the ladle in finishing open hearth steel, but the result is not the same in the two processes for two reasons: First, for want of time, the deoxidation is not completed in the ladle, whereas in the electric furnace it is complete. Second, the MnO in the electric furnace comes under the reducing action of the carbon contained in the slag mixture and is reduced, thus: $MnO+C=Mn+CO$. The carbon monoxide, CO, being a gas, becomes a part of the atmosphere of the furnace, and the manganese returns to the bath, as is indicated by the fact that the per cent. manganese in the steel usually rises after the addition of the carbonaceous flux.

**Desulphurizing the Metal:** With the elimination of oxides from the slag, the lime, under the influence of the extremely high temperature of the arc which prevails under and in the immediate vicinity of the electrodes, begins to be reduced by the carbon of the coke dust, with the consequent formation of calcium carbide, thus: $CaO+3C=CaC_2+CO$. It is at this point that desulphurization takes place. Since manganese sulphide, like the oxide, is less soluble in iron than ferrous sulphide, it is probable that this element also aids in this process. Whether manganese sulphide or ferrous sulphide plays the most important role in the sulphur reactions is difficult to decide, but that the removal of the sulphur from the bath takes place through the formation of calcium sulphide, which is insoluble in molten iron, cannot be doubted. These reactions are two in number and may be written thus:

$$1.\quad \left\{\begin{matrix}FeS\\MnS\end{matrix}\right.+CaO+C=\left\{\begin{matrix}Fe\\Mn\end{matrix}\right.+CaS+CO$$

$$2.\quad \left\{\begin{matrix}3\ FeS\\3\ MnS\end{matrix}\right.+2\ CaO+CaC_2=\left\{\begin{matrix}3\ Fe\\3\ Mn\end{matrix}\right.+3CaS+2\ CO$$

With metallic oxides present in the slag, neither of these reactions will take place, as the oxide would react with the calcium sulphide, thus:

$$CaS+\left\{\begin{matrix}FeO\\MnO\end{matrix}\right.=\left\{\begin{matrix}FeS\\MnS\end{matrix}\right.+CaO$$

and with calcium carbide according to this reaction:

$$CaC_2+\left\{\begin{matrix}3\ FeO\\3\ MnO\end{matrix}\right.=\left\{\begin{matrix}3\ Fe\\3\ Mn\end{matrix}\right.+CaO+2\ CO$$

Hence the presence of $CaC_2$ in the slag is a guarantee that the bath is deoxidized. In the water test the presence of considerable quantities of $CaC_2$ in the slag is detected by the odor of acetylene gas, which is generated in accordance with the following reactions: $CaC_2+H_2O=C_2H_2+CaO$. These facts are further illustrated by the following analysis of heats and slags: Slags AZ No. 3 and AZ No. 5 illustrate an undesirable and a desirable slag, respectively. The relatively high iron and manganese content of AZ No. 3 indicate incomplete deoxidation, with a low sulphur and calcium carbide content resulting.

**Table 42. Analysis of Tests from Electric Furnace Heats.**

| Heat Number | Tests | Carbon % | Mang. % | Phos. % | Sul. % | Si. % |
|---|---|---|---|---|---|---|
| AZ No. 1, (O. H. Heat 83023) | Primary...... | .16 | .35 | .010 | .036 | .. |
| | 1st Preliminary | .80 | .35 | .006 | .023 | .. |
| | 2d " | .80 | ... | .... | .... | .. |
| | Final......... | .82 | .35 | .010 | .020 | .16 |
| AZ No. 2, (O. H. Heat 88026) | Primary...... | .20 | .44 | .012 | .042 | .. |
| | Preliminary... | .61 | .43 | .010 | .025 | .. |
| | Final......... | .67 | .60 | .009 | .024 | .. |
| AZ No. 3, (O. H. Heat 84598) | Charging...... | .18 | .41 | .005 | .024 | .. |
| | No. 1 Electrode | .20 | .60 | .004 | .020 | .. |
| | No. 2 " | .19 | .60 | .006 | .020 | .. |
| | No. 3 " | .21 | .59 | .005 | .020 | .. |
| | Final......... | .22 | .58 | .004 | .021 | .. |
| AZ No. 4, (O. H. Heat 101523) | Charging...... | .19 | .34 | .010 | .032 | .. |
| | No. 1 Electrode | .22 | .53 | .007 | .026 | .. |
| | No. 2 " | .22 | .54 | .009 | .023 | .. |
| | No. 3 " | .22 | .54 | .009 | .023 | .. |
| | Final......... | .20 | .47 | .006 | .029 | .. |
| AZ No. 5, (O. H. Heat 101524) | Charging...... | .28 | .36 | .009 | .040 | .. |
| | No. 1 Electrode | .34 | .54 | .007 | .017 | .. |
| | No. 2 " | .32 | .55 | .006 | .015 | .. |
| | Final......... | .33 | .52 | .007 | .020 | .. |

**Table 43. Partial Analysis of Final Electric Furnace Slags.**

| Heat No.'s | AZ No. 3 | AZ No. 4 | AZ No. 5 |
|---|---|---|---|
| Silica | 19.58% | 20.48% | 18.40% |
| Iron | 1.09 | .72 | .32 |
| Total Lime | 60.38 | 61.82 | 61.26 |
| Magnesia | 10.32 | 8.40 | 7.27 |
| Manganese | .62 | .60 | .35 |
| Sulphur | .85 | .80 | 1.30 |
| Calcium carbide | .32 | .19 | .46 |
| Alumina | 3.04 | 3.61 | 5.95 |

**Difficult Specifications:** While the electric furnace affords means of making steel to very difficult specifications and with a greater degree of accuracy than is possible in other processes, yet it has its limitations. The case of sulphur furnishes an example. From what has just been said, the importance of carbon in the elimination of both oxygen and sulphur is evident. In low carbon steels the lowering of the sulphur content to any considerable degree becomes a difficult problem, because, if the flux be made highly carbonaceous, a necessary condition, there is danger that the steel will absorb carbon from the slag, and thus raise the carbon content of the steel above the requirements. In the high carbon steels, the absorption of carbon by the steel can be allowed for and presents no difficulty, so a more highly carbonaceous flux may be used than with low carbons, and a greater removal of sulphur results. As previously indicated, the elimination of sulphur may be brought about by the use of silicon, as shown in the following reactions:

$$1.\quad \left\{\begin{matrix}2\,\mathrm{FeS}\\ 2\,\mathrm{MnS}\end{matrix}\right. + 2\,\mathrm{CaO} + \mathrm{Si} = \left\{\begin{matrix}2\,\mathrm{Fe}\\ 2\,\mathrm{Mn}\end{matrix}\right. + 2\,\mathrm{CaS} + \mathrm{SiO_2}$$

$$2.\quad \left\{\begin{matrix}2\,\mathrm{FeS}\\ 2\,\mathrm{MnS}\end{matrix}\right. + 2\,\mathrm{CaF_2} + \mathrm{Si} = \left\{\begin{matrix}2\,\mathrm{Fe}\\ 2\,\mathrm{Mn}\end{matrix}\right. + 2\,\mathrm{CaS} + \mathrm{SiF_4}$$

But while it is claimed that little more than the theoretical amount of silicon is required, in actual practice a residue of silicon in the steel is unavoidable. Hence, this method could not be employed to produce silicon free steel. Similar to the method of desulphurizing with carbon, these reactions will take place only after the bath has been completely deoxidized. For low carbon steels, then, the limit for sulphur should be .040%, while for high carbons this limit could be reduced to .030%. To guarantee lower limits than these would mean increased cost in production out of proportion to the benefits to be derived, except in the case of steel that is to be used for certain special purposes. Since the phosphorus is removed in the basic open hearth, the same range in per cent. of this element as is customary to allow in open hearth steel should be allowed in electric steel. As to alloying elements, the variation in the composition of the alloys used makes it desirable to secure as wide a range as possible in the specifications for such elements.

## SECTION X.

### PROPERTIES AND USES OF ELECTRIC STEEL.

**Properties of Electric Steel:** We can deal with this topic in a no more fitting way than to quote from impartial investigators. The following is taken from a paper by Messrs. Lyon and Keeney of the Bureau of Mines: "For many years all high grade steels were manufactured by the crucible process, but since the advent of the electric furnace there has been a gradual adoption of that furnace for refining steel. For the complete refining of the highest grades of steel the use of the electric furnace is now thoroughly established. Any products that can be made by the crucible process can be made by the electric furnace, and in most cases with cheaper raw materials and at a low cost. In the electric furnace complex alloy steels can be made with precision. The high temperatures attainable facilitate the reactions, and alloys need not be used so largely for the purpose of removing gas. Very low carbon steels can be kept fluid at the high temperatures. Steels free from impurities and of great value for electrical apparatus can be made. With the electric furnace large castings can be made from one furnace, whereas in the crucible process steel from several crucibles must be used. For small castings, which require a very high grade metal free from slags and oxides, electrically refined steel is especially adapted. The electric furnace gives a metal of low or high carbon content as desired, hot enough to pour into thin molds, and steel free from slags and gases."

"There is now a tendency among customers of rail and structural steel to require a higher grade steel at an increased price rather than steel of acid Bessemer or even of basic open hearth grade at a lower price. With the high cost of power that now prevails throughout the steel centers of the United States the electric furnace can not compete profitably with either the acid Bessemer or the basic open hearth process in manufacturing steel of like grade from pig iron. It is in combination with either of these processes that the electric furnace seems destined to be prominent in steel manufacture."

"Experiments conducted by the United States Steel Corporation during the past four years show that, as compared with the acid Bessemer and basic open hearth processes, the electric process has the following advantages: A more complete removal of oxygen; the absence of oxides caused by the addition of silicon, manganese, etc;—the production of steel ingots of 8 tons weight and smaller that are practically free from segregation; reduction of the sulphur content to 0.005 per cent., if desired; reduction of the phosphorus content to .005 per cent. as in the basic open hearth process, but with complete removal of oxygen."

"About 5,600 tons of standard electric rails from electric furnace steel have been in service in the United States for the past two years (prior to 1914). These rails have been subjected to all sorts of weather and to temperatures as low as—52° F. It seems that rails made by the basic electric process can be made softer than by either the acid Bessemer or basic open hearth processes and yet show highly satisfactory wearing qualities."

"No steel rails made by the basic electric process in service in this country have been broken. Electric furnace steel of a given tensile strength has a slightly greater elongation than basic open hearth steel and is somewhat denser than basic open hearth or acid Bessemer steel."

The results of some comparative tests, made at South Chicago of electric furnace steel for plates and basic open hearth steel for plates were as follows:—

**Table 44. Comparison of Mechanical Properties of Electric and Open Hearth Plate Steel.**

| ELECTRIC | | | OPEN HEARTH | | |
|---|---|---|---|---|---|
| Carbon Content Per Cent. | Ultimate Strength per Sq. In. Pounds | Elongation on 2 Inches Per Cent. | Carbon Content Per Cent. | Ultimate Strength per Sq. In. Pounds | Elongation on 2 Inches Per Cent. |
| 0.08 | 59,194 | 27.25 | 0.08 | 51,690 | 32.00 |
| .12 | 64,080 | 26.05 | .12 | 56,510 | 29.70 |
| .16 | 69,220 | 25.25 | .16 | 52,901 | 28.61 |
| .20 | 72,853 | 22.82 | .20 | 58,294 | 28.82 |
| .24 | 69,540 | 23.12 | .24 | 63,560 | 26.25 |

The results show a 15.5 per cent. increase in ultimate strength and 11.3% decrease in elongation for electric steel, as compared with open hearth plate steel of approximately the same chemical composition."

**Illinois Steel Company's Tests on Rails:** The Illinois Steel Company have conducted a series of experiments from which it was shown that electric steel is considerably more ductile at low temperatures than either the open hearth or the Bessemer steel. In these tests about 900 pieces of electric, open hearth, and Bessemer rails were tested at temperatures ranging from 70° F. to —50° F., and the results indicated that while all these steels showed a marked decrease in resistance to shock as the temperature was lowered, the electric steel was relatively more ductile than either of the other two. The following table is a summary of the results obtained with two open hearth and two electric heats of similar composition chemically, as shown by analysis, and may be taken as typical of the general results obtained.

**Table 45. Comparison of Tests on Open Hearth and Electric Steel Railroad Rails at Different Temperatures.**
**Number of Tests, 242.**

| Temp Deg's F. | AVE. No. BLOWS TO BREAK RAILS | | | | DEFLECTION BEFORE BREAKING | | | | ELONGATION IN 12 IN. | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Elec. | O. H. | Comparison | | Elec. | O. H. | Comparison | | Elec. | O. H. | Comparison | |
| | | | O. H. Over E. | E. Over O. H. | Inches | Inches | O. H. Over E. | E. Over O. H. | Inches | Inches | O. H. Over E. | E. Over O. H. |
| +60 | 3.48 | 3.64 | 5% | ..... | 2.96 | 3.36 | 14% | ..... | .808 | .929 | 15% | ..... |
| 0 | 4.41 | 3.82 | ... | 15% | 1.41 | 1.23 | .... | 15% | .404 | .397 | .... | 2% |
| —30 | 4.55 | 2.24 | ... | 103% | 1.46 | .58 | .... | 152% | .420 | .201 | .... | 109% |
| —40 | 3.31 | 2.03 | ... | 65% | .91 | .43 | .... | 112% | .297 | .141 | .... | 111% |

**Uses of Electric Steel:** As to the uses of electric steel, little need be said except it may be used with confidence wherever a steel of higher quality than that furnished by the open hearth process is desirable. So far, the demand for this steel has been in advance of the supply, and its application is becoming more and more general. Among those with whom it has found favor and by whom it is now being used, are manufacturers of automobiles, motorcycles, motor accessories, areoplanes, machinery, engines, agricultural implements, tools, guns and munitions, and by the railroads. The fact that it is being used more and more in place of crucible steel is evidence of its superior quality.

**Summary:** In order to cover the whole subject of electric steel making satisfactorily in so brief a manner, it has been necessary to treat the subject from several different view points, which method is likely to be confusing, with the result that the reader may have lost sight of some important points. In order that these points may receive proper emphasis, the following summary of the chapter is appended:

1. Of the many furnaces in use no one can be said to possess any great advantage over any other from a metallurgical point of view, with the exception that higher temperatures may be obtained with furnaces of the arc type than with the induction type.

2. The only effect of the electric current is in the production of heat.

3. The electric process is the only one in which impurities are not added to the steel by the operation.

4. The electro-thermal process affords the only positive means of desulphurizing and deoxidizing steel simultaneously and in the same operation.

5. It permits the addition of all alloying elements while the steel is in the furnace.

6. It provides a way for remelting alloy steel scrap and producing a product of high quality without loss.

7. Steel produced by this process exhibits some unusual wearing qualities.

8. In quality, steel made by this process equals that of the best grades of crucible steel.

9. Much larger quantities of metal may be treated in one operation than is possible by the crucible process.

10. It gives a product that is uniform in quality for any given heat.

11. Steels refined in the electric furnace are freest from segregation.

12. Steels made in the electric furnace are free from slag and other inclusions.

13. Electric steel is comparatively more ductile at low temperatures than Bessemer or open hearth.

14. Considering the various methods from an economical point of view, the duplexing process in which the electric furnace is used in conjunction with the basic open hearth combines the greatest capacity and efficiency with highest quality of product.

## CHAPTER X.

# THE DUPLEX AND TRIPLEX PROCESSES.

### SECTION I.

### GENERAL FEATURES OF THE DUPLEX PROCESS.

**What the Duplex Process Is:** The term duplex process may be applied to a combination of any two processes for manufacturing steel, but it is customary among the steel men of this country, at least, to restrict the term to mean only a combination of the acid Bessemer and the basic open hearth process, in which the latter plays the part of a finishing process. Briefly described, the method, as usually carried out, consists, first, of blowing molten basic iron in the converter until the silicon, manganese and a part of the carbon have been oxidized and then transferring this semi-finished metal to a basic open hearth furnace, where, through the agencies of iron oxide and lime, the phosphorus and the remainder of the carbon to be removed are oxidized. The steel is then finished, recarburized and deoxidized, according to the usual open hearth practice. This combination of processes may be made in other ways, also. One plant, for example, in order to produce a very low phosphorus Bessemer steel for a certain order, first oxidized the silicon, manganese, and phosphorus in the open hearth, and then, by mixing this very high carbon steel with Bessemer iron in suitable proportions, succeeded in blowing out the carbon in the converter, thus reversing the customary procedure. But as stated in the beginning, the duplex process refers to the combination in which the finishing operation is conducted in and from a basic open hearth furnace.

**Advantages and Disadvantages of the Process:** In the northern district of the United States the chief advantages of the process, when there is a pressing demand for steel, is that of the increased tonnage which it produces in a given time. Thus, while the product is similar in quality and of the same grades as basic steel, the time of the open hearth operation is shortened by about half; for, whereas one open hearth furnace will turn out an average of about fifteen heats in a week of straight running by the ordinary way, the same furnace operated as a duplexing unit will produce about forty heats in the same period. This shortening of the time of a heat saves fuel and tends to prolong the life of the furnace, as does, also, the elimination of the silicon in the converter. The process does not require the use of scrap, which fact may also be an advantage to some makers. Offsetting these advantages, however, are the double conversion cost and the decrease in yield, due to the increased oxidation, both of which may be very serious drawbacks to the economical production of steel. In dull times, especially, the extra costs of maintaining two separate units may more than counter- balance the gain from the increased output.

**Methods of Duplexing:** While the details of the process vary widely in the different plants, there are two general methods of carrying out the duplexing process: Thus, the purification in the converter may be carried out to the point where the metal is fully blown and represents a high phosphorus steel which may then be mixed with pig iron in the open hearth, thus taking the place of steel scrap. In this method either a stationary or a tilting furnace can be utilized. But the more common method is the one, already mentioned, in which the carbon is only partially eliminated in the converter, and the purification then completed by the continuous process, which is most conveniently carried out in a Talbot tilting furnace. A brief description of these furnaces will simplify the description of the process to be given shortly.

**The Talbot Furnace:** The object aimed at in the design of these furnaces is to permit the removal of any quantity of slag or metal or the addition of molten metal, oxidizing agents and flux at any time during the working of the charge. They are, therefore, necessarily of the tilting type, and are built upon racers and rollers which rest upon the foundation in a manner similar, in a general way, to that of the large mixers of recent construction. They are rectangular in shape, and of about the same proportions as an ordinary open hearth furnace as to length and width,but they have a much greater depth, which increases their capacity for containing molten metal. The frame work must be of much stronger construction than that for the ordinary open hearth in order to avoid twisting stresses and vibrations which would be very harmful to the brick work. Only that section of the furnace comprising the hearth, side-walls and roof is made tilting; all the ports and flues are stationary, and, together with the checker work, of the same construction as for the stationary furnaces. In the best types of construction, these furnaces are so placed and the racers and rollers so formed that the center of rotation of the furnace coincides with the center line of the ports, so that all its parts always remain in the same relation no matter in what direction or to what degree the movable portion of the furnace may be tilted. By means of water cooled metal joints, the clearance between the movable and stationary parts of the ports is kept very small, so that the heating of the furnace may continue even during the tapping of a heat. On the pouring side, these furnaces usually have but one opening, a tapping hole located above the slag line and provided with a lip or spout for directing the stream of molten metal into the steel ladle. As in the case of the stationary furnace, doors for introducing the materials into the furnace are located in the front side. But unlike the stationary types, the slag notches are also placed in front, usually one on each side of the middle door, and, of course, at a lower level. Since Talbot's method is but a modification of the basic open hearth process, the furnaces are, as a matter of course, provided with basic linings.

## SECTION II.

### OPERATION OF THE PROCESS.

**An Example of the Duplexing Process:** Perhaps the best way to describe the duplexing process is through an example. For this purpose the method employed by a large steel manufacturing company in the North, whose plant represents one of the most recent installations, is selected. Their duplexing plant consists of three 20-ton converters and three Talbot tilting furnaces, each of which has a capacity of approximately 200 tons. While the practice may be varied somewhat to suit conditions, the process at this plant is usually carried out about as follows:

**Preparing the Furnace for Charging:** The process may be said to be continuous for a week, for each week-end the tilting furnace is thoroughly drained, the bottom and slag lines are made up, the ports are cleaned and repaired, and everything is made ready for the week's campaign. Of course, during the interval of this campaign the front and back wall must be attended to and such minor repairs made as are found necessary and there is time for. About 6 p. m. Sunday, after the flues have been burned out and the gas is once more on the furnace, the work of preparing the slag is begun. Four boxes of calcined limestone and three of roll scale are charged and melted down. These amounts are then repeated, and when again molten the same amounts are again charged, the total being twelve boxes of lime and eight to nine boxes of roll scale. The average weight of a box of the lime is 2000 lbs. and of a box of roll scale 3000 lbs. Considerable care is given by the melter to the preparation of a good slag, for, as in all open hearth work, the success of the process depends on the slag.

**Charging Molten Metal from the Converters for the First Heat:** At midnight, or shortly afterwards, the metal is ordered from the Bessemer department. An average analysis of the mixer metal is as follows:

| | | |
|---|---|---|
| Total Carbon | 3.85 | per cent. |
| Silicon | 1.55 | " |
| Manganese | .67 | " |
| Sulphur | .040 | " |
| Phosphorus | .365 | " |

The weight of this metal taken for a Bessemer heat is about 40,000 lbs., less the weight of the scrap in the converter. Two Bessemer heats, blown in different vessels, are poured into a transfer ladle and taken to the tilting furnace. When starting up, the first ladle contains metal blown down to contain 0.60 per cent. carbon, which is allowed to remain to give a little action, or boil, in the furnace. This first ladle is poured into the open hearth furnace about midnight. It is followed by a ladle of "soft" metal, that is, metal blown down to 0.05% or 0.07% carbon, and then by a "kicker," or a ladle of high carbon steel. This metal is blown down to from 1.5% to 2.0% carbon, and when charged into the open hearth produces a vigorous reaction, or boil. The metal and slag are thoroughly mixed together by this boil, and during this reaction the phosphorus is largely removed from the metal bath and passes into the slag. When the action has subsided, another "soft" ladle and a "kicker" are charged. Then, if the bath is found to be low in carbon, another kicker ladle is added to it, but if high in carbon another "soft" ladle is charged. In this way a bath of metal of about 200 tons is produced. The charge is then worked down like an ordinaty basic open hearth heat until ready for tapping, which is usually at about 3:30 a. m.

**Tapping and Recarburizing the First Heat:** When the bath is ready for tapping, the tap hole is opened and plugged with wet sacking. The furnace is then tilted for pouring. Before the sacking is burnt through, the slag is up along the back wall so that clean metal free from slag comes from the furnace. Only enough slag is drawn off at the end to cover the steel in the ladle properly. Some of the steel made in the Talbot furnaces is super refined by the electric process, but by far the greater portion is made into the ordinary commercial grades which is recarbonized and deoxidized in the ladle as for similar grades made in stationary furnaces.

**Preparing the Furnace for the Second Heat:** After the first heat is tapped, there is a bath of about 100 tons of metal with a carbon content of about .15% still in the furnace, covered with the tapping slag. Two boxes of lime and two boxes of scale are charged, and two boxes of burnt dolomite are used along the slag line, around the doors, etc., as found necessary. Then two "soft" ladles of blown metal are charged, and two more boxes of lime, which is followed by a "kicker." During the reaction, the furnace is tilted slightly forward and slag is allowed to flow from the front of the furnace through the slag spouts, which are under the doors directly on each side of the center door. The slag falls into slag cars standing on the tracks below. Practically all the slag taken from the furnace is removed in this way, for, as mentioned before, when tapping a heat only enough is taken to cover the metal in the ladle properly. When the reaction is over, another box of lime is generally charged, and the bath is worked down in the usual way. Very often, another box of lime is spread over the slag shortly before tapping, so that five to six boxes of lime are used per heat, but as a rule only two boxes of scale are used here. After the heat is tapped, this procedure is repeated, enough slag being taken from the front of the furnace at the time of the reaction to maintain a constant and proper volume of slag in the furnace. The average time for tapping one heat to tapping the next is about three hours.

**Closing Down the Furnace for the Week End:** About midnight on Saturday the furnace is drained. The bath is worked down, so that after the heat is tapped there are not more than forty to sixty tons in the furnace. Then this residue of metal is tapped and made into soft steel, for which there is a constant demand, by making the proper additions of ferro-manganese and recarburizer.

**The Slag:** At the high temperature at which its removal is effected, phosphorus is easily reduced, so in order to oxidize, flux and hold the phosphorus in the open hearth slag, it is necessary that the latter be very basic and highly oxidizing, as an analysis shows. The average composition of the slag is about as follows: Silica, $SiO_2$, 6.35%; ferrous oxide, FeO, 21.65%; ferric oxide, $Fe_2 O_3$, 6.90%; manganese, Mn, 1.12%; phosphorus, P, 3.25%; alumina, $Al_2O_3$, .97%; lime, CaO, 44.07%; magnesia, MgO, 8.04%. The high percentage of iron oxides, which are equivalent to approximately 24.0% metallic iron, gives the impression that the process is wasteful of iron, which is true, but due to another cause. While the percentage of iron oxide is high, it does not exceed that of the run off slags of the open hearth process, and the total volume of slag is much less than in the straight open hearth process, so that the loss of iron here is perhaps less than in the latter process. The chief loss is at the converters, and there can be no doubt but that the double conversion loss exceeds the single loss in the straight open hearth process. This matter assumes its chief importance as it relates to the conservation of the iron ore supply.

## SECTION III.

### COMBINATION PROCESSES IN THE SOUTH.

**The Duplex Process in the South:** In the southern district the conditions of steel manufacturing are very different from those in the North, and many additional reasons for the use of the duplex process there are to be found. First, in the South there is no pig iron that is suitable for the Bessemer process manufactured there, whereas, in the North, Bessemer iron is relatively abundant. Second, there is no low phosphorus iron or spiegel commercially available for recarburizing in the southern district as there is in the North, and this lack makes it necessary in manufacturing high carbon steels in the South to catch the carbon on the way down. Third, the phosphorus content of the basic iron in the southern district, which averages about .80%, is very high as compared with the phosphorus content of basic iron in the North, the average for which is about .25%. In the manufacture of high carbon steel from high phosphorus pig iron the duplex process offers exceptional advantages for catching the carbon high, thus reducing the amount of coal or coke-dust required to a minimum and avoiding rephosphorization from the high phosphorus slag. Another advantage of the process, when iron with a high phosphorus content is used, is that it permits the making of a slag which contains a high percentage of phosphoric acid and is therefore suitable for use in the manufacture of fertilizers. This slag is a valuable by-product from one of the southern plants.

**The Southern Triplexing Process:** In operating the duplex process in the South, it has been found that, owing to the high phosphoric acid content of the slag, it is difficult to prevent the reduction of some of the phosphorus after recarburizing. This rephosphorization of the steel occurs mainly in the ladle, particularly in the portion of the metal in direct contact with the mass of floating slag, and is most noticeable in the last two or three ingots from each ladle of steel teemed. In order to overcome this defect and at the same time increase the production of basic slag for phosphate fertilizer, one plant has developed a triplex process in which two basic open hearth units are required to finish the metal after blowing in the converter. Briefly, the process is as follows: After blowing, the metal is transferred from the converters to primary basic tilting furnaces where it is treated with lime and the other necessary oxides for dephosphorizing it. Here the phosphorus content in the metal is reduced to about .07%, when it is poured into ladles and transferred by specially constructed, heavy, extra-wide-gage trucks to a finishing unit composed of an equal number of similar furnaces. In these furnaces the phosphorus content of the metal is brought below .04%, when the steel is finished in the ladle by the addition of the necessary recarburizer and deoxidizers, and any alloys required by the specification. It is said that this process does not reduce the capacity of the plant and materially improves the uniformity and quality of the steel produced.

# PART II.

# THE SHAPING OF STEEL.

## CHAPTER I.

## THE MECHANICAL PROPERTIES OF STEEL.

### SECTION I.

### SOME GENERAL REMARKS PERTAINING TO THE TESTING OF STEEL.

**The Factors that Affect the Mechanical Properties of Steel:** There are four factors that may affect the quality and the mechanical properties of steel; namely, the method of manufacture, or refinement, the chemical composition, the mechanical working it is subjected to, and the heat treatment it receives. The first of these factors is discussed in the first part of this book. The others are now to be taken up, and frequent use of the terms employed in the mechanical testing of steel will be made in the pages to follow. Hence, although in the natural order of manufacturing steel physical tests follow the shaping, it seems well to take up this subject now in order that the reader may be more familiar with the terms employed in connection with these tests, when there is occasion to refer to them.

**The Two Objects in the Testing of Steel:** In the early days it was the custom to order steel according to use, that is, the purchaser asked the steel maker for a certain quantity of steel suitable for a certain purpose, and the manufacturer then furnished steel of a kind or grade he considered most suitable for the purpose. With the growth of the steel business, this custom proved inadequate to the conditions and was superseded by the practice of ordering steel to specifications, which appeared to be, and is, a much more satisfactory arrangement for all parties concerned. The consumer naturally decided that he should know better than anyone else what the requirements were, and the manufacturer, in turn, was very glad to be relieved of the responsibility he assumed under the old system. Now, the only basis upon which the consumer of steel or his engineers originally had to work in determining specifications was experience. Thus, providing that a certain steel had proved satisfactory for a certain purpose, he desired for the new work steel as nearly like the old as possible. With this progress came the need for testing. Then as undertakings involving the use of steel increased in magnitude, it was discovered that steels made by the same methods are subject to considerable variation. Furthermore, in order to obtain the requisite amount of steel, it is often necessary to use, for the same purpose, steels made in different ways. And again the need for testing was felt in order to secure uniformity in the materials. This testing developed along two lines, namely, physical and chemical.

**Relative Importance of Physical and Chemical Testing:** It is evident that, to the consumer of steel, its mechanical properties are of first importance, because it is these properties that determine whether or not a particular steel is suitable for the purpose he intends it. In all cases, then, such as structural steels, in which the material is put in service as received from the manufacturer, the customer does well to order his steel to physical specifications only. In cases where the steel is to be heat treated or is to undergo other treatment in the hands of the customer, then it should be ordered to a chemical specification only. Since the method of manufacture influences the properties of the metal, the kind of steel, whether Bessemer, basic, acid, or electric, should be and is, usually, specified. But for a great many reasons, for a discussion of which time and space are not available, it is unfair to ask the manufacturer to make steel to order in which all three factors are specified. Suffice it to say, that in the one case the customer should be satisfied to get the kind of steel ordered with the required physical properties, irrespective of the means, chemical or otherwise, which the manufacturer may have found it necessary to employ in order to supply metal with the properties called for. In the other case, the purchaser is interested only in obtaining steel properly made and of the proper kind and composition, because with such steel the original physical properties will be replaced by new ones due to the subsequent working or treatments. From the view point of the consumer, then, the relative importance of the physical and the chemical test depends upon the conditions that surround each individual case. But to the manufacturer, chemical testing is of prime importance, because it offers a means of control whereby he is able to produce the steel with a greater degree of certainty. For a description of the methods employed in chemical testing the published standard methods of the Steel Corporation are available.

**Nature of Physical Testing:** It should at all times be borne in mind that the results obtained by any method of physical testing are not absolute, but relative. Obviously, the only sure test is actual service, and it is just as evident that such tests are impracticable. Therefore, the test must be carried out with a small piece of material, the structure and condition of which are likely to be different from that of the section, taken as a whole, from which it was cut. A second objectionable feature is found in the difficulty of subjecting this piece to the same conditions that it would be subjected to in actual service. Attempts have been made to analyze these conditions with the idea of classifying the forces steel is required to overcome in service, so that in testing it might be subjected to the same kinds of forces. With respect to the effect they tend to produce, forces have been classified as (1) tensional, or forces tending to put the material under tension, that is, pull it asunder; (2) compressional, or forces that tend to compress the piece in one or more directions; (3) torsional, or forces tending to twist the material; and (4) shearing, or forces that tend to cut the material across its section. With respect to the manner in which the forces are applied, the following classification has bean made; 1. Static stresses, which are the result of the gradual application of a steady or constant load. 2. Fatigue stresses, such as result from the repeated application of a load or loads. 3. Impact stresses, in which the metal is subjected to a sudden blow. 4. Dynamic stresses, which are repeated impact, or vibratory stresses.

From these are selected the class of force or stress the steel is likely to be required to withstand in service, and the tests will be arranged accordingly. Added to these are a number of miscellaneous tests, such as hardness tests and tests to determine relative resistance to wear or penetration.

## SECTION II.

### THE TESTING OF STRUCTURAL AND OTHER SOFT STEELS.

**The Pulling Test:** A test that is most commonly applied to steel, and one that is always used, and almost to the exclusion of all others, for testing structural steels, is that commonly spoken of as the pulling test. As the name implies, the chief aim in this test is the determination of the tensile strength of the steel, but incidental to the carrying out of the test much additional information as to other mechanical properties of the sample of steel is obtained. The technical terms employed in testing to indicate these properties are tensile strength, elastic limit, elongation, reduction of area, and modulus of elasticity. The exact meaning of these terms is best explained in connection with a description of the method of making the test.

**Procuring the Test Pieces:** Except in one or two cases where it is desirable to modify the usual procedure, the test piece, or sample, is sheared from scrap ends cut from the material as it comes from the rolls. This piece is about eighteen inches in length and two inches in width, and, except in the case of sheared plates from which both longitudinal and transverse pieces are sometimes taken, its long axis is parallel to the direction of rolling. As a rule, the test piece is taken from a position not too close to the rolled edge, but in the case of bars of small sectional area the entire section of the proper length may be taken. The piece is then stamped near the ends with the heat number and any other data necessary to identify it.

**Preparation of the Test Piece:** The working or shearing of the test piece puts it in a state of strain and produces a great number of incipient cracks on the edges, so that if it were pulled in this condition it would fail too easily, and the results of the pulling would not indicate the real value of the properties determined. To eliminate these cracks, the edges of the piece are milled off as shown in the accompanying sketch, and the milled edges are filed smooth. Then if the piece is a heavy, thick one or is an alloy steel, such as nickel steel, it is allowed to rest for a period, the length of which will depend upon the conditions and the kind of steel. This resting is necessary to allow the steel to relieve itself of the condition of strain which the working has set up in it. This condition seriously affects the ductility of the steel, as is shown by the fact that some test pieces, particularly of alloy steels, show a marked improvement in elongation after resting, but with little, if any, change in the tensile strength. In the case of soft steels of moderate thickness, the resting period is not so important, as the working does not produce severe strains, and such steels recover quickly from strains. After the test piece has been machined and filed and otherwise made ready for testing, its dimensions are taken. From a point estimated to be the middle of the machined portion of the piece, two spaces of two inches each are laid off, with a double pointed punch, longitudinally along the bar and in both directions from the center punch mark, thus making a distance of eight inches between the two punch marks that are the farther from the center one. This space fixes the length of bar that is later to be the basis for calculating the percentage of elongation. Finally, with screw micrometers the width and thickness of the test piece are taken and recorded. A careful operator will measure these dimensions in three or four places to determine to what extent they are uniform. The test piece is then ready to be pulled.

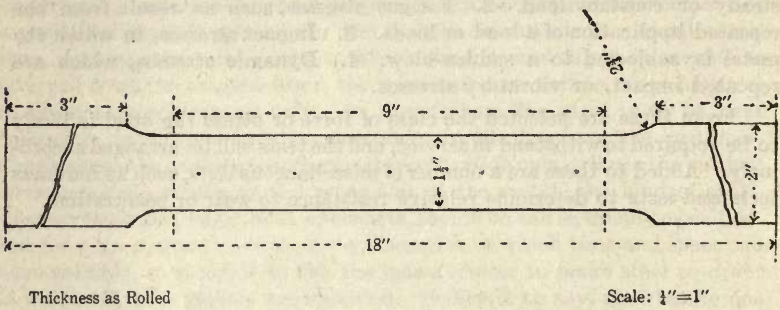


Fig. 45. Diagram Showing the Usual Form of the Test Piece Used in Pulling Structural Steels. Occasionally the edges are milled parallel for the full length of the specimen.

**Pulling the Test:** The testing machine may be likened to a beam scale or weighing machine, and if, instead of lying upon the platform of the scale, the test piece be thought of as being attached by one of its ends under the platform with its other end free for the attachment of some device for exerting a vertical pull, the analogy is almost exact. In modern machines the pulling device is either an electric motor, attached through gears and screws to a gripping device that clamps one end of the test piece, or an hydraulic ram connected directly with the clamping device. With such an arrangement the amount of the pull is registered in pounds on the graduated beam of the machine. This beam is provided with a travelling weight, which, by means of a screw and worm drive actuated by hand, may be rolled out along the beam as the pull increases, thus keeping the beam in the neutral position and registering the amount of the tension at all stages of the pull. When the test has been properly marked and measured, it is placed in the machine in a vertical position and securely clamped in the gripping boxes, or shackles. Then, the pulling device is started at low speed, and the weight is cautiously moved out along the beam, the operator keeping it in a perfectly horizontal position with the free end midway between the upper and lower beam-end stops. The continued action of the pulling machine is an indication that the test piece is stretching slightly. That such is actually the case could be proved by stopping the machine and measuring with delicate instruments the distance between the two extreme space marks and comparing this measurement with the original length. As the pulling is continued uniformly, the beam weight is advanced at a uniform rate, indicating that the piece is obeying the law of stress and strain; but a point is soon reached where the beam suddenly drops, indicating that, without any increase in the load, there has been a sudden increase in the length of the test piece. In testing parlance this point is called the **elastic limit**, the **yield point**, or the **point of permanent set.** To be accurate, the point reached immediately before this sudden stretch, or give, occurs marks the **true elastic limit**, while the drop of the beam marks the **yield point.** A reading of the weight indicated by this position of the beam weight is therefore taken, and the pulling is continued as before, with the exception that the speed of the pull may be increased somewhat. As the beam rises again, it is necessary to advance the beam weight much more rapidly than before, which fact indicates a more rapid stretching of the test. In a short time another point is reached where the beam suddenly drops for the second time, but here, though the pulling is continued, the beam will not rise again. A second reading is therefore made, and the weight recorded is taken as a measurement of the tensile strength of the test piece. Finally, as the machine continues to elongate the specimen, the point of rupture is reached, and the piece breaks apart. In practice no reading is taken at the breaking point, but if it were, it would be necessary to reverse the direction of motion of the beam weight, because the breaking load is generally less than the tensile strength. The latter, therefore, is usually referred to as the **ultimate strength, maximum stress,** or **maximum load.**

**Graphic Representation of Tests:** The pulling of a test is admirably illustrated by means of a graph, which is also a great aid in understanding the relations of the various terms employed in designating the points described above. The following graph, while not absolutely accurate and to scale in some of its parts, will serve to illustrate the scheme for preparing graphs and to make clearer the description of the pulling of the test piece. The diagram requires no explanation.

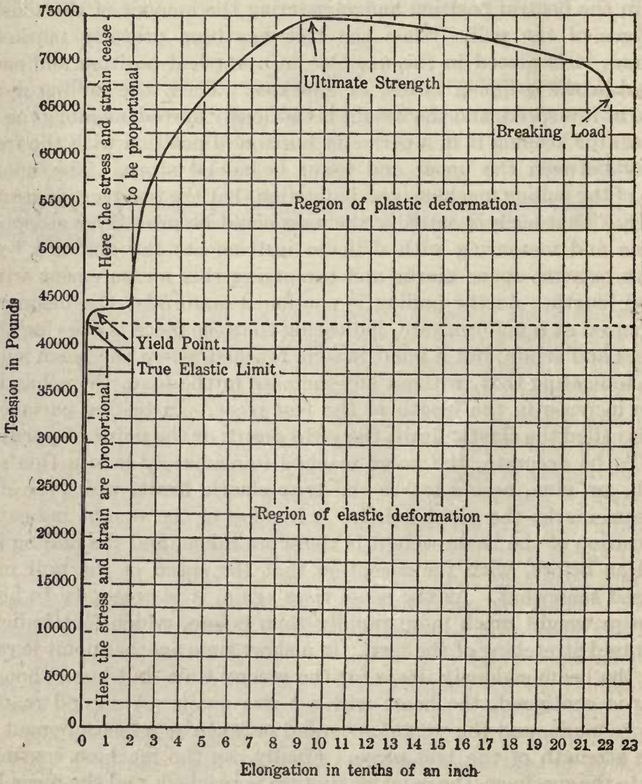


Fig. 46. Graph Representing the Pulling of a Structural Steel Test Piece.

**Reasons for the Points of Yield and Maximum Stress:** No very satisfactory reason for the occurrence of the yield point has yet been advanced. Some think that it is due to some rearrangement of the molecules. Again, grain structure may be the cause. Since steel is made up of small grains or crystals, it appears reasonable to suppose that they have at the time of their formation assumed a form and an arrangement that is most natural, and that they will offer resistance to any force tending to change this form or arrangement. This resistance is made up of two forces of attraction, namely, one that tends to keep the grains in contact and another that tends to preserve the arrangement of the molecules within the grain. At the elastic limit this resistance is just balanced by the tension, but under any greater tension, deformation of the grains begins, and the structure "gives" suddenly, becoming at the same time longer and smaller in cross section. Up to the elastic limit the slight stretch may be due to a partial rearrangement of the grains. When the tension is removed the natural arrangement is restored, with the result that the piece immediately assumes its initial form and size. When subjected to tension under this limit the body remains in an elastic condition, and the deformation it undergoes is called **elastic deformation.** Above the yield point the grains are undergoing deformation, that is, they are in a way destroyed, and the piece of metal reacts more like a plastic than an elastic body. Therefore the body is said to be undergoing **plastic deformation.** This change in grain form is continuous, and requires an ever-increasing force, or stress, to make it so. The condition is strictly analogous to cold working, which will be discussed later. Consequently, the piece becomes stronger, but at the same time it is becoming longer and correspondingly smaller in cross section. Ultimately, as the necking of the piece becomes pronounced, the loss in strength due to the decreased area of the section, plus the external stress applied, balances and then exceeds the maximum stress that the cold working can develop. From this point, then, the external force necessary to balance the forces of attraction between the grains becomes less and less as the area continues to decrease rapidly. Finally, the maximum deformation of the grains is reached, when, if the tension applied externally exceeds the forces of attraction tending to keep the grains together at the point of least cross sectional area, the piece is fractured at that point.

**Examination of Test After Pulling:** After fracture the two parts of the test piece are removed from the machine, and the fractured ends are fitted together as neatly as possible for the measurements to follow. The distance between the extreme punch marks is now measured. The difference between this distance and the original space of eight inches gives the elongation for the piece, which is properly recorded. An examination of the piece shows that while it has been reduced in section throughout its length, the reduction is most pronounced in the region of the fracture, where the piece underwent the characteristic deformation known as **necking** before it broke. It is here, as near to the fractured ends as possible, that the width and thickness are again measured in order to ascertain the reduction in area. Finally, the fractures are designated as angular, cup-shaped, half cup, and irregular. Very little importance can be attached to the form of the fracture, but some inspectors believe that the cup shaped fracture indicates more nearly perfect uniformity in the material than the other forms.

**Calculating the Results of the Test:** The results obtained in the test are for the given piece only, and, in order that the results from different tests may be comparable, they must be calculated to a common basis. Tensile strength and elastic limit are always expressed in pounds per square inch in the United States, in tons per square inch in England, and kilograms per square millemeter in France and other countries using the metric system. The elongation is expressed as the percentage of increase on the original length of the bar. In the United States this length for structural and other low carbon steels is usually eight inches, as formerly stated, but other lengths, as ten and twelve inches, ten centimeter, etc., may be used. For this reason it is always important that the original length of the bar be stated, as the percentage of reduction on two inches, for example, would be much greater than that based on eight inches because of the pronounced local contraction, or necking, at the point of fracture. This variation in the length of test pieces is made, because the relation between the length and the thickness of the test affects the elongation. Hence, in order that tests of different thicknesses may be comparable, the ratio between the thickness and length is kept constant by varying the length. The ideal thickness for a length of eight inches is about three-fourths inch. Over or under this thickness, the specification is usually modified either by changing the length or by making the proper allowance from the elongation as determined. The reduction of area is expressed in percentage contraction of area of the cross section as compared with the original area of the cross section. An example will serve to clear up any doubtful points that may not have been made clear in this explanation.

**Table 46. Data on the Pulling Test Represented by the Graph of Fig. 46.**

| | Dimensions of Piece | |
|---|---|---|
| | Before Pulling | After Pulling |
| Length................ | 8.0 inches | 10.20 inches |
| Width................. | 1.41 " | 1.00 " |
| Thickness............. | .860 " | .60 " |
| Area.................. | 1.213 sq. in. | .60 sq. in. |

Readings on pulling bar: Elastic limit=44600 lbs.; Ultimate strength=74600 lbs.

**Calculations:**

Elastic Limit $= \frac{44{,}600}{1.213} =$ 36770-lbs. per sq. in.

Ultimate Strength $= \frac{74{,}600}{1.213} =$ 61500- " " "

Elongation $= \frac{10.20-8}{8} =$ 27.5% in 8 inches

Reduction of Area $= \frac{1.213-.60}{1.213} =$ 50.5%

**The Modulus of Elasticity, or Young's Modulus:** The Modulus is seldom determined in practical work, as it involves the determination of the absolute increase in length of the test bar up to the elastic limit, which is a quantity so small as to be very difficult to determine accurately. It may be defined as that force, expressed in pounds, tons, or kilograms per unit of cross section area, that would stretch a test piece to twice its original length, when applied to one end of it and acting in the direction of its length. It may be found by applying the following formula: $M = \frac{f \times L}{A \times l}$ where M= modulus of elasticity, f=force applied, L=original length, A=original sectional area, l=increase in length. For low carbon steel Young's Modulus is about 29,000,000 lbs.

**Relative Importance of the Mechanical Properties as Determined by the Pulling Test:** From what has been said it is plain that the quantities that may be taken as indicative of the strength of the material are tensile strength and elastic limit; but while most engineers will insist on both tensile strength and elastic limit being given and a few are content to get the tensile strength only, it is evident that, in its practical application, the elastic limit will determine the working strength of the steel, that is, the maximum load a given piece may carry with safety. In the elastic range the body stretches and recovers with increase and decrease in the load; in the plastic range it cannot recover but continues to elongate as long as tensional stresses are applied, and in this condition it is a very unsafe material to use. The percentage reduction of area and the percentage of elongation are, when considered together, an index of the ductility of the metal, for both are required to give an idea of the amount of the deformation before rupture. However, engineers are divided in their opinions as to the relative importance of the two factors. In a general way, it may be stated that the reduction of area is regarded as more reliable than elongation, because, as previously explained, the quantity denoting the latter is affected by the ratio of the length of the test piece to its cross sectional area. In many foreign countries this ratio is always specified.

**Bending Tests:** On certain classes of material, bending tests are made in addition to the pulling test. These tests, simple in character, consist merely in bending test pieces similar to those used for pulling, and similarly prepared, through certain specified arcs. The bending is usually on cold material, but some orders call for hot bending tests, also. Such tests are employed to make sure that the steel is not cold short or hot short and, in a way, to indicate the ductility of the metal.

## SECTION III.

### THE TESTING OF THE HIGHER CARBON AND HEAT TREATED STEELS.

**Kinds of Tests Applied to the Higher Carbon and Heat-treated Steels:** For testing the class of material referred to under this heading, a large number of different tests have been devised. These tests may be classified under the headings of tensile tests, compressive tests, torsional tests, impact tests, and hardness tests. Of these, the tensile, impact, and hardness tests are the ones most frequently met with, and will, therefore, be described later. Of the others the torsional test is perhaps the most important, as it is largely used in the testing of steel for automobiles. It consists in twisting a small round specimen of steel held in a suitable machine until rupture occurs. In it a test piece of standard size is used, and values for this piece corresponding to the elastic limit and ultimate strength, but expressed in inch-pounds, are obtained very much as in the tension test; the amount of distortion, however, is given in degrees. The compression test is carried out by means of a machine similar in construction to the pulling machine. The test piece may be in the form of a small cylinder or a one inch cube. The elastic limit under compression is determined, and the distortion is indicated by the decrease in length.

**The Tensile Test:** The test for determining the tensile strength of the higher carbon and heat treated steels is carried out in a manner similar to that for the softer steels, but since the material is so much stronger and the items made from such steels do not lend themselves to the same method of sampling, the test piece is much smaller than that employed in the case of structural steels. This specimen is in the form of a small round, as shown in the accompanying figure, and is often obtained by boring with a hollow drill about midway between the center and outside surface of the section sampled.

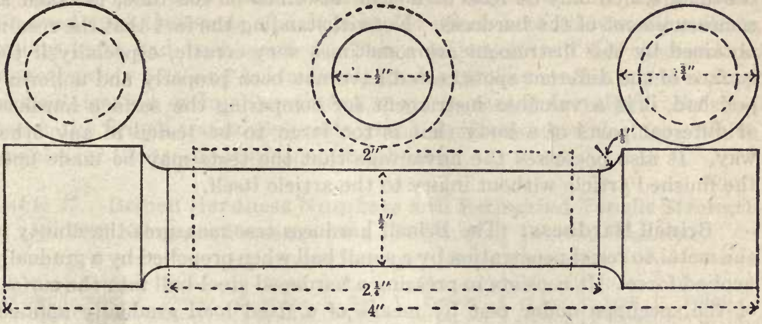


FIG. 47. Drawing Showing Usual Size and Form of Test Piece Used in Pulling High Tensile Steels. The ends may be of any form desired but the central machined portion must be as shown in the figure.

**Impact Test:** While several different types of machines for measuring the resistance of steel to impact have been invented, the results obtained with any of these machines so far have not been considered very reliable, as widely varying results may be obtained on the same steel tested on the same machine. In practice, therefore, the nearest approach to an impact test is what is commonly and correctly called the **drop test.** It is applied to full size pieces of rails, to axles, and to other sections. It consists in allowing a specified weight to drop from a specified height a specified number of times upon the sample, which is supported at two points on a heavy anvil or block resting upon strong springs. All three of these factors may vary greatly with different classes of material and with the different ideas of the engineers. While it does not measure absolutely any property of the metal and is to be considered as comparative or qualitative only, it is, nevertheless, one of the most useful of practical tests, for it determines, in a crude way, the ductility and homogeneity of the metal and its resistance to shock. In the case of axles, and other round bodies, the deflection from a given weight may be kept constant for different sizes by varying the height, for since the strength of such a section varies as the cube of the diameter, for equal deflections, the height varies as the cube of the diameter of the specimen at its center.

**Hardness Tests:** The best known and the most widely used instruments for measuring the hardness of metals are the Shore scleroscope and the Brinell ball testing machine. The Shore instrument consists of a small diamond-faced tup enclosed in a glass tube which is provided with a suction bulb, whereby the tup may be raised to the top of the tube and dropped from a definite and fixed height. To make a determination, the instrument is held in the vertical position with the lower end resting upon a smooth and highly polished spot on the surface of the metal to be tested, when the tup is allowed to drop by compressing the bulb. The height of the rebound, which may be read on a scale inscribed on the tube, is taken as a measurement of the hardness. Notwithstanding the fact that the results obtained by this instrument are sometimes very erratic, especially if the surface of the different spots tested have not been properly and uniformly polished, it is a valuable instrument for comparing the surface hardness of different parts of a body that is too large to be tested in any other way. It also possesses the advantage that the tests may be made upon the finished article without injury to the article itself.

**Brinell Hardness:** The Brinell hardness test measures the ability of the metal to resist penetration by a small ball when propelled by a gradually applied force. It consists in pressing a hardened steel ball into the surface of the specimen under test by means of a fixed load gradually applied. The instrument consists essentially of a small hydraulic press, which is operated by a small hand pump and is provided with a pressure gauge for reading the pressure, and a special contrivance for automatically holding the pressure when it has reached a maximum of 3000 kilograms. The piston of the press, which acts vertically downward, is provided on its end with a hardened steel ball, ten millimeters in diameter, by means of which an impression may be made on the smooth surface of the specimen, which rests on a firm but an adjustable base. The operation of the instrument is very simple. The specimen, the surface of which has been planished with a file, a whetstone, emery wheel or similar means, is laid on the base and is then brought in contact with the ball by turning a small wheel for adjusting the base, or platform. By operating the hand pump until the maximum pressure is attained and maintained for about one half minute, the steel ball is pressed into the surface; then the pressure is relieved, the base is lowered, and the diameter of the impression made in the specimen is measured by means of a microscope fitted with a millimeter scale, vernier, and cross hair. From this diameter the spherical area of the impression may be calculated, which, divided into the maximum load of 3000 kilograms, gives the hardness number. The formulas for making these calculations may be combined into a single formula, thus:

$$H = \frac{P}{2 \pi r \left( r - \sqrt{r^2 - \frac{D^2}{4}} \right)}$$

where $P = 3000$ Kilograms pressure, $r = 5$ mm., radius of the ball, $D =$ diameter of the impression, and $H =$ the hardness number. In practice it is most convenient to have a table, such as that shown below, prepared, from which the number may be obtained direct from the diameter of the impression.

**Relation of Brinell Number to Tensile Strength:** It is both a curious and a significant fact that the Brinell hardness number bears a close relation to the ultimate strength, as may be seen from an inspection of the following table, which was prepared only after comparing results obtained upon thousands of specimens, to which both the Brinell and the pulling tests had been applied. This relation, it will be observed, is approximately 500, and holds for all grades of carbon steel whether they be heat treated or in their natural state as forged or rolled. For this reason the Brinell test is applicable to the rapid testing of steel from which samples for the tensile test cannot be obtained.

**Table 47. Brinell Hardness Numbers and Estimated Tensile Strength for 3000 Kilogram Pressure on a 10 MM. Ball Testing Machine.**

| Diam. of Impression in m/m | Hardness Number | Ultimate Pounds per Sq. In. | Diam. of Impression in m/m | Hardness Number | Ultimate Pounds per Sq. In. | Diam. of Impression in m/m | Hardness Number | Ultimate Pounds per Sq. In. |
|---|---|---|---|---|---|---|---|---|
| 2.00 | 946 | 465100 | 3.35 | 332 | 162700 | 4.70 | 163 | 80100 |
| 2.05 | 878 | 442100 | 3.40 | 321 | 157800 | 4.75 | 159 | 78300 |
| 2.10 | 857 | 421600 | 3.45 | 311 | 153100 | 4.80 | 156 | 76600 |
| 2.15 | 817 | 402000 | 3.50 | 302 | 148600 | 4.85 | 153 | 74900 |
| 2.20 | 782 | 383700 | 3.55 | 293 | 144300 | 4.90 | 149 | 73300 |
| 2.25 | 744 | 366600 | 3.60 | 286 | 140200 | 4.95 | 146 | 71700 |
| 2.30 | 713 | 350600 | 3.65 | 277 | 136200 | 5.00 | 143 | 70200 |
| 2.35 | 683 | 335700 | 3.70 | 269 | 132400 | 5.05 | 140 | 68700 |
| 2.40 | 652 | 321600 | 3.75 | 262 | 128800 | 5.10 | 137 | 67200 |
| 2.45 | 627 | 308400 | 3.80 | 255 | 125300 | 5.15 | 134 | 65800 |
| 2.50 | 600 | 295900 | 3.85 | 248 | 121900 | 5.20 | 131 | 64500 |
| 2.55 | 578 | 284300 | 3.90 | 241 | 118700 | 5.25 | 128 | 63100 |
| 2.60 | 555 | 273300 | 3.95 | 235 | 115500 | 5.30 | 126 | 61800 |
| 2.65 | 532 | 262900 | 4.00 | 228 | 112600 | 5.35 | 124 | 60600 |
| 2.70 | 512 | 253100 | 4.05 | 223 | 109700 | 5.40 | 121 | 59400 |
| 2.75 | 495 | 243800 | 4.10 | 217 | 106900 | 5.45 | 118 | 58200 |
| 2.80 | 477 | 235000 | 4.15 | 212 | 104200 | 5.50 | 116 | 57000 |
| 2.85 | 460 | 226600 | 4.20 | 207 | 101600 | 5.55 | 114 | 55900 |
| 2.90 | 444 | 218700 | 4.25 | 202 | 99100 | 5.60 | 112 | 54800 |
| 2.95 | 430 | 211200 | 4.30 | 196 | 96700 | 5.65 | 109 | 53700 |
| 3.00 | 418 | 204100 | 4.35 | 192 | 94400 | 5.70 | 107 | 52700 |
| 3.05 | 402 | 197300 | 4.40 | 187 | 92200 | 5.75 | 105 | 51700 |
| 3.10 | 387 | 190800 | 4.45 | 183 | 90000 | 5.80 | 103 | 50700 |
| 3.15 | 375 | 184600 | 4.50 | 179 | 87900 | 5.85 | 101 | 49700 |
| 3.20 | 364 | 178800 | 4.55 | 174 | 85800 | 5.90 | 99 | 48800 |
| 3.25 | 351 | 173200 | 4.60 | 170 | 83900 | 5.95 | 97 | 47900 |
| 3.30 | 340 | 167800 | 4.65 | 166 | 82000 |  |  |  |

$\frac{\text{Pressure}}{\text{Area of Impression}}$=Hardness Number.

Tensile in Kg. per Sq. MM.=Coefficient .346 x Hardness Number.

Factor to Convert Kg. per Sq. M/M to Lbs. per Sq. In.=1422.3

# CHAPTER II.

## THE MECHANICAL TREATMENT OF STEEL.

### SECTION I.

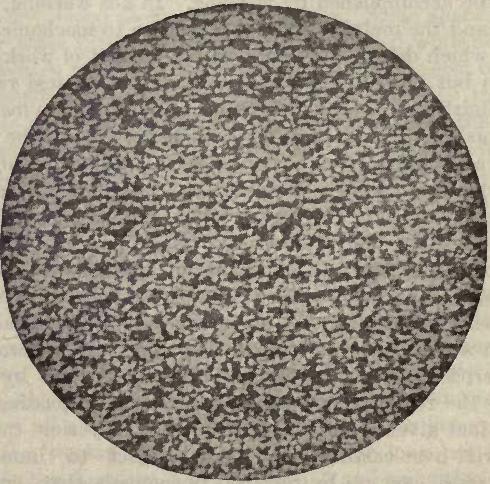
### METHODS AND EFFECTS OF MECHANICALLY WORKING STEEL.

**Methods of Shaping Steel:** After the separation of the metal from its ores, which in modern practice is accomplished by means of either the blast furnace or a form of electric furnace, and its purification in the Bessemer converter, open hearth, puddling furnace, or electric furnace, the third step in the metallurgy of iron is the reduction of the large bodies of metal thus produced to the various forms and sizes required by the many uses to which it is to be put. In general this shaping may be brought about either by pouring the metal while in a molten state into moulds, which act is called casting, or by mechanically working it. Since by all the methods of purification, puddling excepted, the metal is obtained in the fluid state, casting would appear to be the simplest and cheapest method of shaping; but for forming articles of very small section, it is evident that this method is impracticable; nor is it used, unless unavoidable, to form the larger sections in which the mechanical properties of the metal must be devoloped to the highest degree. Some shapes on account of their size or their intricate design require casting, while others are cast because they require no great strength in service and the cost of production only is to be considered. A lack of strength and ductility in castings is inherent, and is due to chemical and physical phenomena that accompany the solidification of the molten metal, something about the nature of which will be explained later in connection with the cooling of ingots. Suffice it to say now that the weakness of castings is due chiefly to any or all of three causes, namely, blow holes, segregation, and crystallization.

**Benefits of Mechanical Working:** On the other hand, mechanical shaping improves the quality of the metal by forcing its particles into more intimate contact, closing up cavities, and by refining its crystalline structure, and so has important functions aside from the mere reduction to form and size. The change in properties that may be attributed to the process of mechanical working is a marked one, for the strength, ductility and hardness are all affected. Of these properties the strength is always increased by the working, the hardness may or may not be markedly increased, while the ductility, i. e., elongation and reduction in area, may be either increased or decreased, depending on the conditions of the working. The amount of change in each of these properties for a given steel of a certain chemical composition is affected by the amount of work done and by the temperature at which the working is carried on.

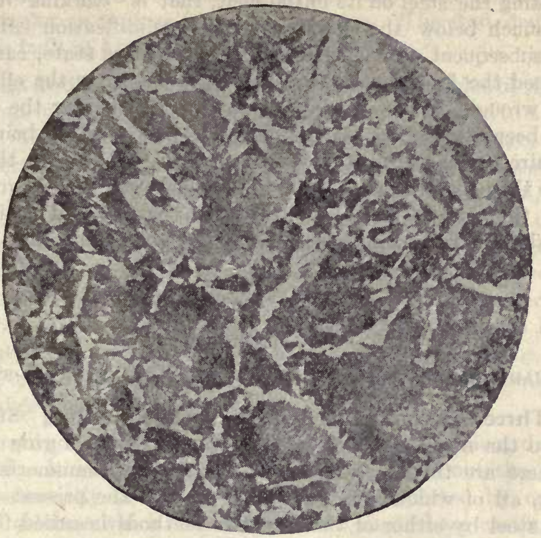
**Hot and Cold Working:** In the mechanical treatment of the metal, the first distinction to be made is that of hot and cold working. The study of metallography has shown that the term hot working of steel should be applied to the working of it at temperatures above its upper critical range, the temperature of which varies, inversely with the carbon content, from 700° to 900° C., while all work done at temperatures below this range should be called cold working. It will be shown in the next part of this book that a sharp change in structure due to working takes place as the critical temperature of the steel is passed. This change is due mainly to the fact that above this range iron exists in an allotropic crystalline form, the gamma form, in which carbon dissolves to form a homogeneous mixture, while below it the metal assumes the alpha form and is a crystallized aggregate of ferrite and cementite. A metallographic examination of specimens shows that the result of working this aggregate structure is one of permanent distortion, or strain, and one in which the properties of the metal are deeply affected, as indicated by the different physical tests. The elastic limit, tensile strength, and hardness are increased, while the ductility is reduced. The extent of this change varies according to the temperature, and is most marked when the working is done at or below atmospheric temperatures. Cold working becomes less effective as the critical temperature is approached, which is due to the increase in molecular energy and the resulting loss of rigidity by the solid. It should be noted that below the critical range no refinement of the granular structure can be accomplished by working. In hot working, the grain size is decreased, and the metal is subject otherwise to mechanical refinement, the extent of which depends not only on the amount of work done and size of the section but on the temperature above the critical range at which the work is finished. However, if, after a working, the metal be heated above this finishing temperature, as is often the case in the actual rolling of steel, the grain refinement of the previous working may be partly or entirely destroyed, depending upon the temperature to which the piece is reheated. Owing to the plasticity of the metal at the higher temperatures, the distortion due to working above the critical range does not produce a permanent strain in the structure of the solid. After each distortion the structural components, the crystals or grains, are free to return to the shape and arrangement peculiar to their state of equilibrium. Besides, since the steel takes on a new structure and a new condition is born upon cooling through the critical range, any internal tension set up by the working is relieved by the rearrangement that takes place in passing through this range. This fact gives another reason for the superior quality of hot worked material over castings, which are subject to immense internal tension, or stresses, set up by physical phenomena that accompany the solidification and by the forces of contraction due to the unequal rates of cooling between the exterior and interior of a casting. Such severe stresses do not occur in hot worked material. Referring to the more common prac-

1. Cast steel. Carbon .35 per cent. Magnified 100 diameters.

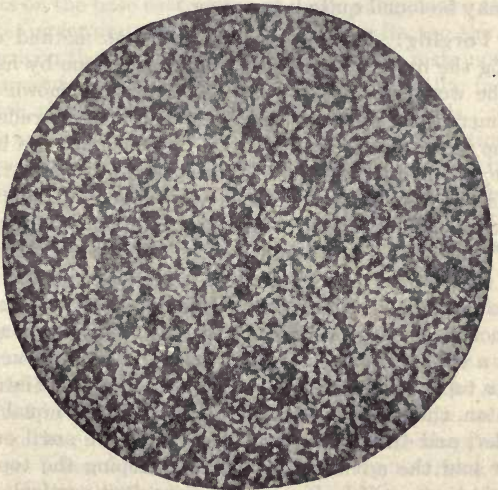


3. Cold worked hypo-eutectoid steel. Carbon 0.30 per cent. Magnified 100 diameters.

FIG. 48. Showing Effects of Working



2. Hot worked steel. Carbon 0.50 per cent. Finishing temperature high. Magnified 100 diameters.



4. Hot worked steel. Carbon 0.50 per cent. Finishing temperature low. Magnified 100 diameters

upon the Grain Structure of Steel.

tice of working the steel on its initial heat, that is, working it before it has cooled much below the temperature of solidification after having been cast subsequent to manufacture in the molten state, careful study has developed the fact that it matters little, so far as the effect on the refinement wrought by the working is concerned, whether the ingot has or has not been allowed to become completely cold before being brought to the required temperature for working. Therefore, while the idea is contrary to the popular notion, the primary object in the steel workers mind should be the improvement in quality of the material he is working, while the shaping of the material may be looked upon as a secondary object.

## SECTION II.

### SUMMARY OF THE HISTORY AND PRINCIPLES OF WORKING STEEL.

**The Three Methods for Mechanically Working Steel:** With reference to the manner of applying pressure to steel during mechanical working there are three possible methods; namely, hammering, pressing and rolling, all of which are extensively used at the present time. The shaping of steel by either of the first two methods is called forging. As an introduction to the study of the rolling of steel, a brief resumé of the history, principles, and effects of each of these methods will not be out of place and may be found quite interesting.

**Hammer Forging:** Hammering was the first method employed by man in shaping the metals. The first forging was done by hand hammers wielded by the workmen. The first power hammer, known by the name of tilt hammer, was built in England, and was a crude affair compared with the steam hammers now used. It consisted of a beam of wood hinged at one end and provided with an iron hammer head at the other. At an intermediate point, engaging cams on a revolving shaft alternately raised the free end and allowed it to fall on a bottom die fixed upon a suitable foundation. Thus the top die could be parallel to the bottom die in only one position, and the larger the piece to be forged the less power there was available to forge it. The first steam hammer was built in France in 1842. It consisted of a two piece frame constructed so as to support, directly over a die or anvil, a steam cylinder, to the piston rod of which was attached a tup, or hammer head. By admitting steam into the cylinder below the piston, the hammer was raised for a distance equal to the stroke of the cylinder, and then allowed to drop upon the anvil or bottom die. This hammer had the advantage of always keeping the top and bottom dies parallel, but was still lacking in one important particular. Its power being derived from the inertia of the falling tup, the hammer had the least power when it was most needed, that is, when pieces of large diameter or of great thickness were being worked. This fault in the single acting hammer was corrected by the invention of the double acting hammer, in which steam is admitted at the top of the piston and employed on the downward stroke as well as for lifting the tup. The first double acting hammer was built at Midvale, Pa., in 1888.

**Principles and Effects of Hammering:** The principles of the hammer are that of an instantaneous application of pressure applied to a relatively small area. The strains set up in the metal are compressive and take place in a vertical direction in the region below the area subjected to the force of the blow. The crowding of the metal into one region, however, causes a small portion of the blow to be transmitted in horizontal directions. The suddenness of the blow tends to localize the effect and confine the refinement to the exterior. This fact results in a high degree of refinement, provided the amount of reduction is great or the section worked is a thin one, and is one of the reasons why it is possible to make some hammered material superior to rolled material. The resistance of the metal to deformation under shock, combined with the intermittant action of the hammer, makes shaping by hammer a slow process.

**The Forging Press:** The press is an English invention, dating from the year 1861. It was introduced into this country about the year 1887. It consists essentially of a hydraulic cylinder supported by one or two pairs of steel columns which are anchored to a single base casting of great weight and strength. The ram of the cylinder points downward and carries an upper forging bitt vertically opposite a similar lower and stationary bitt which rests on the base casting to which the columns are attached. By admitting water under pressure to the cylinder at its top the upper pallet is forced down upon the material to be forged, which rests upon the lower pallet. The pressure is applied slowly and is gradually increased to a maximum which may be maintained till the metal yields. By means of small auxiliary cylinders the ram is lifted after each application of pressure. The pressure exerted by the forging press is very great. In practice it is found that the lowest pressure that can be employed to be effective at a full forging heat is about 1.2 tons per square inch, but the pressures employed in actual work will often reach 13.26 tons per square inch.

**The Effect of Pressing:** The press differs very much from the hammer, both in action and the effects produced. Unlike the instantaneous application of the pressure as in the case of the hammer, the action of the press is so slow that a kneading of the metal takes place, and the strain, instead of being confined to the surface, penetrates deep into the material. An illustration cited by Messrs Harbord and Hall will serve to demonstrate the difference in the effect produced by the two methods of working.[1]

"If tests are taken from the outer parts of a gun forging which has the center trepanned out, little difference is found in the strength of the material, whether the forging was done under the press or under the hammer, provided the latter was sufficiently heavy for its work; the

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[1] See The Metallurgy of Steel. Vol. II. Page 855. Published by J. B. Lippincott Company, Philadelphia, Pa.,

press showing, if anything, slightly better results. If, however, the test pieces are taken from the cores which have been cut out of the center of the forgings, the difference in the results is so very marked as to have induced all the best makers of heavy steel forgings to install presses in place of, or in addition to, their large hammers."

**Advantages of the Press:** Aside from its increased beneficial effect upon the material, the press has many advantages over the hammer, some of which it may be of interest to cite. The absence of shock in the press is a decided advantage both in the construction of the machine and in the working of material. The cost of working material under a press is less than with the hammer because the output is greater, the press reducing faster than the hammer, fewer men and less skilled labor are required, and the fuel consumption per ton of output is less. A much greater proportion of the total work put into a press is transmitted to the metal than is the case with the hammer. Much of the energy of the latter is dissipated through being absorbed by the spring in the anvil block and by the earth. For certain work, however, this impact gives the hammer two advantages: first, it serves to remove scale; second, it enables the hammer to strike forgings in molds with greater ease than the press. The difficulty of retaining water under the extremely high pressures required by presses gives the hammer an advantage, but this advantage is offset by its greater liability to breakage.

**Rolling:** Of all the known methods of shaping steel from the cast material, that of rolling, as introduced by Henry Cort in 1783, though perhaps not producing the best quality in certain classes of product, has come to be the most extensively employed. Though Cort is rightly credited with being the father of modern rolling, the use of this principle in shaping metals antedates his mill by many years. Thus, there are records to show that in the year 1553 a Frenchman employed rolls to produce sheets of uniform thickness for the stamping of gold and silver coin. In Sweden rolls were employed to produce certain steel sections prior to the year 1751, and even at that time the assertion was made that as much as twenty times more bars could be reduced in a given time than could be shaped under the tilt hammer of those days. This fact, coupled with the great efficiency of the rolling method, is responsible for the universal adoption of rolling as the favorite method of shaping. The rapid growth in the production due to the ever increasing demand for iron and steel, made it imperative that the most rapid method of shaping be employed. From the days of Cort to the present time, the rolling mill has kept pace with the growth in production and has passed through a surprisingly rapid process of development, not only in size and power but in design and in the shapes of sections turned out. This development, together with the introduction of numerous appliances for handling the material mechanically during the rolling, has multiplied the capacity of the mills many times.

Some modern mills, like the rod mill, will now turn out a hundred times as much tonnage in a given time as a mill of the same size and working on rods of the same size could have done fifty years ago.

**Principle and Effect of Rolling:** The process of shaping steel by rolling consists essentially of passing the material between two rolls revolving at the same peripheral speed and in opposite directions, i. e., clockwise and counter clockwise, and so spaced that the distance between them is somewhat less than the height of the section entering them. Under these conditions the rolls grip the piece of metal and deliver it reduced in section and increased in length in proportion to the reduction, except for a slight lateral spreading which is almost negligible in some sections. The extent of the spread will be found to depend mainly upon the amount of reduction and width of the piece. Thus in rolling plates, the total spread may be less than that of the first pass in the reduction of two-inch billets, especially if the percentage reduction in sectional area in the latter is great. The nature of rolling may be best explained by means of the following diagram.

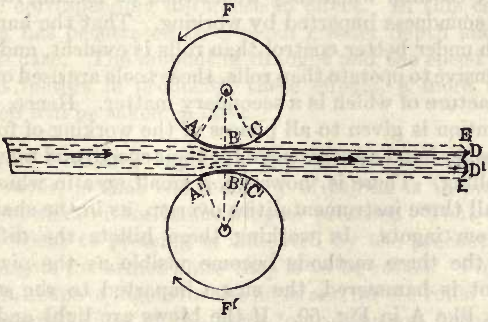


FIG. 49. Diagram Illustrating the Nature of Rolling.

Let O A C and O′ A′ C′ be two plain motionless rolls which are being forced into the bar AA′ E′E by means of pressures applied vertically from F and F′. The force exerted by the resistance of the bar will act along the radii of the rolls, as OA, OC, O′A′, and O′C′. The resultant of all these forces will be in the vertical lines O B and O′B′. Vertical compression of the metal will, however, occur only between the points B and B′. At all the other points between AC and A′ C′ the metal is forced away from the rolls and the bar is elongated. If now the rolls are made to revolve, the lower one in a clockwise direction and the upper in a counter clockwise direction, the piece is reduced in size and elongated as shown by figure A A′ D′D. This turning of the rolls introduces a second force, which acts in the direction of tangents to the arcs AB and A′ B′ and is equal to the force of friction and therefore proportional to the pressure between the rolls and the piece. The result of this force is to subject the piece to a longitudinal pull in the direction of B to D, this pull being at its maximum at B and at its minimum at A. The compression, however, is at its maximum at A and its minimum at B. The net result of this double action is to cause the metal to flow forward so that the piece, reduced in size, is delivered at a higher velocity than the peripheral speed of the rolls, the evidence for which is found in the fact that the marks on the piece caused by a depression or elevation on the rolls is farther apart than the circumference of the rolls. A slight retardation of the forward speed of the piece on the entering side may take place, but this point has not been very well established as a fact.

**Rolling Compared with Hammering and Pressing:** It is a very difficult matter to institute a fair comparison between the effects of rolling with those of hammering or pressing. Each method has a field of its own with rather well defined boundaries. Thus, many shapes are so intricate in design that rolling them is out of the question, and so they must be formed under the hammer or the press. A crank shaft and a hammer head serve as examples of these classes of shape, which can be produced in no other way, unless by casting, when they would then be lacking in the strength, ductility and soundness imparted by working. That the hammer and the press are both under better control than rolls is evident, and being slower and more expensive to operate than rolls, these tools are used on material the cost of manufacture of which is a secondary matter. Hence, extraordinary care and attention is given to all phases of the working of forged articles. Rolls on the other hand are cherished for their speed, and tonnage is always a factor in rolling. There is, however, a small area in which the field of operation of all three instrumentalities overlap, as in the shaping of billets or blooms from ingots. In working these billets the different effects produced by the three methods become visible as the piece is shaped. When an ingot is hammered, the shape imparted to the section is very liable to look like A in Fig. 50. If the blows are light and delivered at high velocity, the upper surface only will be elongated as shown at B in the figure. These facts show that the impact is almost entirely absorbed by the surface of the metal, and to obtain the best effect from hammering it is necessary to continue the work until the section has been reduced to one of relatively small size. The deeper penetration of the work of the press is shown by the rounded corners of the section represented by the figure at C. Any cavity at the center of the piece is closed under the action of the press, whereas the tendency of the hammer would be to enlarge it. The effect of rolling is influenced very markedly by the temperature. In the first place the temperature, in order to secure the greatest efficiency from the rolls, is likely to be higher than that required for either hammering or pressing. In a piece uniformly heated, the flow of the metal is slightly faster at the two surfaces than in the center in the smaller sections, while in larger sections the flow at the surface may be very much greater. The effect of the additional plasticity imparted by even a slight rise in temperature upon the flowing properties of the metal is plainly visible in the results obtained in rolling ingots under the two conditions as illustrated by the figures at D and E. The fishtailing of the piece represented at D shows that the flow of the metal is faster at the surface due to the lack of plasticity at the colder center. The reverse of these conditions is shown at E with the corresponding difference in effect. In this case the effect of the working has penetrated to a much greater depth and extent than in the previous case. The amount of draught and the speed of rolling are also important factors in producing these effects, a more thorough discussion of which will be taken up later.

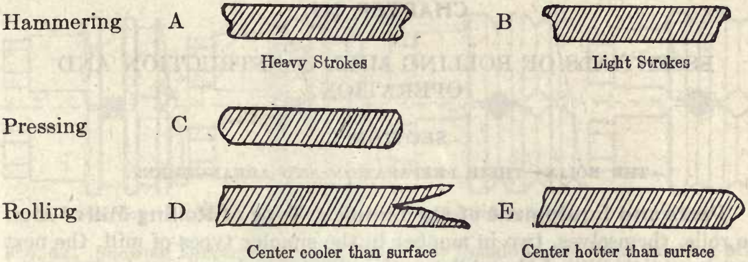
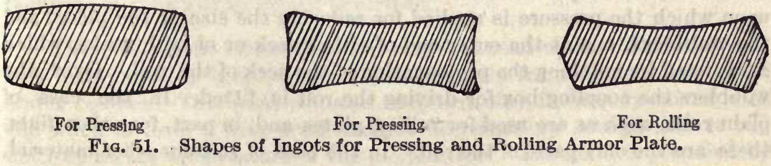


FIG. 50. Diagram Illustrating the Effects of Hammering, Pressing and Rolling.

**Rolling and Pressing Ingots:** The notion most prevalent among steel men, however, is that the tendency of rolling is to produce a more superficial effect than either hammering or pressing. That this notion is correct with respect to pressing is indicated by the precautions taken in casting large ingots for armor plate that is to be rolled. Figure 51 shows the difference in shape of ingots for the press and for the rolls. The concave and diamond shaped sides of the ingot for rolling are formed to prevent the loss due to fishtailing, as already explained. Under the press the two surfaces of a square sided ingot are slightly rounded, but, in rolling, a square sided ingot would make a concave sided plate which in many cases progresses to such an extent as to cause actual overlapping. It is admitted by nearly every one, however, that with very slow rolling and carefully regulated temperature that the quality of rolled material may be made the equal of that reduced under the press.



For Pressing For Pressing For Rolling

FIG. 51. Shapes of Ingots for Pressing and Rolling Armor Plate.

# CHAPTER III.

# ESSENTIALS OF ROLLING MILL CONSTRUCTION AND OPERATION.

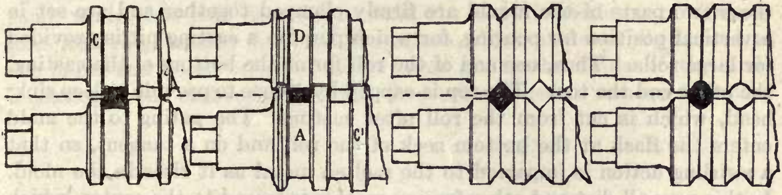
## SECTION I.

### THE ROLLS—THEIR PREPARATION AND ARRANGEMENT.

**Parts and Equipment of the Simplest Type of Rolling Mill:** After the rolls, themselves, two in number in the simpler types of mill, the next most essential part of the mill are the **chocks** or bearings which support the ends of the rolls and permit them to be turned without displacement. The chocks in turn are kept in place by means of the **housings,** which together with the adjusting screws also furnish a means by which the distance between the rolls is regulated. These parts constitute a **stand** of rolls. The housings are bolted to **shoes** which rest upon a firm foundation, to which they are always securely bolted. Next in importance are the parts which connect the mill with the driving shaft. First, there are the **spindles** that transmit the power from the pinions to the rolls, to both of which they are connected by means of loosely fitting **coupling boxes.** The **pinions,** supported in housings similar to the roll housings, are gears, one of which is driven through a driving spindle in line with one of the rolls. They serve to impart opposite motions to the rolls. The last part of equipment essential to the mill is the prime mover, which in modern mills may be a steam engine or an electric motor. As to other equipment, reheating furnaces are first in importance. Large mills must also be provided with **roll tables** for handling the material. A discussion of the driving apparatus is an engineering subject which lies beyond the intended scope of this book and will receive no further mention here. All the remaining parts, however, should be studied somewhat in detail.

**The Rolls and Their Parts:** Of the essential parts of the rolling mill the rolls furnish a subject of great interest. There are three parts to a roll; namely, the **body,** which is the part on which the rolling is done; the **necks,** or the parts which rest in the chocks and furnish the surface upon which the pressure is applied for reducing the size of the piece; and the **wobblers,** one at the outer end of either neck or of both necks, which are formed by notching the prolongation of the neck of the roll. Over the wobblers the coupling box for driving the roll is fitted. In the case of plain rolls, such as are used for rolling plates and, in part, for other flats, these are the only parts of the roll. In the case of rolls for other material, **grooves** are cut into the surfaces of the rolls to form the section required.

A groove in one of the rolls or a combination of grooves in the two rolls, which at the line of contact forms an opening corresponding to the shape of the section desired, is called a **pass.** The three most common passes are shown in the accompanying figure.



I Open Box II Closed Box III Diamond (90°) IV Gothic

Fig. 52. Showing Different Types of Passes For Roughing and Semi-finishing Mills I, III and IV are spoken of as **open passes** while II is called a **closed pass.** In the closed pass the piece is buried in one of the rolls so that three sides are enclosed by the groove A, the fourth side being closed by the tongue or former D, on the other roll. **Collars** are represented at C and $C^1$. Passes I and II are commonly spoken of as **box passes,** while III is called the **diamond pass,** and IV the **Gothic pass.**

**The Manufacture of Rolls** is a separate industry, and the art of roll-making is not widely known even among the users of rolls. When the work the rolls have to do is considered, together with their effect upon the product of the mill, the importance of good rolls is better appreciated. Most rolls are castings, yet they must be ductile to withstand the shock produced as the piece enters them; strong to resist sufficiently the great pressure applied to their ends; hard to give them good wearing qualities; and sound, so that they may not develop surface defects which would leave their marks on every surface rolled on them and cause the material to be rejected. To secure these qualities the best of materials and the greatest of skill are required in their manufacture. The materials are of three kinds, namely, cast iron, steel and alloy mixtures. From these materials four kinds of rolls are produced. They are known as **sand rolls,** which are made of pig iron; **chilled rolls,** also of cast iron; **steel rolls,** made of steel by casting; and "**adamite" rolls,** which is a trade name for a metal produced by mixing steel with pig iron containing certain percentages of chromium and nickel, or by mixing steel and the ferro alloys of these elements with the proper amount of an ordinary pig iron of high grade. As an example of how rolls are made, some of the processes as carried out by one of the leading manufacturers of rolls will be briefly described.

**The Sand Roll:** Sand rolls are cast in a sand mold. The sand used is a loamy sand of a special kind obtained only from deposits left in old water courses. This sand contains sufficient clay intimately mixed with the silica to form a firm bond and yet be refractory enough that it will not fuse at the temperature of the molten iron. The mold is prepared by ramming this sand, moistened a little, into a half flask, and then sweeping the sand from the half flask with a sweep, the outline of which is similar to the contour of the roll. Two such half flasks are required for each roll, each one containing one-half of the roll divided longitudinally. After sweeping and smoothing, the half molds are coated inside with a plumbago or other carbonaceous dressing and carefully dried. Just before casting, these two parts of the mould are firmly clamped together and are set in a vertical position for pouring, for which purpose a casting pit is provided for large rolls. Thus, one end of the roll forms the bottom of the casting, the other end the top. The top is capped by a cope to provide a deep sink-head, which is cut from the roll after casting. The gating to the mold enters the flask at the bottom neck of the roll and on a tangent, so that a swirling action is imparted to the molten metal as it rises in the mold. In this way all dirt and other foreign matter is forced to the center, which condition insures the outer portion of the roll will be composed of clean metal.

**The Materials Used in Sand Cast Rolls** are charcoal iron and roll scrap. The mixtures are melted in coal fired reverberatory furnaces. The bath, sealed off from outside air, is separated from the grate by a bridge wall, over which a non-oxidizing flame sweeps and furnishes the heat for melting. In the melting a little carbon, silicon, and manganese are removed from the metal, and by the time the charge is melted a highly silicous slag has formed, which protects the metal from any further action that might be produced by the flame. As soon as the metal is melted, fracture tests are taken, by means of which the metallurgist in charge is able, from long experience, to determine when the bath is of the right composition to produce the kind of roll desired. The molten metal is tapped from the furnace into a small tilting ladle, which is carried by overhead crane to the molds, and the metal is poured into the gate over the lip of the ladle. The pouring is very rapid and must be continuous, as the slightest interruption would ruin the casting. After the metal has solidified and cooled sufficiently, the mold is removed, and the roll is cleaned of the adhering sand, when it is ready to be machined to the size and shape required.

**Chilled Rolls:** Rolls of the chilled type are made up of three layers of metal, each of which represents a type of the same original metal. The interior of these rolls is composed of grey iron, which is enclosed by a cylinder of mottled iron, and outside of this a similar layer of white iron, called the **chill.** This composite structure is procured by taking advantage of the peculiar properties exhibited by pig iron on cooling from the molten state. In this state iron holds in solution all the carbon which it contains at a given temperature. In cooling some of this carbon separates in the form of crystals of graphite, which is distributed throughout the mass; the remainder is spoken of as combined carbon, the effect of which is to increase the hardness of the metal. The separation of the graphite depends mainly upon the rate of cooling, so that if the iron is cooled very suddenly all the carbon may be retained in solution as combined carbon, which renders a chilled iron that is dense, white, intensely hard, and capable of receiving a very high polish. In making these rolls only the body of the roll is given a chill. This chilling of only a part of the roll is effected by making that part of the mold corresponding to the necks and wobblers of sand, while that part destined to form the body is made up of a heavy cast iron ring, usually built up in sections which are carefully turned at the joints and bored out true inside. After giving the inside of the mold a coating of the carbonaceous wash, they are warmed to remove moisture, then assembled, and the casting is made as for sand rolls. The rapid cooling, caused by the absorption of the heat by the cold casting in contact with the molten metal, causes the chill on the outer surface of the roll, the depth and hardness of which is controlled by varying the composition of the molten iron. Chilled rolls, once they are formed, cannot be softened or hardened by heat treatment, as such treatment would destroy the chill A patented chill is now in use. It is made in the form of a ring composed of segments of solid metal on the inside and a water cooled ring on the outside. This construction has the effect of causing the mold to become smaller as it is warmed by the heat from the molten metal, thus subjecting the roll to a high pressure, which is said to give a more even chill and a denser and tougher material than the common chill. The chill

The line in the cut marks the limit of clear chill. When depth of chill is designated, it is assumed to mean clear chill.

FIG. 53. Method of Measuring Depth of Chill on Rolls.

is measured by the least depth of clear chill as shown in the accompanying photograph, while the analysis of each of the three regions here depicted is given in the following table:

### Table 48. Analysis of Different Parts of a Chilled Roll.

| | TOTAL CARB. | COMB'D. CARB. | GRAPH. CARB. | SIL. | SUL. | PHOS. | MANG. |
|---|---|---|---|---|---|---|---|
| Chill......... | 3.00 | 3.00 | .... | .90 | .04 | .200 | .25 |
| Mottled...... | 3.00 | 2.25 | .75 | .90 | .04 | .200 | .25 |
| Grey......... | 3.00 | 1.00 | 2.00 | .90 | .04 | .200 | .25 |

**Difficulties in Making Chilled Rolls:** The greatest of skill and experience are required in the making of chilled rolls. The process of chilling causes the different parts of the roll to cool at different rates and sets up stresses in the casting which make it liable to crack and break. The range of temperature at which the metal may be poured is very narrow, while a very slight change in the chemical composition of the metal will sometimes produce a marked effect upon the chill, changing both the depth and the hardness. The size of the roll also affects the nature and extent of the chill. Besides, the roll in use is subject to great pressure, uneven stresses, uneven heating, over heating, and sudden cooling, all of which tend to cause the chill to crack and spall. This tendency to spall is overcome by the manufacturer to some extent, but careful handling of the roll in use is essential also. Large rolls are especially difficult to cast properly. The largest chilled rolls are made for rolling plates, and a very tough chill is required. The chills for one of the largest of these rolls weighs 105,000 pounds and the roll itself requires 80,000 pounds of metal to cast it, while the total length of the mold is twenty-three feet. A large percentage of these rolls are lost in casting, due to the cracking of the roll at places where the different sections of the chill are joined. Small chilled rolls are used in guide, rod, hoop and bar mills, and for a variety of purposes, but chilled rolls for shapes are very difficult to make owing to the fact that the collars in such rolls are liable to bind in the chill and crack off. All these factors tend to make chilled rolls very expensive, but a much greater tonnage is obtained from them than from any other kind, and their use is imperative where a very fine finish is required to be imparted to the product.

**Steel Rolls** are cast in sand in much the same way as sand rolls. In this case, however, ganister sand mixed with a little fire clay to act as a bond is used, because the higher temperature of molten steel will heat any but the most refractory sands to their fusion point. Steel rolls are stronger and more ductile than sand rolls. The deflection of a steel roll under a given load is only about half as much as that of a common sand roll. Besides, they may be annealed, when they become almost unbreakable. They cannot be permanently hardened, because any hardening by heating and quenching is removed by contact with the hot metal, the heat from which produces the same effect as a drawback. On account of their unavoidable softness, then, steel rolls do not wear well, and hence cannot be used on finishing stands. For blooming mills and roughing stands of other mills where great strength is required, these rolls are invaluable, and they are used in such stands almost exclusively. Occasionally, where a good finish on the product is not required, steel rolls will be used on the finishing stands. The material used is, for the most part, acid open hearth steels varying from .40% to .65% in carbon content. When steel rolls are used for finishing, the carbon content is increased to .85%, and sometimes to as high as 1.25%.

**Other Rolls:** In an attempt to overcome the defective softness of steel rolls and at the same time retain their great strength and toughness the alloyed mixture previously referred to as "adamite," has been developed. These rolls are being used with considerable success, and seem to hold promise of even greater efficiency. Forged steel rolls have also been tried and found to be very satisfactory, but their high cost prohibits their use except where exceptional strength is required.

**The Size of Rolls:** In length of body, rolls vary from one to seventeen feet, and in diameter from seven to forty-eight inches. The largest rolls are used on the plate mills, the smallest on the small hand guide mills. On account of the smaller surface exposed to pressure, small rolls cut into the metal with greater ease than large ones and so require less power to do the same work. Therefore, the heavier the rolls, the heavier must be the machinery throughout the mill. The factor most important in determining the size of the roll is that of strength, and for the sake of safety rolls as large as practicable will be employed; first cost is of secondary importance. The resistance of a plain roll to transverse stress is proportional to the cube of its diameter, and inversely proportional to the length of its body. The diameter of the roll at the base of the deepest groove determines the strength of a grooved roll; so, for grooves of the same depth, one set of rolls may be many times stronger than another only one or two inches smaller in diameter. The size of rolls is expressed by writing the diameter and the length of body in inches, with the × sign between. Thus 42″ × 60″ means that the roll is forty-two inches in diameter and sixty inches long in the body.

**Roll Design:** Designing the rolls was originally one of the duties of the mill superintendent, the roll turner or the roller, but the demands upon the mills in the way of new sections made it necessary to place this work in the hands of men specially trained to the work, so that, now, roll designing is a distinct profession. There are few rules in the trade, and the roll designer must depend mainly upon experience for guidance. It is seldom, therefore, that two roll designers will be found to develop a section in precisely the same way. That exceptional ingenuity and extreme resourcefulness is required in this profession is attested by the wonderfully intricate shapes these men are turning out, and that, too, with the most astonishing accuracy.

**Methods of Procedure in Designing Rolls:** Given a new section to evolve, the roll designer proceeds in some such manner as follows:—From a drawing of the section, if he has decided it is one that can be rolled successfully, he will have a templet made of the exact dimensions of the section, and from this templet another for the finishing pass in which an allowance of about .015 inch per inch of dimension of the finished piece is made for contraction of the metal in cooling from the finishing temperature to atmospheric temperature. He must then decide on the proper size of rolls to use, which determines the mill that is to roll the section. This decision made, he has given the approximate size of the billet or bloom from which to begin, the number of sets of rolls, and the number of passes in which the work must be done. Having given, now, the first and last passes with their dimensions, and the total number of passes, he may begin the design of the intermediate passes. This he does by drawings which are begun by setting off a "construction line" or "pitch line" as it is sometimes called. This line locates the center of gravity, or the center of figure, of the various passes and is usually placed midway between the axis of rotation of the two rolls.

**Difficulties in Designing Rolls:** Having drawn the pitch line, the roll designer then proceeds to mark off the passes from billet to finishing pass, and in doing so he has a multitude of things that must be kept in mind, some of which are: 1. The method of shaping is one of squeezing, spreading, and bending. 2. The total amount of reduction is best distributed among the various passes as evenly as possible, excepting the finishing, which is reserved to true up the shape. 3. All sides of the piece should be thoroughly worked. 4. The piece should not enter two successive passes in the same position, as otherwise the metal will be squeezed out between the roll and form what is known as a fin. 5. Since they weaken the roll very much, deep cuts into a roll should be avoided. 6. The passes should be so shaped as to eliminate side thrust on the rolls. 7. A piece will not enter a pass in the rolls if all its dimensions are larger than the pass. 8. The thin parts of a section cool faster than the heavier parts, and must, therefore, be formed in the last passes. 9. Sections that require deep grooves in the rolls are difficult to roll successfully on account of the difference in the peripheral speed of the bottom and the top of the groove. The part of the roll having the greatest diameter elongates the piece more rapidly than the part having the smallest diameter and tends to cause the piece to twist and curl on leaving the rolls. This difficulty can be overcome by using rolls of slightly different diameters, by raising or lowering the center of mass of the piece from the pitch line or by reducing the amount of reduction on the part that elongates the more rapidly. 10. The draught on the various parts of a section must be properly proportioned, as otherwise the piece will contain waves or be distorted in other ways. 11. He must also keep in mind that all kinds of steel do not work alike, and what can be done with open hearth steel, for instance, would be impossible with Bessemer and vice versa. With these difficulties to contend with, even highly experienced roll designers may fail on the first trial at a new section. In that case an entirely new set of rolls may be required, which adds much to the expense of rolling the section. Besides questions, such as those above, that affect the shaping of the material, the roll designer is also expected to consider time and cost. So, he will endeavor to avoid roll changes or other operations that will delay the work or add to the cost of the rolling operation. Thus, it will be found that in most mills one set of roughing rolls will be used to produce a great number of different sections. This has the effect of giving the designer a fewer number of passes with which he forms the shape, and adds much to the difficulty of his task.

**Turning the Rolls:** Having designed all the passes for the rolling of a given section, a set of templets, one or more for each pass, is made. These templets are to be used in turning the roll, for which purpose a special set of tools may be required. In the roll shop, the rolls are first centered. Various methods may be used for finding the center. When this point has been located, a lead hole may be made with a ratchet drill, and then widened out to the proper angle with a reamer to a depth of about ¾ inch. The roll is then placed in the necking lathe, when, supported by the center holes, the necks may be turned to exact size, or they may be machined to near the exact size and finished by grinding and polishing. Since the center holes are liable to wear down irregularly if used throughout the process of turning, the body of the roll is turned in another lathe in which the roll is supported by chocks that fit the necks. Here the roll is turned down to size, and the passes cut in to fit the templet supplied by the roll designer. When one roll is completed, it is placed in chocks higher up in the housing, and the second roll is placed below it, where it may be turned with the finished roll as a guide, so that the two parts of the passes may be made to fit exactly. With ordinary tools, chilled rolls are seldom turned with a surface speed of more than fifty-six inches per minute, but with tools made of high speed tool steel this speed may be increased to seventy-two inches per minute. Speeds twice as great as these may be employed for turning the other kinds of roll.

**Dressing the Rolls:** After a set of rolls has been in service a variable length of time, the passes become worn to such an extent that they no longer produce the section to the required dimensions, and they must then be replaced by another set. In most cases these worn out rolls may be turned again, or dressed down, so as to give the correct size once more, or if the section is of such shape that this refitting is impossible, the passes may be enlarged to produce a section similar in shape to the first one but of greater weight. This wearing of the rolls is one reason why rolling tolerance is required on all materials.

**Types of Mills:** Before proceeding farther it may be well to explain that there are two main types of mill, referred to as **Two-high** and **Three-high** mills. As the names indicate the classification is based on the manner of arranging the rolls in the housings, a two-high stand consisting of two rolls, one above the other, and a three-high having three rolls thus arranged. In all three-high mills, each roll revolves continuously in one direction only, whereas in two-high mills the direction of the rolling may be in one direction only, or in opposite directions at different intervals, in which case they are called **reversing** mills.

In the old days before the invention of the three-high mill or the reversing engine, if it was desired to pass the bar more than once through the same stand of rolls, the catcher returned the piece to the roller by placing it on the top of the upper roll, which carried it in the direction opposite to that in which it moved at the bottom of the roll. Mills in which this practice prevailed were called **pull-over** or **drag-over** mills and are to be looked upon as the fore-runner of the reversing mill. In the first mill of the reversing type a ratchet gear furnished the means for reversing the mill. Pull-over mills are still in use, and are the mills most often employed for rolling sheets. Another kind of two-high mill is the **continuous** mill, which consists of several stands of rolls arranged in tandem and propelled with a single engine. **Guide, loop** and the so called **Cross country** mills are made up of several two-high stands and one or more three-high stands. Guide mills are small hand mills consisting of several stands of rolls in a train. They take their name from their having metal guides to support the piece as it enters the various passes. In many guide mills it is the practice of the catchers, in order to save time, to start the piece through each of the passes before it is through the preceding one, thus forming a loop. After the institution of this practice it was found that the loop could be made by means of a tube or trough, called a **repeater,** and thus dispense with the catchers. Such a contrivance is a part of many modern bar and strip mills. The cross country mill is made up of several stands of rolls, arranged in trains or trains and tandem sets. The bar, propelled mechanically by means of live rolls, transfers, etc., must reverse its course two or more times to pass through the various sets of rolls from the furnace to cooling tables. These mills represent one of the latest and most efficient types. **Combination mills** are those in which the roughing or major part of the reduction is done in continuous rolls and the shaping in a guide or loop mill. **The Universal Mill** is one, which, in addition to the horizontal rolls, usually arranged two-high but occasionally three-high, is provided with vertical rolls, all set in one housing. These mills originally contained but two vertical rolls on one side only of the horizontal rolls, but in modern mills there are two sets of vertical rolls, one set on either side of the horizontal ones. The mill is used for rolling plates and eye bars that require rolled edges. Besides these types, there are many special mills, usually named from the inventors, such as the Gray mill for rolling beams and H-sections; the Wenstrom mill, a kind of universal mill for rolling bars; Sack's mill for rolling shapes, also a development of the Universal mill; and the Schoen mill, which rolls car wheels. Opportunity will be given later to become better acquainted with most of these mills.

## SECTION II.

### PARTS OF THE MILL ESSENTIAL TO THE OPERATION OF THE ROLLS.

**The Chocks:** As previously indicated, the chocks furnish the bearings in which the necks of the rolls turn. They are usually made in two parts. The surface in contact with the neck is made of brass, bronze, or white metal, which can be replaced as necessary. The use of these alloys is necessary in order to reduce friction, which is much less between metals of different kinds due to difference in size of the molecules or grains, and to the tendency of the softer metals to flow. The approximate composition of some of the more common of these alloys is given in the sub-joined table of analyses.

**Table 49. Composition of Bearing Metals.**

| NAME OF ALLOYS | % COPPER | % ZINC | % TIN | % ANTIMONY | % LEAD |
|---|---|---|---|---|---|
| Red Brass....... | 85 | 15 | .. | ....... | ....... |
| Yellow Brass.... | 65 | 35 | .. | ....... | ....... |
| Bronze, No. 1... | 85 | .. | 15 | ....... | ....... |
| Bronze, No. 2... | 82 | 15 | 3 | ....... | ....... |
| White Metals.... | 0 to 6 | .. | 10 to 15 | 12 to 20 | 65 to 80 |

Since 1915, a new white metal composed of lead, about 98.5%, and sodium, about 1.5%, has been used with much success. As all these metals are soft and not very strong, it is necessary to carry them in castings, which are set into the housings. These castings are box-like in shape, each one containing on one side a semi-circular groove corresponding to, but larger than, the necks of the rolls. In order to reduce their weight, they are cored out, and may be made of either iron or steel.

**The Arrangement of the Chocks** in two-high mills is a simple matter. Two chocks under the necks of the bottom roll, and two similarly placed above the top roll furnish the main bearings. In case the top roll is adjustable, light bearings must also be placed under its necks to make it possible to support this roll. In the heavy mills hydraulic jacks or balance weights, placed under the mill, are connected by vertical rods to the lower chocks and serve to lift the roll as desired; in the small mills, screw bolts extending through the housing serve the same purpose. The exposed half of the neck of the lower roll will usually be covered to protect it from scale, etc. The arrangement of the chocks in three-high mills is more difficult. The simplest way is to place double groove chocks between the top and middle and the middle and bottom rolls, and then set them in the housings one above the other, so that all the adjusting made necessary by the wearing away of the brasses and the material of the rolls, themselves, may be made with the large set screws in the top of the housing. But this arrangement causes the bottom bearing to wear down rapidly and increases the power required to drive the mill, due to the additional friction induced on this bearing by the weight of the two upper rolls and their chocks. This fault may be overcome in two ways: (1) By making the bottom roll fixed and supporting this extra weight on the shoulders of the chocks themselves, the distance between rolls may then be regulated with shims, or "liners," by adding or removing the shims as the bearings wear down. (2) A better way, and the one most often employed in modern mills, is to make the middle roll fixed, in which case the bottom roll is raised and lowered by means of an adjusting wedge attached to a screw in the housing which permits it to be moved back and forth with a wrench from the outside of the housing. Other methods of adjusting this roll are in use also. A method of supporting each roll separately by means of hooked screws and cross bars has also been developed, the details of which would be unprofitable to study here. In all mills, two-high as well as three-high, the top chocks are held down by means of two strong screws which work in threaded holes or nuts in the tops of the housings.

**The Function of the Chocks** is not only to furnish bearings for the rolls vertically but to prevent their movement laterally as well. This lateral displacement of the roll is prevented by the inner edge of the bearing which is formed to fit against the shoulder of the roll. Adjustments for wear in this direction are provided for by adjusting screws which extend through the side of the housing and bear on the ends of the chocks. This lateral adjustment is a matter of great importance in rolling sections that require grooved rolls, the reason for which is self evident.

**The Housings:** There are two housings for each stand of rolls, they may be made of either iron or steel, the choice of materials depending upon the size of the mill, the strength required, and the preference of the management. They are castings of an O-or U-form, each enclosing a space, called the **window,** which serves as a receptacle for the chocks. Housings may be either **closed topped or open topped**; in the former, the base, the two legs, and the top are all cast in one piece, while in the latter the top may form a separate part which can be removed. The base of the housing is cast with a projection on each side, the two forming the feet of the housing. In the bottom of each foot is cut a groove which fits over a girder, called a **shoe,** running parallel to the rolls. Suitably shaped bolts then serve to clamp the foot of the housing to the shoe, which is firmly fastened to the foundation by means of long bolts. This method permits the housing to be moved laterally, and much facilitates the plumb-ing and lining up of the mill. The tops of the two housings in a set are prevented from spreading apart by means of suitable tie rods, or the tops of both housings may be cast in one piece. Similarly, tie rods will usually be placed at the bottom. Recesses or other openings are cast in the inside of each housing to receive the supports for the guards and guides, these supports being usually in the form of square bars which extend from housing to housing in front of the rolls. The immense pressure applied to the rolls between the top and bottom of the housing acts as a stretching force on the uprights of the housings, and is an important factor in determining the reduction that can be effected in one pass and also the exactness with which the thickness of the piece is controlled.

**The Adjusting Equipment** for the rolls has already been located and partly described in the preceding paragraphs. In addition it should be pointed out that in large mills, in which the top roll is adjusted during the rolling, power must be supplied to operate the screws. To provide for the transmission of the power, the top part of each screw, which is made square or hexagonal for a distance slightly greater than the rise of the roll, passes through the core of a pinion. These pinions may then be turned directly or indirectly with a horizontal hydraulic cylinder located at a proper height, usually on top of the housings of the driving pinions; or, by means of a worm shaft and the proper worm gears, the screw down may be effected with a small electric motor. In small mills where the adjustment is only occasional, the screws will be operated by hand by means of spanner bars. In all cases the compression of these screws is unavoidable and combined with the stretch of the housings produces the spring of the mill, which in some cases is surprisingly great.

**The Pinions:** An important part of the mill is the pinions. They are broad faced steel gears located between the prime mover and the rolls. Their functions are to divide the power, which is delivered by the engine or motor through a single shaft or driving spindle, usually spoken of as the leading spindle, among the rolls and to control their direction of rotation. They run in bearings contained in a pair of housings similar to those for the rolls, and should be completely and tightly covered to protect them from dust and dirt which would cause them to wear out rapidly. They need to be well lubricated, and the present practice of giving them an occasional dressing of pine tar, plumbago, and tallow, or other mixture of grease, is giving way to the better plan of having the housings cast in one piece so as to form an oil bath at the bottom in which the bottom pinion is partly submerged. Pinions are of three kinds, based on the arrangement of the teeth. In the oldest form the teeth ran straight across the face, but eventually it was found that a smoother running pinion results if the face be divided into two parts and the teeth of the two halves staggered, i. e., set in so that the teeth in one half are in line with the space in the other. This design gives an effect like that which would be obtained if the pitch were decreased. This scheme was also found to effect a saving in power. Still another improvement results from the use of pinions with helical or "herring bone" teeth, which also tend to eliminate vibration in the pinions, as some parts of the teeth are always in contact, thus making the transmission of the power continuous. This presence of jar when each tooth comes into action has an effect on the material, as in certain classes of material the old form of pinion was found to produce marks on the bar by the jarring of the teeth meshing being transmitted to the rolls. In all mills except plate mills, the distance from center to center of the pinions determines the size of the mill.

**The Connections:** Each roll, except in the case of friction driven rolls, is connected to its pinion by means of **spindles.** They are usually made of cast steel and are fitted at each end with wobblers like those on the rolls. The connections between pinions and spindles and rolls and spindles are made with **coupling boxes.** The coupling box is a hollow cylindrical casting, the space in which corresponds in section to that of the wobbler, one end of the box fitting over the wobbler on the roll and the other over that of the spindle. In order to safe-guard the mill, the coupling boxes are usually made the weakest part of the mill. In some mills this weak spot is the leading spindle, which connects the pinions with the engine or motor, instead of one of the coupling boxes. Since the spindle must be put in place with the two coupling boxes on it, the length of the spindle must be a little more than twice the length of the box. In mills, the top roll of which moves up and down through a great distance, the upper spindle is thrown out of line horizontally. As it is very difficult to operate with a spindle more than 15° out of level, this angle must be kept within the allowable limit by increasing the length of the spindle. In such cases the ends of the wobblers are cut from a section of a sphere to give them the rounded form necessary to permit them to work at different angles, and the spindle is supported by means of saddles which rise and fall with the roll and hold the spindle in place.

**Guides and Guards:** In order to prevent collaring and to insure that the piece enters and leaves its pass in the correct position, guides are employed. These guides vary in form and size to fit the conditions. In some cases they are merely grooved fore-plates; in others they are blunt edged plates set up in front of the collars, dividing the space in front of the rolls into a series of pigeon holes; in large mills rolling heavy sections, they may take the form of grooved rollers; in the smaller mills like the guide mills, they are trumpet shaped castings that fit close up to the roll and have exit openings to conform to the shape and size of the section of the entering piece; in other mills, like the continuous mill, they may be so constructed as to twist and thus turn the piece between two successive passes. Guides may be employed on both sides of a pass, in which case they are designated as entering guides and delivery guides. They are held in place by means of the rest bars previously mentioned in connection with the housings. Guards are devices employed mainly on the delivery side of the mill to control the direction of the piece after leaving the pass. Reversing and three-high mills will be provided with guards on both sides of the mill.

**Additional Equipment:** In addition to the parts of the mill already described, every mill must be provided with suitable appliances for heating and handling the materials and disposing of the product. The various furnaces for the heating of the raw materials will be described later. As to the handling of materials, it is evident that reliance on man power places such restrictions upon the size and output of the mill that, in the case of certain small mills and of all the larger mills, the appliances for handling the materials mechanically are to be considered as essential parts of the mill. The number of these appliances is so great and the kinds are so varied that a detailed description of all of them is impossible, and since it would be unprofitable to describe only a few forms, little more than an attempt to mention some of the more important ones will be made here. For getting heavy material in and out of furnaces and delivering it to the mill, electrically operated charging and drawing machines are used. These machines are of two general types, namely, those that travel on overhead tracks and those that move on a track laid on the mill floor. For handling material during the rolling process, roll tables are provided for large mills, while various forms of appliances, called repeaters, are used on small mills. Roll tables consist of a frame work and a number of rolls, which may be rotated at will, mounted thereon. For operating these rolls, the steam engine has been replaced by the electric motor in all new mills and also in most of the old ones. Roll tables may be either stationary or movable. Movable tables, often used on three-high mills, may be of the **tilting,** the **lifting,** or the **traveling** type. Tilting tables are mounted on an axis of rotation, which may permit one or both ends, depending on the location of the axis, to be raised and lowered, whereas lifting tables always remain in horizontal positions and may be moved in up-and-down directions only. Traveling tables, which are now to be found only on the old mills, move along on tracks laid on either side of a roll train, and may be of the tilting type also. After the rolling, cooling beds, of which there are many types and forms in use, must be provided to receive the material from the mill. The straightening of the material, which irregularities of the rolling and cooling often makes necessary, is done in roll, or machine, straighteners or by means of gag presses. In order to keep up with the mill only the most rapid methods of cutting are permissible. For this purpose only two instrumentalities are available, namely, the saw and the shear, either of which may be used on hot or cold material. Shears are of three general types; namely, the alligator, used only for cutting light weight material; the guillotine, which is employed generally for all classes of work; and the flying shear, designed to cut billets or bars while they are in motion. The power employed to operate the shears is hydraulic for the heavier materials, such as slabs and large blooms, while steam and electric power are used for all other work.

## SECTION III.

### SOME GENERAL FEATURES PERTAINING TO OPERATION OF THE ROLLING MILL.

**The Mill Force:** Of equal importance with the equipment of a mill, are the men who operate it and the organization and system back of them. Under the general superintendent of the steel plant there may be a number of rolling mill superintendents, each of whom will have charge of a group of mills turning out similar products. As his assistants, the mill superintendent selects foremen, each of whom are responsible for the successful operation of one or two of the mills. Below the foreman the mill is divided into departments, with a man at the head of each, who is charged with the performance of a certain part of the work. Thus, there is the heater who has the heating of the material to look after; the roller, who superintends the actual rolling process; the engineer who tends the engine, or an electrician, if motors are used for running the mill; and the shearmen, whose duty is to see that the product is properly cut. Besides these, other departments, such as the machine and the electric shop, the inspection and shipping departments, play important parts in the mill operation, though they do not come under the direct authority of the mill superintendent. When it is remembered that the failure of any one of these may close down the whole mill, the importance of system and of the personnel of the organization is more fully appreciated.

**Duties of the Roller:** So far as the product of a given mill is concerned, it would appear that the roller and roll designer are the chief figures. Co-operation between these two men is essential, for in a measure their interests are identical; the roll designer decides how the work is to be done, and the roller sees that it is done properly. The latter will, therefore, concentrate his attention upon the product, and with caliper, gauge, or templet will take frequent measurements to make certain the material is being rolled true to the dimensions specified. He will keep a sharp look-out for underfills, overfills, fins, guide marks, collar marks, laps and any other rolling defects, and make the necessary adjustments to correct them.

**Fins:** It is the intention to discuss the defects of materials in connection with the rolling of each particular class of product, but in all rolling where grooved rolls are used, the occurrence of fins is so liable to happen that it is well to consider them here, more especially since there will be occasion to use the term frequently. Fins are formed when the section is too large for the pass it is entering, or whenever, in designing the pass, proper allowance has not been made for the spread of the material, thus causing the metal to flow out between the flat bodies of the rolls on each side of the groove. If this fin is thin and wide it will be folded over without welding and form a **lap**, when the piece, after turning, has been sent through the next pass. Besides, fins may be dangerous, for if the rolls are very close together any spreading of material between them is likely to break them.

**The Different Passes and Stands** in mills that roll finished shapes are given class names. Thus the first rolls the piece enters in the mill are used mainly to reduce the size of the bloom or billet, and the piece generally leaves them in the same shape it entered. These passes are called the **roughing rolls** and the stand or stands is spoken of as the rougher, or roughers. If the succeeding stand merely carries this reduction further, it is called the **pony** rougher. The stands and passes in which the actual shaping of the piece is done are called the **strands,** usually numbered 1, 2, etc. The pass next to the last is called the **planisher,** but since in roll designing this pass may be looked upon as the first pass leading back from the finished section to the bloom, some designers call this pass the **leader.** The last pass is always called the **finishing.**

**Factors Affecting the Rolling Operation:** In the rolling of steel there are five factors to be considered, namely, the temperature of the steel during the rolling, the chemical composition of the metal, the speed at which the rolls are revolved, the draught in each pass, and the diameter of the rolls. Furthermore, these factors should be considered from the three different standpoints of power, or energy, required to deform the steel; their effect upon the rolling properties of the metal, that is, the way it will spread, bend and flow in the rolls; and their effect on the quality of the finished product. All these matters have not been fully investigated, and our knowledge concerning them is somewhat meager, but in order to invite attention to these subjects, a brief summary of what is known about these factors is appended.

**Effects of Temperature:** The influence which the working of steel at different temperatures may have upon the quality and properties of the product has already been discussed under the caption of Hot and Cold Working, (Chap. II, Sect. 1.). Relative to the power or energy requirements and the rolling properties of the metal, it is to be observed that the higher the temperature is raised the more plastic the steel becomes. Thus, while, a .10 per cent. carbon steel, for example, will give a tensile strength of about 50000 pounds at atmospheric temperatures, at 600°C it will break under a pull of 20000 to 25000 pounds per square inch, at 700°C under a pull of about 11000 pounds, and at 800°C under a pull of about 6000 pounds. Between 800°C and 900°C a distinct discontinuity in the tensile strength occurs, with the result that at 900°C the tensile strength will suddenly increase to nearly 9000 pounds. From this point the strength decreases with rising temperature, being about 6500 pounds at 1000°C., about 4600 pounds at 1100°C., about 3000 at 1200°C., and approaching zero at 1460°C., the fusion point. From these facts it would appear that the higher the temperature of the steel the easier will it be deformed. But there are other features that tend to keep both the initial and final working temperatures within certain well defined limits. Since steel assumes a semi-fluid state at temperatures somewhat below its fusion point, heating to within less than 200°C of this point exposes it to the danger of overheating or so-called "burning". For dead soft steels the initial temperature should not exceed 1250°C, and for high carbon steels, (1.00% to 1.20% carbon) this temperature should not exceed 1050°C. In order to secure the greatest refinement of grain, either the initial temperature or the speed of rolling should be adjusted so that the finishing temperature of the rolling will be above, but as near the critical range of the steel as possible.

**The Effect of Chemical Composition** need be considered here only from the standpoint of energy required and rolling properties. As to the energy required, experiments have shown that slightly more work is required to roll a steel containing 1.00% carbon than for steels containing only .10% carbon. Whether this difference was due entirely to the lower temperature at which the higher carbon steel was rolled or also partly to the higher content of carbon could not be determined. In the hope that it would help to solve this question, an experiment was performed with the object of comparing the tensile strength of high carbon and low carbon steels at rolling temperatures. For this purpose three steels having a carbon content of .10 percent, .22 per cent. and 1.10 per cent. but otherwise of approximately the same composition, were selected. The results from pulling the first have already been given. The mechanical properties of the other two were compared at 900°C only. The average results obtained from pulling ten pieces of each under similar conditions at the initial temperature of 900°C are as follows:

| Carbon Content | Tensile Strength | Elongation in 8″ | Reduction of Area |
|---|---|---|---|
| .22% | 13,500 lbs. | 110% | 94% |
| 1.10% | 18,800 lbs. | 58% | 83% |

These results would indicate that the higher carbon steel is somewhat less plastic at rolling temperatures than the lower carbon steel. Therefore, it would require more energy for rolling, and would not spread or elongate as readily as the steel of lower carbon content. As to the effect of the other elements in plain steel, phosphorus may produce effects similar to those of carbon, sulphur tends to produce red shortness, while manganese tends to offset the effects of sulphur and oxygen and improve the rolling properties. Open hearth steel, which is low in its phosphorus content, tends to spread more in the rolls than does Bessemer steel, which is higher in phosphorus. The rolling properties are still more strongly affected by certain alloying elements, such as nickel and chromium. The difference in rolling properties produced by difference in chemical composition may not be noticable in the rolling of the simpler sections, but may cause much trouble in the rolling of complicated sections with wide thin flanges or legs. Thus, in one instance of such a complicated section, it was found that while the section rolled perfectly with one heat of steel, it was imperfectly formed when rolled from another heat in which the carbon content was ten points, the manganese fifteen points, and the sulphur two points higher.

**The Effect of Speed:** The speed of rolling is the factor which has received the least attention from the viewpoint of its effect upon the material. It is the consensus of opinion among steel workers, however, that the speed of rolling undoubtedly has an influence upon the quality of the product. It is evident that the faster a piece of steel is deformed the less time the molecules have in which to adapt themselves to the deformation and the greater their resistance to the deformation. Consequently the stretching effect of the rolling, as previously explained, increases in undue proportion to the compression. If the speed of the rolls were increased sufficiently they would then have a greater tendency to slip on the piece, and the stretching effect would tend to become a tearing effect. However, it is not speed alone that produces this effect but draught and speed together.

**Draught:** Draught is the difference in sectional area between one pass and the next succeeding one, and is usually expressed in per cent. While there are cases where as high as a 50% reduction occurs, and one case in which a 70% reduction is made in a single pass, the draught will seldom exceed 36%. These heavy draughts take place in the roughers, where most of the reduction occurs. In the strands the reduction will be as evenly distributed as possible, and will sometimes be as low as 10%. If the leader is used as a planishing pass very little reduction is effected there either, while very little reduction, with a few exceptions, ever occurs in the finishing pass. This pass being intended to give an exact finish to gauge and to true up the piece, it is important that very little work be done in it in order that it may be subjected to as little wear as possible. Since a piece must be finished before it has lost its heat and has cooled below the rolling temperature, which cooling is very rapid in the case of small sections, the rolls must be run at a speed that will carry the piece through the rolling before it has become too cold. The number of passes and the size of the piece to start with controls the draught. Aside from these features the desire to increase output acts as an incentive to increase both the speed and the draught to the limit the material will stand. There are many considerations, however, that operate to hold down both speed and draught below that which will do injury to the steel. One of these is the additional power required for very rapid reduction; another is the severe strain on the rolls and other machinery when the piece enters the rolls at high speed and with large draught. In mills composed of several stands, especially in the case of the continuous mill, the speed of all preceding stands is determined by the speed of the finishing stand. In hand mills, the speed is restricted to the highest velocity, about six hundred feet per minute, at which the catchers can grasp the piece with the tongs. The magnitude of the draught is restricted by the limiting angle at which the rolls will "bite". the piece on entering. This angle is found, by experience, to be about 30°'

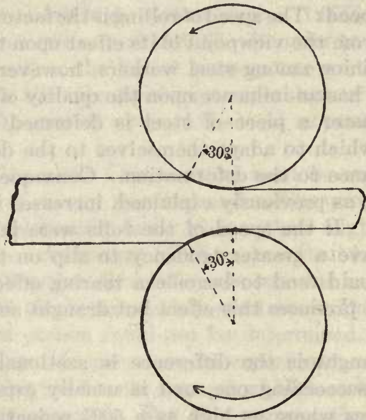


Fig. 54. The Limiting Angle of Rolling.

Above this angle the resultants of the forces of compression have receded so far from a parallel to the line joining the centers of the rolls that they exert a push on the piece, and the resultant of the forces of elongation is so nearly vertical that the horizontally inclined component due to friction only is not sufficient to balance this backward push and drag the material between the rolls. In order to increase this limit, a series of horizontal and well rounded grooves, called **ragging**, are often cut in the surface of the roll, giving it the appearance of a half formed cog wheel. Since these grooves leave ridges in the material, they can be resorted to only in blooming mills, billet mills, or roughing stands. Even then the grooves must be cut with considerable care in order to prevent these ridges being folded over into laps in succeeding passes and rolled into the material, to appear as seams in the finished product.

**The Effect of Diameter of Rolls:** From a study of Fig. 54, it will be seen that the larger the roll diameters are the greater will be the draught that may be taken without exceeding the limiting angle of rolling. For the same draft, however, a large roll gives a greater roll surface area in contact with the metal than a small one and therefore requires more pressure to force it into the metal. thus putting a greater tension on the housings and requiring more energy to drive it. The large roll gives an affect more like that of pressing than the small roll, and, with the draft and speed properly regulated, the effects of the rolling can be made less superficial with the large roll. The large roll tends to cause the metal to spread more than the small roll. Hence, the size of the rolls is a factor to be considered in designing rolls for flats and other products in which the spread of the metal may affect the dimensions of the finished article.

# CHAPTER IV.

## PREPARATION OF THE STEEL FOR ROLLING.

## SECTION I.

### INGOTS AND THEIR DEFECTS.

**Preparation of Ingots:** In order that the large bodies of metal refined at one time by the various methods of steel making may be obtained in a convenient shape for rolling, it is necessary that these large bodies be divided into smaller ones, called ingots, of a uniform shape and size. These conditions are obtained by pouring the metal while it is still molten into moulds of the desired dimensions, where it may be allowed to solidify in part or in whole before the mould is removed. Before rolling begins, however, the ingot must have been allowed to solidify throughout, and the whole mass should be of uniform temperature. But in cooling naturally, these conditions are not fulfilled, because the outside of the ingot, being the part from which the heat is removed the most rapidly, is the first to solidify. With this fact in mind, it is easily understood how, in any case of natural cooling, the interior is the last to drop to any given temperature. In fact, the moulds are stripped from many ingots while the central portion is yet in the liquid state. This fact was early recognized by steel workers, and so it was originally the custom to strip the ingots as soon as possible and place them in a tightly covered hole or pit in the ground, where the heat from the interior of the ingot was slowly conveyed to the outside by conduction, and sufficed not only to heat up the colder exterior part of the ingot but also to supply heat to the pit, which, with careful manipulaton, was sufficient to maintain a rolling temperature. This process was called **soaking,** hence the name **soaking pit.** In order to bring the soaking under better control and make it adaptable to varying conditions, means for supplying additional heat was introduced, so that the modern soaking pit is in reality a kind of heating furnace, a detailed description of which will be given later.

**Ingot Defects:** A prerequisite to faultlessly finished material is perfect ingots, and by a perfect ingot is meant one free from all cavities or openings and made up of material that is homogeneous throughout. Unfortunately, the natural laws that govern the solidification of the liquid metal operate against both these requirements, and develop the well known natural defects in ingots called piping, blow holes, segregation and crystallization. Added to these are other defects, both incidental and accidental, such as checking, scabs, and slag inclusions. A brief discussion of these defects follows; but an understanding of their causes requires a study of the laws that control the cooling of ingots.

**The Nature of the Cooling of an Ingot:** The ingot moulds in common use are tall box-like shapes made of cast iron; they are open at both ends, one of which is a little smaller than the other to give the mould a little taper; and have a square or rectangular section slightly rounded at the corners. In use, one end of the mould, usually the larger, is closed by the **stool** on which the mould stands in an upright position. Immediately the molten steel is poured into this mold, the metal next to the mold and stool is chilled by contact with the cold surfaces and solidifies on the bottom and sides to form what is called the **skin** of the ingot. As more and more heat is absorbed by the mold, this skin grows in thickness, but due to the increase in the temperature of the mold and the insulating effect of the skin, itself, it grows at a rapidly reduced rate, until the process becomes so slow that it can be considered as a normal cooling. The cooling then takes place by a dissipation of the heat through this skin along lines perpendicular to the surface of the solidified shell, which acts as the conductor, with the result that this shell gradually grows in thickness, the growth progressing toward the center until all the metal is in the solid state. The laws of freezing which the metal obeys, combined with this manner of freezing, gives rise to the natural defects enumerated above.

**Pipes:** One of the most noticeable effects of the freezing is the production of a more or less cone-shaped cavity at the top of the ingot, known as the **pipe.** Pipes are the result of the contraction of the metal on solidifying in the manner just described. This contraction amounts to about two-hundredths of the linear dimensions of the ingot, and if the manner of cooling did not set in play forces which oppose the contraction, no pipes would form, and a perfect ingot would measure one-fiftieth smaller than the mould in all its dimensions. In ordinary ingots much of this difference in volume is represented by the pipe. Since the skin and the more slowly formed walls built up by the cooling are rigid, the void left by contraction is filled by the metal in the central portion that still remains fluid, the force of gravity directing the flow downward at all times. After solidification of the metal is complete, further contraction on cooling tends to open this pipe still farther towards the bottom, because the exterior, being the colder, is the more rigid and is capable of stretching or tearing the more plastic interior. The greater portion of the surface of this cavity is likely to become more or less oxidized, and, since the oxidized portion is not welded up in the rolling, the pipe will appear in the smallest rod or wire into which this part of the ingot may be rolled. Aside from injuring material, pipes are liable to cause accidents in rolling, so the steel maker is very anxious to get rid of them as early as possible.

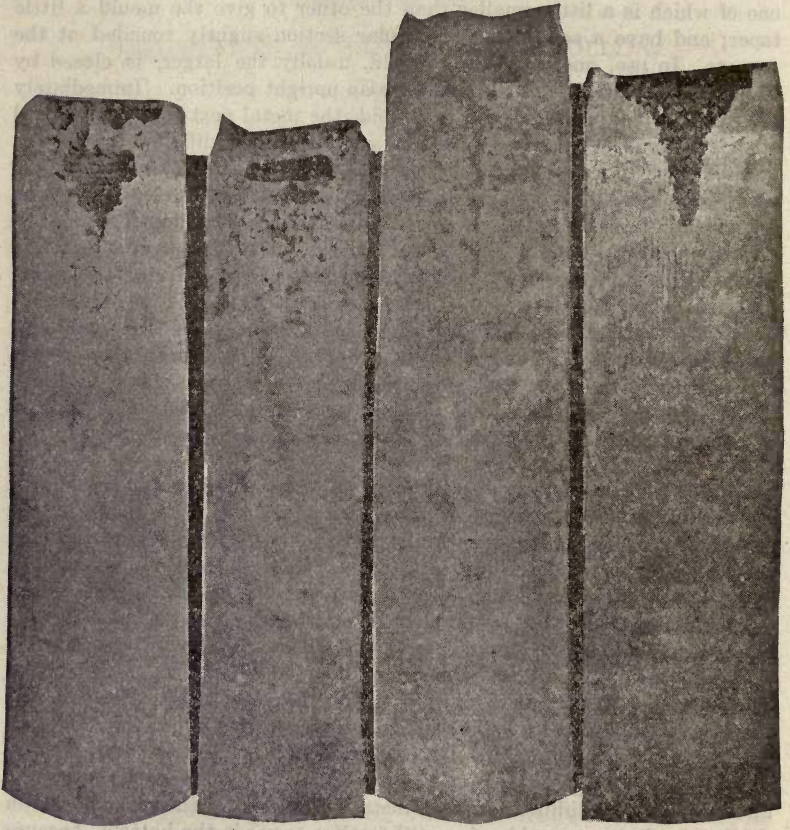


FIG 55. Split Ingots Showing Various Forms and Degrees of Pipe.

FIG. 55—Continued.

**Methods of Reducing Waste due to the Pipe:** Obviously, the only way of avoiding this pipe is by discarding the portion of the ingot affected. Various schemes for reducing the waste due to this cause have been and are being tried, and some of them are fairly successful, among which the most promising seems to be the so-called **hot top mould.** As explained in connection with the open hearth process, in one form of these moulds the ingot is cast with the smaller end down, while the larger end is surmounted with a short mould which is lined with refractory and non-conducting material, such as clay. This lining reduces the size of the top section and keeps the top of the ingot in the molten state until the ingot proper has solidified. Thus, the pipe is brought up into the cope, or sink head, which is of much smaller section than the ingot, and the waste due to the cropping is decreased accordingly. This ingot is stripped by first removing the insulated top section, gripping the sink head with tongs and then lifting the ingot out of the mould. In a patented form of this mould, known as the Gathman mould, a similar effect is produced by decreasing the thickness of the mould at the top. Since the heavy part of the mould causes a more rapid cooling than the thin portion, the metal at the top is the last to freeze.

**Blow Holes:** In the molten state iron, or steel, is capable of dissolving large volumes of gases, such as oxygen, carbon-monoxide, nitrogen and hydrogen, this solvent power increasing with the temperature. The iron probably unites with all the oxygen immediately it is dissolved, hence it is retained by the metal in the solid state if chemical means are not employed to remove it. In case of the other gases, however, no such stable combination takes place, and they are largely thrown out of solution just previous to the time when solidification of the metal occurs. As the metal is in a more or less plastic condition at this time, the last gases thus liberated may not be able to escape from the body of the metal, in which case they collect in bubbles, as a gas will in making its way out of any fluid. Each bubble will then form a small cavity in the metal which is known as a **blow hole.** These holes will vary in size from those visible through a microscope to large pockets, the dimensions of which can be measured in inches. The smallest ones are liable to occur just below the skin of the ingot where the rapidly cooling metal gave the tiny bubbles of evolved gases time neither to escape nor to collect in larger bodies. Here the gases, unable to escape upward on account of the very viscous nature of the metal, form tube-like cavities that extend at right angles to the skin wall of the ingot and toward the center. In the rolling of the steel, the blow holes are closed up and welded together provided their surfaces have not been oxidized, in which case they will not weld and will produce defects in the finished articles. Blow holes near the center of the piece, known as deep seated holes, are less liable to oxidation, hence are the least harmful. But the small blow holes beneath the skin of the ingot are liable to be exposed to the air, or be filled with liquid oxide of iron, in which case

Fig. 56. Transverse Sections of Ingots Showing Blow Holes

they produce **seams** in the finished articles. Blow holes are an ever present menace. But correctives may be employed successfully, and they are seldom a source of serious damage in steel that has been properly worked in the process of manufacture and thoroughly deoxidized at the time of recarburizing. In this respect the use of aluminum in the mold at time of casting has been found to be very effective. Blow holes have the effect of reducing the size of the pipe, and on this account are to be desired if they are deep seated. Various attempts to overcome both blow holes and pipes mechanically by means of subjecting the metal to compression while in the molten state have been tried, but the expense of operating these appliances more than outweighs the good derived, especially since the steel discarded on account of pipe is available for use as scrap in the open hearth.

**Crystallization** is the property possessed by iron, in common with many other substances, of forming crystals on solidifying. The size of the crystals depends on the composition of the steel and the rate of cooling; in general, the slower the cooling the larger the crystals will be. It is plain that the temperature at casting and the size and shape of the ingot and mold control the rate of cooling. If the crystals are large, the force of cohesion among the crystals is decreased by the increased area of contact and the larger size of their cleavage planes. The effect of unduly large crystals is to make ingots liable to tear in rolling. This condition is sometimes called **ingotism.** The deformation and refinement of the crystals in rolling prevents their effect showing up in finished product that has been properly worked.

**Segregation:** Steel is a mixture of various compounds and elements; some of these are to be looked upon as impurities because of their detrimental effects, but others are necessary to impart the properties most desired in the product. While in the molten state these solid ingredients, like the gases just mentioned, are held in solution by the iron, a power which it does not possess to the same degree at temperatures below its freezing point. Some of these ingredients freeze at a lower temperature than the iron. Furthermore, the solution, following the laws of selective freezing, undergoes a series of changes and recombinations with the formation of various eutectic solutions, which increase the number of substances that solidify normally at much lower temperatures than pure iron. With such an aggregate, it is easy to see how the process of solidification results in an isolation of the ingredients. Those substances having the highest melting, or freezing points, of course, are the first to crystallize. This separation, then, has the effect of concentrating the solution of the substance having the lower freezing points in the mother liquor. This process continues until the mother liquor is made up only of that substance that has the lowest freezing point, when it, too, will freeze, forming in the ingot a solid mass very different in composition from the metal that crystallized out at the beginning. Under such conditions, it is to be expected that the substances with the low melting points would be found in one spot or locality in the ingot and that this spot would be located near the top and center of the ingot, that is, at the bottom of the pipe, where the metal was the last to freeze; and to some extent, this is what actually does occur, so that this central position of the ingot is spoken of as the **line of segregation.** That the condition is not even more pronounced is due to the closing in, or entrapping, of the small pockets of the mother liquor during the freezing and to the high viscosity of the fluid. Like the pipe and the blow hole, segregation cannot be overcome, but by rapid cooling and the use of aluminum to quiet the metal it may be lessened somewhat. In conclusion it should be remarked that this is one of the fundamental reasons why a range in chemical and physical specifications is imperative, at least from the manufacturer's point of view.

**Checking and Scabs:** If the surface of a mold is very rough, or contains cavities, so that resistance is offered to the natural contraction of the steel, transverse cracks in the skin of the ingot may result. However, in spite of all precautions that may be taken cracks in ingots will occur, and a study of this matter indicates that this defect is more liable to occur in certain grades of steel than in others, and particularly in those steels in which the carbon content is between .17% and .24%. These cracks become oxidized and subsequently produce a seamy product. Scabby material is often caused by improper pouring. If care is not taken to prevent it, the metal may be splashed against the side of the cold mold during the pouring. These splashes tend to stick to the mold, and, becoming oxidized on the surface, will then appear as scabs on the ingot after it is stripped. These defects very often show up after rolling in the form of seams and slivers; in plates they will form serious surface defects. Such defects are entirely avoided by bottom casting the ingots. A cracked mold that must be forcibly drawn by the stripper may produce similar defects.

**Slag Inclusions:** Various explanations are offered to account for the presence of slag particles held within steel. Slag inclusions may be due to an improperly finished bath, or in case the furnace practice has been good, they may be caused by slag being stirred into the steel and mechanically held by it while the heat is being poured. They may also be due to dirt in the ladle or molds, or they may be the result of slag forming reactions that occur during the deoxidation of the metal in the ladle or molds. The latter cause would seem most conducive to the formation of the minute slag particles that occur so frequently in nearly all steels. Slag particles if given the opportunity, will rise to the top of the metal in the ladle, but for lack of time small particles do not always do so. Slag particles remaining in steel after it has been teemed have little opportunity to rise, because the chilling of the steel by the mold is so rapid, and they

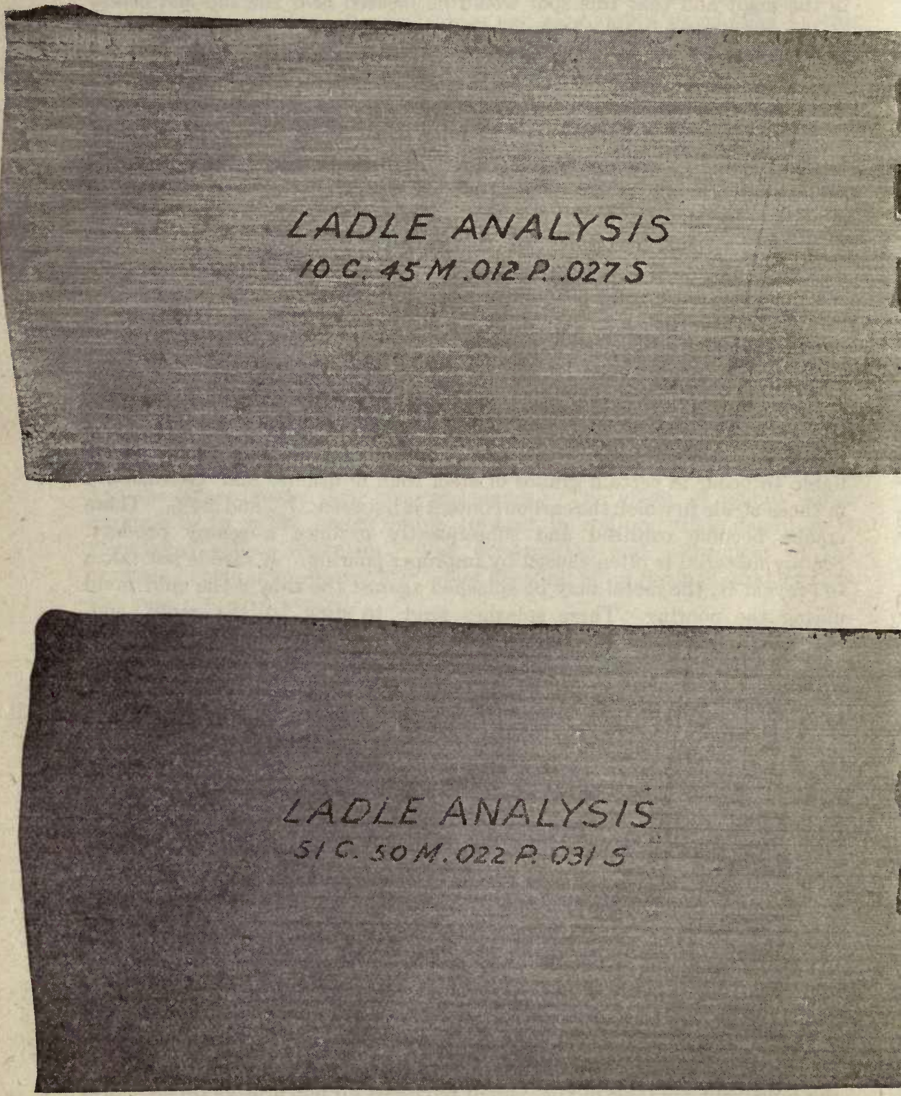
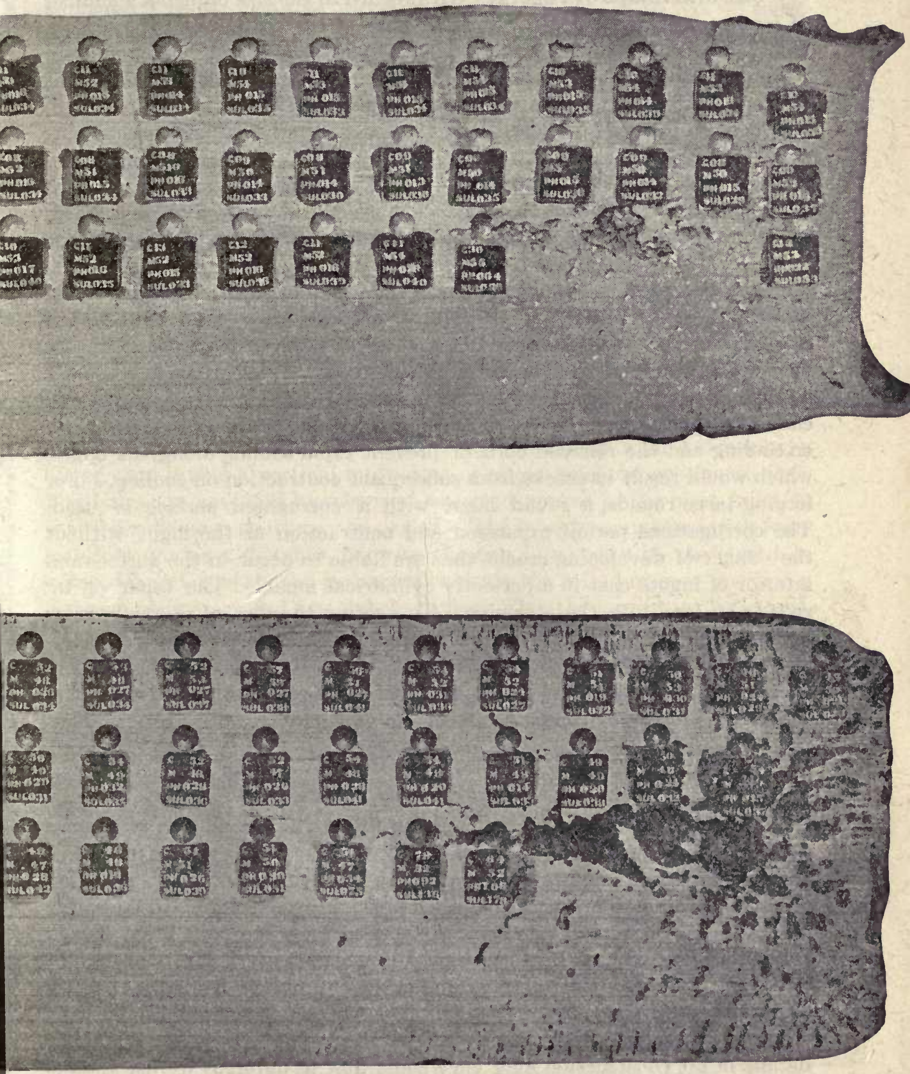


Fig. 57. Split Ingots



Showing the Region of Greatest Segregation.

are, therefore, entrapped. Hence, deoxidation in the mold should be controlled by good judgment and avoided when possible. Large slag inclusions are an original source of blisters in finished products.

**Size and Shape of Ingots:** With regard to the size of ingots a number of factors operate to control both the size of the section and the length. First of these is pouring cost. It is obvious that the cost of teeming a 50-ton heat into two-ton ingots will be much greater than if the same heat is cast into four-ton ingots due to increased number of molds required, the increase in scrap produced, and the longer time consumed in stripping and charging into the soaking pits, etc. The cost of rolling may be increased, also, for a long ingot may be rolled with the same number of passes as a short one of the same section. The product desired, also, is a factor in determining the size and the shape of the ingot. In plate mills, for instance, which operate independently of slabbing mills, the size of the plate to be rolled determines the size of the slab ingot. The blooming and slabbing mills and their equipment, once installed, fix a limit to the size of the ingot both as to section and length. As to their shape, ingots may be of any convenient form, though for rolling they are usually square or rectangular in section with rounded corners. These forms are easiest on the steel, as the flat sides offer the least resistance to contraction on cooling and the rounded corners prevent rapid cooling along the edges, which would result in cracks from subsequent contraction on cooling. For forging large rounds, a round ingot with a corrugated surface is used. The corrugations permit expansion and contraction of the ingot without the danger of developing cracks that are liable to occur in the surface and interior of ingots cast in a perfectly cylindrical mould. The taper on ingots is to facilitate the stripping. To express the size of a rectangular ingot the dimensions of its largest section are always given, unless otherwise specified. Thus, a 23½ inch ingot means it is 23½ inches square at the butt; an 18½ x 21½ inch ingot means it is rectangular in section and 18½ x 21½ inches at the butt.

## SECTION II.

### THE CONSTRUCTION OF THE SOAKING PIT.

**General Features of the Soaking Pit:** The soaking pit of modern construction is so built that it can be used either as an old time pit or as a heating furnace. Briefly, soaking pits are deep chambers, or underground furnaces of square or rectangular sections, heated by the regenerative principle and opening at the top. As to size, they are built large enough to contain four, six, or eight blooming mill ingots per hole, in an upright position. The older furnaces contain four ingots per hole, while the capacity of the most recent ones is eight ingots. The increase in size is due mainly to the economy in fuel which is obtained by the use of large pits. While the details of pit construction may vary somewhat at different works, yet the form and principle of all are alike. Therefore, it is sufficient to study but one, which may serve as an example of all. For this purpose, a six ingot furnace at Duquesne will be described somewhat in detail.

**Arrangement of the Pits:** For heating the ingots for the two blooming mills at these works, the 38-inch and 40-inch mills, there are 11 rows of pits, or to be more exact, 11 furnaces of 4 holes each. The holes are numbered 1 to 44, inclusive, No. 1 to No. 20 and No. 37 to No. 40 serve the 38-inch mill; the other 16, No. 21 to No. 36, inclusive, serve the 40-inch mill. In case a furnace for the 40-inch mill is off for repairs No. 5 furnace, containing holes 17, 18, 19 and 20, may be substituted. The first nine furnaces are built to contain six 22″ x 22″ ingots per hole, but numbers 10 and 11 are constructed to hold eight ingots per pit. This gives a pit capacity for the 40-inch mill of 96 ingots, and for the 38-inch mill, 184 ingots. The furnaces with the exception of No. 1, are built in groups of two each. From center to center of each two adjacent furnaces, the distance is thirty-three feet.

**Equipment for Handling Ingots:** Spanning these soaking pit furnaces are electric traveling cranes, two of which are over furnaces No. 10 and No. 11, and four are over No. 1 to No. 9, inclusive. These cranes are Morgan 6-ton machines, and are equipped with Westinghouse motors as follows: 50 h. p. on the bridge, 50 h. p. on the hoist, 10 h. p. on the trolley, and 5 h. p. on the tongs. The main hoist is operated by a gear hoist and shafting rack. The tongs are connected up with a drum on a lifting arm, giving a vertical movement of about nine and one-fourth feet. The tongs are actuated by means of a curved groove in the main hoist so that their distance apart may be varied. The tongs are equipped with four-inch bits, giving a distance between the two bits, when in the closed or lowered position, of sixteen inches and when in the raised or open position a distance of nineteen and five-eighths inches. Thus the largest ingot that can be gripped is one about eighteen inches at the top. When larger ingots, such as the 22″ x 22″ size, are to be handled it is necessary to remove one bit.

**Construction of the Pits:** In detail the construction of a six-ingot soaking pit furnace is as follows: Each furnace or pit contains four rectangular holes, eight feet long, five feet three inches wide and eight feet seven inches deep. These holes are built side by side in the furnace, and are separated only by firebrick walls. Each hole has two air regenerators, one on each side, so that in connection with each furnace there are eight regenerators. The holes are closed by firebrick covers, each cover being supported on four wheels which roll on cast steel rails lying on the division wall between the pits and fastened at their ends to the I-beams supporting the platform about the pits. The walls enclosing the checkers and those supporting the pit proper rest on a concrete foundation twelve inches thick. These walls are built of firebrick, faced on the outside with river brick. The outside walls are about eighteen feet high, and the river brick wall directly under the pit is about eight feet high. The top of this river brick wall is protected by cast iron coping plates. Placed vertically on these coping plates and extending up into the firebrick bridgewall are cast iron end plates. On the coping plates rests also the

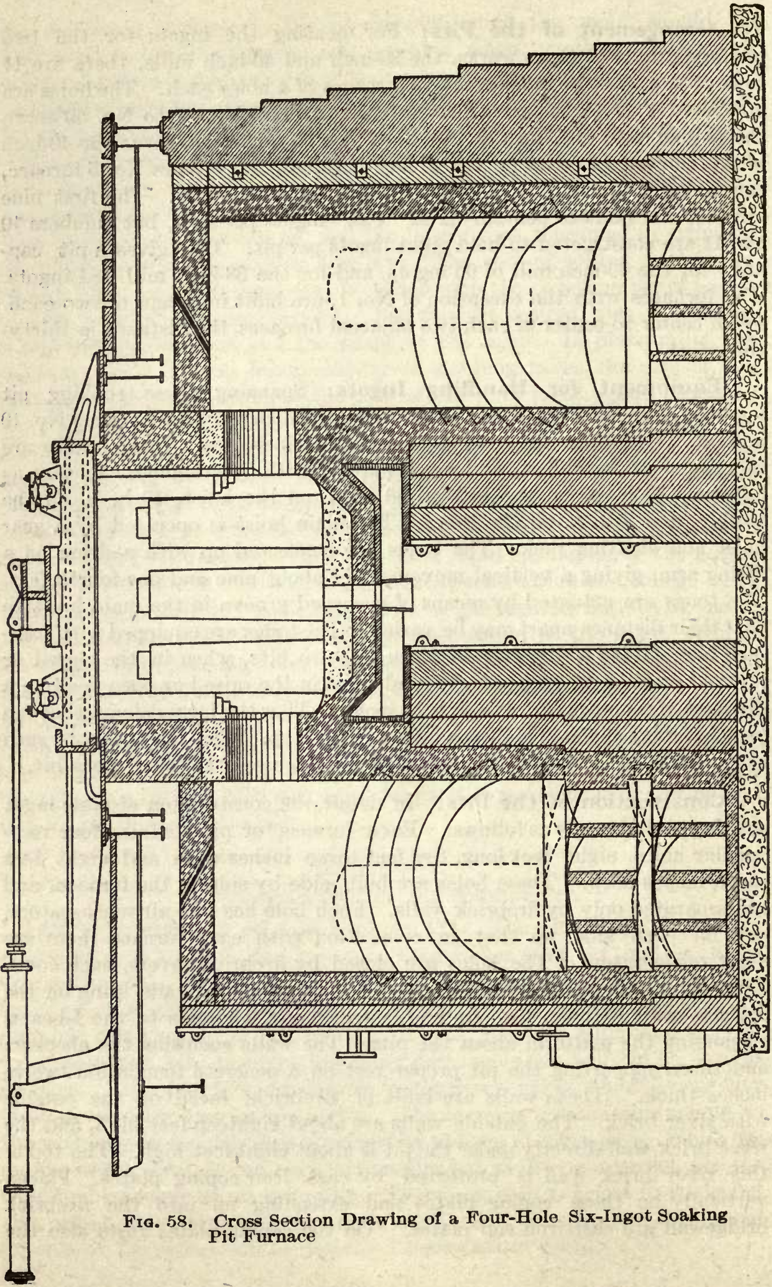


FIG. 58. Cross Section Drawing of a Four-Hole Six-Ingot Soaking Pit Furnace

steel I-beams supporting the cast iron pans which form the bottom of the pits. A pan is made in two sections with a semi-circular hole on the inside edge of each section, so that when they are fitted together there will be a circular opening about ten inches in diameter through which the cinder can be removed from the pit. Each section rests on three ten-inch I-beams. About one foot on each end of the pan is flared upward at an angle of 45°. There are five cooling boxes resting on the I-beams, three inside, or intermediate cooling boxes, and two end ones. The inside cooling boxes are in the division walls between the pits, and the end ones are in the end walls of the two outside pits. Each of these boxes rests on two I-beams. The boxes are hollow, being open on the bottom, and the lower half of the end of the bottom is cut off at an angle of about 45°. Thus, these cooling boxes and pans form with the end plates a triangular space through which the air circulates and forms the air cooling system for the bridgewall. On the top of the cooling boxes and near each end, there is a four-inch hole, and when the walls between the pits are built up, this opening is extended up to the surface so that a circulation of air is maintained through it. The boxes are cast iron, one inch thick, eight feet nine inches long, twenty-eight inches high and are fourteen inches wide inside at the bottom and four and three-fourths inches inside at the top. The pans are lined with nine inches of firebrick set in firebrick mortar. The cinder hole is built up of nine-inch side-arch brick. The pit, then, to above the slag line, is lined with chrome brick, as these are the only bricks that are not fluxed by the slag formed. Next to the coolers, however, there is one four and one-half inch course of firebrick, laid in fireclay, but on these there is a four-inch course of chrome bricks, laid dry, and at the front and back of the pits, at the bridge wall, this chrome brick lining is nine inches thick. There are, in all, seven courses of chrome bricks, which brings the wall even with the top of the cooling box. Above this level, the walls are built entirely of fire brick. The side of the bridgewall next to the checker chambers is capped with heavy firebrick tiles (13½ x 6 x 2½″) giving a width to the firebridge of twenty-two and one-half inches. The chrome bricks are heavily coated with silica slurry, which affords an added protection. The use of this slurry is especially important on the front and back, for the bridgewall is the weakest part of the furnace, because it is subject to the intense heat of the products of combustion leaving the pit and, therefore, has a tendency to crack and spall. The firebrick part of the walls inside of the pit are coated with a slurry of fire-clay. This coating fills up the cracks and forms a glaze which protects the bricks.

**The Air Regenerators** are about six feet square in horizontal section and seventeen feet four inches deep. The sewer which conducts the air from the air valve to the two chambers on the same side and farthest from the stack is beneath the air sewer for the two pits nearest the stack. Thus, the regenerator chambers and, hence, the pits are fired in pairs. The bottom sewer is two feet seven inches high and the arch is nine inches thick. Therefore, the regenerator chambers for the two pits, on each side, nearest the stack are three feet four inches less in height than the back chambers. Between the two regenerators on the same air flue, starting at a height of about five feet above the bottom of the chambers, there is an eighteen inch firebrick wall separating the two adjacent chambers. The two pairs of regenerators on the different air sewers are entirely separated from each other. The bottoms of the chambers are separated into four spaces (fourteen and one-half inches wide) by firebrick withe walls. These walls extend back into the air sewer to the air valve and provide for the even distribution of the air. On these withe walls there is one course of firebrick tiles on which the checkers rest. The withe walls are three feet seven inches high in the two pairs of regenerators farthest from the stack and two feet four inches in the other two pairs, thus making the height of the first mentioned checkers nine feet six and one-half inches. In the two pairs of chambers farthest from the stack, the checkers extend up to within thirty-one inches of the bridgewall and in the other two pairs to within eighteen inches. The top row of checker bricks are laid so that the openings are in the same direction that the air must take in entering the pit. The roof of the regenerator chamber is arched, being built of firebrick thirteen and one-half inches thick, but the arch over the bridgewall, for a distance of twenty-seven inches, is of silica brick nine inches thick and laid in silica slurry on top of which is a thirteen and one-half inch firebrick arch. Silica brick is used in this construction because it is very refractory and can withstand a heavy load when highly heated. The whole furnace is securely tied together by cast iron corner binders, tie rods, and buckstays. Each of the four outside corners of the furnace has a corner binder fifteen feet ten and one-half inches high, and the four corners directly under the pits have binders eight feet one inch high. These binders have a twelve inch flange, two inches thick, provided with lugs for the tie rods. The binders are connected by two inch tie rods. Along the two outside walls of the regenerators there is a structural steel buckstay, the ends of which are connected, across the furnace end, by two inch tie rods.

**The Pit Covers** consist of four iron castings which are bolted together and are held rigid at the center by a cast iron separator. Inclosed in this frame is a firebrick arch. As already stated, to these castings are fastened the wheels on which the covers roll. To each separator is fastened a steel piston rod connected to the piston head in a hydraulic cylinder. These cylinders furnish the means by which the covers are moved. In some plants the covers are moved by lowering the tongs into a special box in the separator casting and then moving the crane in the direction desired. The hydraulic cylinders operate under a water pressure of 500 lbs. per square inch. They rest on cast iron stands fastened to the floor beams, and the bearings for the cylinders are placed about the center of the cylinders, thus making them free to rotate about this point. This construction is made necessary, because, as the furnace becomes old, the dividing walls between the pits sink and the rails bend. Therefore, the connection of the piston rod and the separator has a constantly varying elevation due to the different elevation of the rails, and it is necessary to have the cylinders on a rocker so that they may follow this motion and constantly adjust themselves in line with the piston. The extreme stroke of the cover piston is nine feet nine inches. In order to make the covers fit nicely the tops of the pits are surrounded by floor plates of cast iron.

**Fuel and Air Valves, etc.:** These pits were built to use natural gas for fuel, but this fuel has been replaced by coke-oven gas. When natural gas was used for heating the pits, it was admitted through the roof of the regenerator chamber by means of two three-fourth inch pipes twenty-one inches long. These pipes were placed at such an angle (about four and one-half inches of slope per foot) and distance from the pit that the flame did not play directly on the face of the ingot, and a reducing atmosphere could be maintained inside the pit. The pipes, or burners, were twenty-one inches apart and were fed from a one and one-fourth inch pipe which in turn was connected up to a four inch gas manifold supplying the gas to the four chambers on a particular side. For coke oven gas it was thought it would be necessary to modify this scheme of firing somewhat in order to make the conditions suit the difference in the heating properties of these gases, but trial runs indicate that satisfactory results are obtained if the coke oven gas is burned in the same manner as the natural gas. For reversing the direction of the air there are two thirty-inch Ahlen sliding valves, and for reversing the direction of the gas a three-way valve. Each set of valves consists of two cast iron bed plates, two cast iron sliding plates, two hydraulic cylinders, and two hoods. The distance from center to center of the hoods is five feet three and one-half inches. The bed plates are bolted together and the cylinders are bolted to them. Each of these bed plates has three openings connected to flues, of which the two outside ones lead to the regenerators and the center one to the stack. These flues are twenty-two inches wide, the division walls being nine inches thick and the wall between the two sets of valves twenty-two and one-half inches thick. As to the sliding plates they are also bolted together and the two are then connected directly to the piston of the hydraulic cylinder. The total length of the sliding plate is eleven feet one inch. Each plate has six openings, two pairs of which are used as air dampers, while the other two form, with the hood, a part of the flue to the stack. The hood rests on the sliding plate, and both the hood and the sliding plate are water cooled. The hydraulic cylinder has a stroke of two feet seven inches and a plunger diameter of six inches.

**Stack-Flues and Stack:** The flues leading from the valve to the stack are three feet eleven inches high and twenty-two inches wide. In these flues are the stack dampers. These dampers are hand operated by means of a chain and a counter-weight. They slide in a guide frame made in the form of a casting set in the brick work. The stacks are one hundred three feet eight inches high, and consist of a riveted steel shell and a lining of brick work. The plates of which the shell is made are one-fourth inch thick at the bottom of the stack and one-eighth inch at the top. The outside diameters of the shell at the top and bottom are respectively four feet six inches and five feet ten inches. The lining consists of a four and one-half inch course of firebrick.

**The Course of the Gases Through the Pits:** Of the two thirty-inch air valves, the one nearest to the pits is for the two front pits and the other for the two back pits. Thus, for the two front pits, the air enters the inside valve through the top sewer, goes through the two front regenerator chambers, the two front pits, down through the opposite checkers, through the top sewer, through the inside reversing valve, then past the right hand stack damper to the stack. For controlling the sliding valve so that the two hoods work in unison, a double-acting Critchlow valve is provided. Each of the sliding plates is provided with two air dampers so that it is impossible to shut off the air from the two adjacent pits with the valves in either position. The gas on all four pits is reversed by one three-way valve, but on each side of this valve there are four other valves, so that the gas can be shut off separately on any pit. To reverse the direction of the gas and air, the gas is shut off, then the air reversed, and after it the gas is reversed.

**Eight Ingot Pits:** The main difference between the six ingot and the eight ingot pits, aside from increased dimensions, lies in the fact that the air regenerators are provided with a special division wall. This wall is built parallel to the end of the pit and extends to the top of the checkers, the object being to retain any cinder running over from the pit in the first few checker openings, thus preventing the choking of all but a few of the checker spaces, and maintaining a higher efficiency of the regenerators. Also, these pits are provided with two cinder holes instead of one as for the six ingot holes. The furnaces are spaced forty-one feet four inches from center to center, and the holes are five feet three inches wide and ten feet seven inches long, and are spaced eight feet three inches from center to center. The covers on these pits can be separated about two-thirds of the distance from the back. On these covers the piston is connected to the end casting of the cover frame instead of to the separator, and there is a separator on each portion of the cover. When closed, the separators fit together and are fastened thus with hooks. With this arrangement it is possible to move the entire cover or, by unhooking, the back portion only may be moved.

**Making Up the Bottom of the Pit:** Bottom making is done by a group of men called the bottom-makers, who are provided with shovels, long handled pokers and cutters. To clean out a pit, the pit cover is pulled back slightly, and a shield is drawn up over the front of the pit. The cinder hole in the bottom of the pit is then opened with the poker, and by means of the cutters the cinder is shoved out through this hole. After the cinder has been removed, a piece of iron sheeting is put over the hole, and then the process of making bottom is begun. Coke breeze from the blast furnace coke bins is used to make up the bottom. Coke breeze is used because it absorbs and makes fragile the molten oxide that runs off the ingot, protects the brick work, and helps to maintain a reducing atmosphere in the furnace. The depth of the coke on the bottom should be maintained at about eighteen inches. To provide the desired depth, making up for the coke and cinder that are pushed out each time, requires for each bottom six to eight wheelbarrow loads of breeze, which weighs about 250 pounds per barrow load, for the six ingot pits; for the eight ingot pits ten to twelve wheelbarrow loads, or about 2500 pounds, is required. This coke is thrown in from the front, the ends being made up first, the sides next, and lastly the center. The bottom is made up so that there will be two troughs into which the ingots may be placed. The object in providing these troughs is to keep the ingots away from the walls so that they will have a better chance to heat but at the same time will not be placed so near the center that they will be hit directly by the flame. During the time that the bottoms are being made up, the gas and air are shut off, and the stack is made to draw air through the cover opening so that the heat is drawn away from the men. Before charging ingots on a new bottom, the coke breeze should be allowed to become well heated throughout, as a cold bottom in the pit allows the butts of the ingots to remain cold, and when ingots are put through the mills in this condition they are liable to break the rolls.

## SECTION III.

### SOAKING THE INGOTS FOR ROLLING.

**Charging the Ingots:** Ingots should always be charged into the soaking pits in an upright position, which explains the peculiar construction of the pits. There are two reasons for this method of charging. First, the best practice for the care of ingots demands that they be stripped as soon as possible after pouring and delivered to the soaking pits before they lose much of their original heat, because the hotter they are charged the quicker will they reach the rolling temperature, and little fuel for reheating will be required. In pursuance of this practice, most ingots, except high carbon, high sulphur and alloy steels, which are allowed to become solid throughout before stripping, reach the pits while their central portions are still molten and must, therefore, stand in an upright position until this portion has become solid, as otherwise the extent of the pipe might be increased and its position would be changed. Second, by charging ingots vertically more surface for ingress and egress of heat is exposed to the atmosphere of the furnace, thus causing them to come to a uniform rolling temperature much quicker than would be the case if they were placed in any other way.

**Heating the Ingots:** From what has been said, it is easy to surmise that great injury can be done in the heating of the ingots. This injury consists of under-heating, over-heating, uneven heating, or worse than all, burning. Of these, under-heating and over-heating are the least harmful to the steel; the former increases the power required for rolling and decreases the time permissible for the rolling; the latter, by increasing the grain size and lessening the force of cohesion, makes the steel tender and liable to crack. Uneven heating increases the difficulties of rolling very much. A cold butt of an ingot, for example, may cause a roll to be broken. Burning may range from extreme over-heating to a temperature just below the melting point, where the more fusible constituents melt and run out of the ingot, forming cavities that, on rolling, result in defects that will be cause for rejection of the material. In the case of thin skinned ingots, severe over-heating may have a like result by exposing the blow holes. Besides these general precautions, different conditions and different grades of steel require different treatment. As an example of the point in question a summary of the soaking practice as carried out at Duquesne is given herewith.

**Week-End Charges:** If hot steel is charged Saturday evening just before the mill shuts down, it will be allowed to soak until one or two o'clock Sunday morning, when gas will be admitted for about an hour. Soaking will then be continued until the day turn comes out at seven o'clock a. m. But if cold steel should be charged before the week-end shut-down, gas is admitted for three or four hours, the flame being reversed at intervals of from one-half to one hour; and the steel is then allowed to soak until Sunday morning. During the soaking, the stack and air dampers are kept closed.

**Soaking Hot and Cold Ingots:** To bring hot steel to the required rolling temperature requires approximately the same amount of time as the interval between the time the heat was tapped and the time it was charged into the pits. Hot special steel of medium carbon content must be in the pits about one and one-half hours and spring steel about one hour. Thus, the period, from the time the heat is tapped at the open hearth until it can be rolled, is about three hours for Duquesne special, about two hours for spring steel, and one and a half hours for ordinary steel. To heat six cold soft steel ingots in the 6-ingot pits requires about six hours. For about four hours after the pits are charged, the gas and air may be admitted on each side alternately for half hour periods. The period of reversal should then be cut to fifteen minutes. Towards the last, as the temperature of the steel approaches the rolling temperature, the period of reversal may be cut to five or ten minutes, for the more frequent the reversal the more even will be the temperature of the pits. Cold steel is very rarely charged in the ingot pits, the practice being followed only after a shut-down when the mills start operating at the same time as the open hearth, for at such a time there is no hot steel on hand. The period required for heating cold steel in the eight ingot pits is about eight hours.

Soft steel is heated to a temperature of about 1200° C. (2200° F.) With both high and low carbon steels, should only four or five ingots be charged in the smaller pits, the period required for heating would be greatly reduced. This is true especially for the low carbon steel, for with only four ingots to a pit it is possible to prepare the cold steel in four hours. By charging only six ingots in the large pits, the period may be reduced to about six hours. Before a cold high carbon heat (.70% carbon or over) is charged, the pits should be cooled for about a half hour, for if these ingots are heated rapidly they are liable to crack. After the pits have been cooled, the ingots are charged, and sometimes the covers are left open for a half hour, so that the steel will be heated very slowly. The period between reversals should not be as long as for low carbon cold steel, and so at first the reversals for steel of this grade are made at intervals of a half hour or less, and during the balance of the time the period between the reversals is about ten minutes. The rolling temperature of spring steel is about 1090° C. (2000° F.)

**Soaking Hot Spring Steel:** This grade of steel is charged in a hot pit. The gas may be admitted for a half hour, the flue being reversed every five or ten minutes; the steel should then be allowed to soak for fifteen minutes, and then gas should be admitted for about fifteen minutes to bring up the temperature of the outside of the ingot. This steel should be ready to roll in about an hour. While the steel is soaking, in addition to shutting off the gas, it is best to shut off the air supply, also, for the effect of the hot air on the ingot is to oxidize or even to burn it. If the steel is very hot when charged, it should be allowed to soak for a half hour before gas is admitted; then gas and air should be admitted for about a half hour, with reversals every five or ten minutes. The steel should then be soaked for a half hour without air, and then, just before drawing, the temperature of the outer part of the ingot should be brought up by admission of gas and air again.

**Soaking Low Carbon Hot Steel:** Hot low carbon steel ingots may be heated without danger for a half hour, the direction of the gas and air being reversed every fifteen minutes. The steel should then be allowed to soak for fifteen minutes, and before drawing the outside temperature should be raised. Since there is not as much danger of burning this steel as there is with the high carbon grades, it is not always necessary to close the air dampers during the time the steel is soaking.

**Soaking Medium Steels:** The practice with respect to medium steels, .30% to .60% carbon, is to heat the ingots to about the same temperature as for low carbon steel. The steel, if charged hot, should be ready to roll in one hour after charging.

**Soaking Screw Stock:** High sulphur steel is charged as quickly as possible after stripping. The time required to heat it is about one and a half hours. The steel is heated to dripping, that is, until the scale melts and flows readily from the surface, and is rolled when in that condition. Owing to the high sulphur content, it is necessary, to maintain good practice in rolling, to heat it very hot, so that the steel will be very plastic. This condition is obtained only at a very high temperature, about 1240° C. (2240° F.). Since these screw stock ingots are heated until they are dripping a large amount of liquid cinder is always formed, so that it is necessary to add a little coke in the pits after every heat of this kind to absorb this cinder.

**Soaking Alloy Steels:** Nickel steel is heated to about the same temperature as spring steel, 1090° C. Chrome vanadium is heated to about 1250° C. Copper steel is heated according to its carbon content in much the same way as carbon steels.

**Drawing the Ingots:** The craneman draws the ingots from the pits according to the orders of the heater. Usually, a definite order is followed; at Duquesne the regular method is to draw the two front ingots from each of two holes, then the two middle ones from each of the two holes, and then the two back ones from each of the two holes. The operation is then repeated on the next two holes. However, the operation may be varied; the two front ones in each of four holes may be drawn, thus affording more time for the middle ingots to heat while the others are being drawn. To transfer the ingots from the pits to the blooming mill tables three pot cars, two of which are extras, are provided. These cars are operated by 19 h. p. Westinghouse motors. At the 38-inch mill they are controlled and dumped from the manipulator of the mill, but on the 40-inch mill, the man that operates the pit covers controls the movement of the car. When the car receives an ingot it is run to the first table roller, and there the car is tipped, when the ingot falls upon the table.

**Heat Balance of Pits:** That the soaking of ingots is an expensive process is evident from the equipment required. The cost of the up-keep of this apparatus is high, and the efficiency is very low, even on up-to-date furnaces, as the following heat balances as determined by experiment on some Duquesne furnaces using natural gas will show:

**Table 50. Data Relative to the Efficiency of Soaking Pit Furnaces.**

| | |
|---|---|
| Sensible Heat in Steel Charged | 619,701 B. t. u. |
| Heat of Combustion of the Gas | 781,808 |
| Heat Carried in by Regenerated Air | 384,970 |
| TOTAL | 1,786,479 |
| Heat in Steel when Drawn | 773,597 B. t. u. |
| Heat in Gases Entering Stack | 173,862 |
| Heat Given up to Regenerators | 386,329 |
| Radiation and Unaccounted for Losses | 452,691 |
| | 1,786,479 |

$$\text{Pit Efficiency}=\frac{\text{Heat Absorbed by Steel}}{\text{Total Heat Delivered to Furnace}}=\frac{153,896}{1,786,479}=8.6\%$$

**Disposition of Ingot Products:** Since the ingot is the starting point for all mechanical working, it is interesting to trace the material through the various processes that the steel undergoes to produce the many articles in which it is used. For this purpose the following table has been prepared, and requires little by way of explanation. Each dash marks a reheating of the material, while each word means a mill, or a set of mills, where work is done to produce the article named.

**Table 51. Disposition of Steel from Ingots.**

- Ingots—
  - Universal Mill Plate.
  - Armor Plate.
  - Bloom, Sheet Bar—Sheets.
  - Shaped Bloom, Large Shapes.
  - Slabs—
    - Universal Mill Plates.
    - Eye Bars.
    - Sheared Plates.
  - Bloom, Billet—
    - Rods.
    - Bars.
    - Bands.
    - Hoop.
    - Small Shapes.
  - Rectangular Bloom—
    - Billet—
      - Rods.
      - Small Shapes.
      - Bars.
      - Bands.
      - Seamless Tube.
    - Sheet Bar—Sheet.
    - Structural Shapes.
    - Rails.
    - Rail Joints.
    - Skelp—
      - Tube.
      - Pipe.
    - Forgings.
  - Cylindrical Blooms—
    - Wheels.
    - Circular Shapes.
    - Shell.
  - Large Forgings.

# CHAPTER V.

## THE ROLLING OF STEEL—BLOOMS AND SLABS.

### SECTION I.

### INTRODUCTORY.

**Outline of the Plan of Study:** Rolling mills are somewhat like houses. Thus, while they are alike as to gross features, they differ greatly as to details of construction. Just as the architect will strive to impart individuality to a building, so the rolling mill engineer and builder will endeavor to introduce new ideas looking to greater improvements in construction; and just as it is desirable to adapt a building to its location and surroundings, so is it found necessary to alter the details of mill construction to suit the conditions, local and otherwise. The result of all these influences on mill construction has been to produce such a variation in mills that there are no two mills exactly alike. Evidently, to describe all the details of mills and their operations is well nigh an endless task; yet it is desirable that the reader be given an opportunity to become so well acquainted with the rolling of each product that he will be more or less familiar with the more essential details of its production and thoroughly understand the conditions under which it is produced. The plan decided upon as best to pursue is this: An attempt will be made to describe the rolling of as many products as possible, and in doing so the order followed will be from the rolling of material from ingots, to semi-finished products, to finished products, as indicated in the previous diagram. In this connection one mill rolling the material in question will be described, as well as the operation in detail; after which the product itself will receive special attention. In describing mills, the details of one mill of each type or class will be given. As a sort of working outline of the plan, the following classification of mills will give an idea of the ground to be covered and the order in which the subjects are to be treated. The general discussion preceding this part of the study should supply information to fill in any gaps that may occur in the studies to follow.

### Table 52. Classification of Mills.

- A. Mills Rolling Material from Ingots.
  - 1. Semi-finishing Mills:
    - a. Blooming (Cogging) Mills.
    - b. Slabbing Mills.
  - 2. Finishing:
    - a. Universal Plate Mills.
- B. Mills Rolling Material from Blooms and Slabs.
  - 1. Semi-finishing:
    - a. Billet Mills.
    - b. Sheet Bar.
    - c. Skelp.
  - 2. Finishing:
    - a. Plate Mills:
      - i. Sheared.
      - ii. Universal.
    - b. Rail Mills.
    - c. Structural Shape Mills.
    - d. Wheel Mills—Schoen Mill.
    - e. Wheel and Circular Shape Mills.
- C. Mills Rolling Material from Billets.
  - 1. Merchant Mills.
    - a. Guide Mills.
    - b. Bar Mills.
    - c. Hoop or Strip Mills, etc.

**Blooms, Slabs and Billets:** As a preliminary step toward forming steel into the various sections which its many uses require, the heavy ingots, except in certain plate mills and some large shape mills, are first roughly reduced, in mills especially designed for the purpose, to much lighter but still very simple sections, as the round, the square and the rectangle. When the ingot has been reduced to the dimensions of a square between one and one-fourth inches and six inches it is cut into convenient lengths, called **billets**; if these pieces are six inches square or larger, they are known as **blooms**; and if reduced to rectangular forms but with widths which are less than twice the thickness and within the dimensions specified for the square, the same names apply. But if the width far exceeds the thickness of the rectangular section, then it is called a **slab**. If the output of the mill is mainly blooms, it is called a blooming mill in the United States or a cogging mill in England; if billets, a billet mill; and if slabs, a slabbing mill. The blooming and slabbing are the largest and strongest mills used to roll steel, if the mills that roll heavy armor, of which there are no longer any in this country, be excepted. The reasons for the existence of these mills are evident.

## SECTION II.

### SOME GENERAL FEATURES PERTAINING TO BLOOMING MILLS.

**Size of Blooming Mills:** The size of blooming mills is popularly supposed to be based on the diameter of the rolls, or on the distance from center to center of the rolls. Both these quantities are constantly changing, due to the wearing of the rolls, which affects their diameters, and to the fact that they are adjustable. The size is, therefore, based on the distance from center to center of the pinions, which corresponds to the distance from center to center of the rolls and also to their diameters, and is always constant. The blooming mills in use at the present time will range in size from twenty-eight to forty-six inches. The older mills are the smaller, because it was formerly the practice to cast the ingots much smaller than at present, and large mills were not required. The size of ingots having been gradually increased for the reasons already pointed out, the size of the mills designed to roll them were necessarily increased also. This size seems now to have approached a standard, and most mills of recent construction have rolls in the neighborhood of forty inches in diameter.

**Types of Bloomers, Their Advantages and Disadvantages:** Blooming mills are of three general types, namely, **reversing, continuous,** both of which are **two-high,** and **three-high.** Of these, two-high reversing and three-high mills are the most common. As an example of the continuous blooming mill, the billet mill at Gary, Ind., is cited. It consists of nine stands of rolls arranged in tandem and separately driven by electric motors. Since its blooms are delivered directly to a continuous billet mill, the reduction of the ingot to billets is made in one continuous operation. The chief advantage in this arrangement is an extraordinarily large output. As to reversing and three-high bloomers, each of these types has its advantages and disadvantages, some of which it may be of interest to enumerate here. The main advantage of the reversing mill over the three-high lies in its greater flexibility. Thus, the top roll being adjustable, various sizes of blooms, billets or slabs can be rolled on one set of rolls, and the draught can be regulated to suit steel at different temperatures and of different grades. Even different methods of reducing the ingot may be employed with the same rolls. On long lengths the two-high mill is to be preferred on account of the greater ease with which such material can be handled, while the simplicity of the roll design is also a factor in favor of these mills. On the other hand, a reversing mill is a much more expensive mill than a three-high mill. In the first place the tonnage is much lower. On two-high forty inch mills the average output is about 2000 tons per twenty-four hour day, to produce which about 2500 tons of ingots are required, while a three-high mill of the same size will roll almost twice as much steel. Again, the power equipment of the reversing mill is costly and the loss of power is great. Reliable tests show that the total power

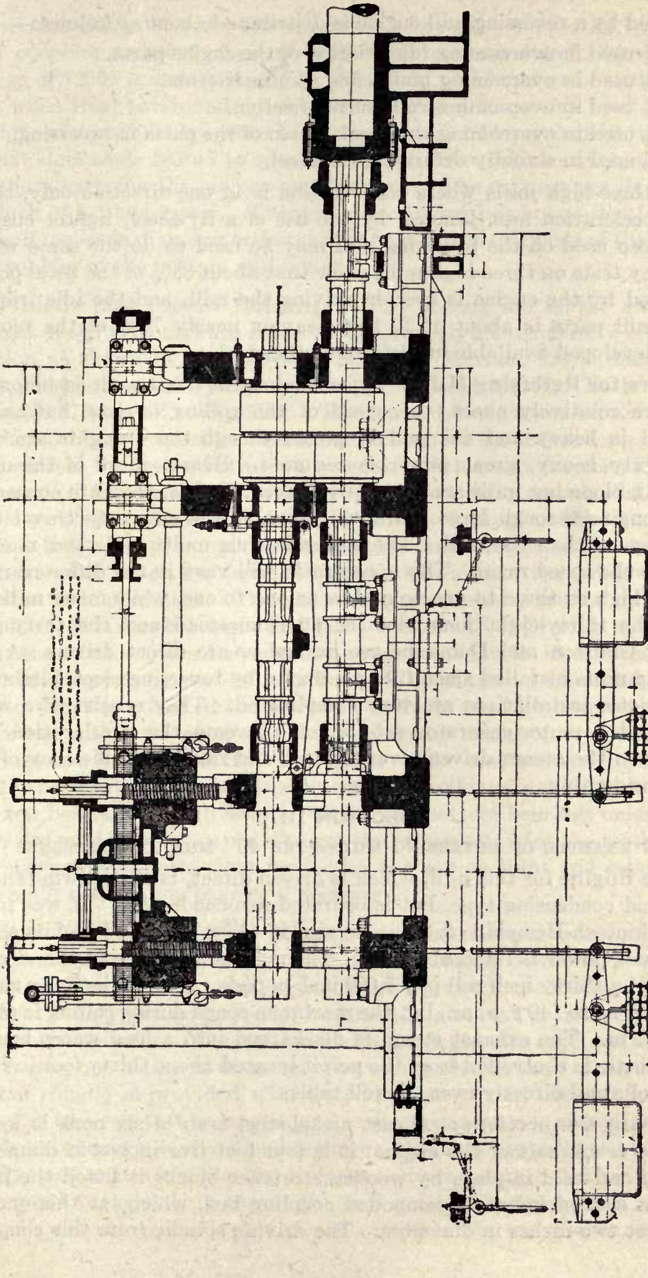


FIG. 59. Longitudinal Section Through Rolls and Pinions of a 40″ Mill.

developed by a reversing mill engine is distributed about as follows:—

27% used in overcoming idle friction of the engine parts.
9% used in overcoming pinion and spindle friction.
13% used in overcoming roll journal friction.
21% used in overcoming the acceleration of the parts in reversing.
30% used in actually deforming the steel.

In three-high mills where the rotation is in one direction only, there is no acceleration loss, besides, by the use of a flywheel, lighter engines than those used on the reversing mill may be used to do the same work. Efficiency tests on three-high mills show that about 85% of the total power developed by the engine is used in driving the mill, and the idle friction of the mill parts is about 15%, thus leaving nearly 70% of the motive power developed available for deforming the steel.

**Drive for Reversing Mills:** Since the lengths dealt with on blooming mills are relatively short, the speed of the rolling is slow, but as the material is heavy and the pull is great, though the draughts are only moderately heavy, great power is required. Hence, most of the older reversing blooming mills are indirectly driven, that is, they are connected to the engine through large gears which enable the engine to travel at a higher speed than the mill. The power is thus multiplied by a number equal to the speed ratio. This speed ratio will vary in the different mills from as high as three to one to as low as one to one, while many mills, of which the thirty-eight inch bloomer at Homestead and the forty inch mills at Clairton and Duquesne are examples, are direct driven. A few reversing mills installed since 1914 are driven by reversing electric motors. These motor installations are very complicated. They consist of a main motor and a motor-generator set, which prevents the acceleration loss peculiar to the steam driven reversing mill and raises the efficiency of the mill considerably.

## SECTION III.

### AN EXAMPLE OF REVERSING MILLS—THE 40″ MILL AT DUQUESNE.

**The Engine** for this mill, which is driven direct, is of the twin tandem compound condensing type, but is operated non-condensing. It was made by Mackintosh-Hemphill & Co. Its size is 44″ x 70″ x 60″ and its maximum horse power is rated at 20,000. The maximum torque at the circumference of a thirty inch roll is 465,000 inch-pounds. The engine may run at any speed up to 140 r. p. m., but the maximum speed during rolling is about 130 r. p. m. The exhaust steam is discharged into a feed water heater. The throttle is controlled from the pulpit located about thirty feet in front of the rolls and directly over the roll tables.

**Driving Connections:** A cast nickel-steel crab of six pods is keyed onto the crankshaft of the engine; it is four feet five inches in diameter. Over it, and held in place by wooden stretcher blocks is fitted the large end of a cast nickel steel compound coupling box, which, at this end, is three feet two inches in diameter. The driving spindle from this coupling is five feet eleven and one-fourth inches long and is supported by a cast steel coupling carrier resting at its four corners on standard spiral car springs of 12500 pounds capacity, which stand eight and one-fourth inches high when free, seven and one-fourth inches at 4700 pounds load, and six and nine-sixteenth inches when fully compressed. The springs in turn rest on cast steel seats bolted to special cast iron shoes which are anchored to the shoes carrying the pinions and housings. The carriers are lined with one inch of babbitt metal. The mill end coupling box is two feet four and one-half inches in diameter and is cast to fit over the four pods of the engine-end wobbler of the bottom mill pinion.

**Pinions and Pinion Housings:** The pinions are of the staggered straight tooth type and are made of nickel steel, approximately of a composition as shown by the following analysis: Carbon, .29%; manganese, .66%; phosphorus, .020%; sulphur, .030%; and nickel, 2.97%. Their average life is 253,575 tons of steel rolled. The top and bottom pinions are similar and hence interchangeable. Each one is ten feet six inches long over all and four feet ten inches between the necks, which are twenty-one inches in diameter. This diameter is further reduced to twenty and one-half inches at the wobblers. The pitch diameter is forty inches, and the number of teeth is fourteen. The pinions run in solid cast steel babbitted bearings, the bottom of which are beveled to fit on the sills of the window of the cast iron pinion housings. The pinion housings are bolted to the mill shoes, are nine feet six inches high, and have windows 2′ 7½″ wide by 7′ 6½″ deep; the windows are lined with one and one-fourth inch forged steel liners held in place by stud-bolts through the housings. A cast steel housing cap, to which is attached the hydraulic cylinder used for lowering the top roll of the mill, is fastened over the housings by means of key bolts. The bearings are each two feet six inches wide and twenty inches from front to back and may be adjusted by set pins reaching through the housings. The top bearings rest directly on top of the bottom bearings unless plate liners are used in between them to get the proper pitch for the teeth. The bearings are held down tight by keying the cap on tight and using liners between it and the top bearing if necessary.

**Spindles and Coupling Boxes:** Over the mill-end wobblers of the pinions are fitted cast steel coupling-boxes uniting the wobblers with the spindles. The coupling boxes, of cast steel, are two feet six inches in diameter and twenty-two and one-half inches wide, and cast to fit over the four pods of the spindles. The bottom and top spindles are each ten feet long and twenty-one inches in diameter where they rest on their carriers. The bottom spindle is provided with wobblers twenty and one-half inches in diameter and two feet in length, and is nineteen inches in diameter at the center between the two carrier bearings. On the top spindle the wobblers are nineteen inches in diameter, thirteen and seven-eighths inches long and are curved at the ends to permit the mill end to ride up or down with the top roll. Twenty-three inches at the center of the top spindle is turned smooth to a diameter of twenty-one inches to give a bearing for the spindle carrier, which is movable. The bottom spindle rests at two points near its ends on two stationary spindle carriers bolted to the mill shoes. The carrier for the top, or vibrating, spindle consists of a cradle formed by two cast steel arms hung at their engine ends from two supporting rods pivoted on spring-supported bolts which pass through supporting brackets bolted to the pinion housings. In the center of the carrier is a rest for the spindle, and on its mill end the carrier is supported by the carrier bearing for the top roll, being fastened to this bearing by a forged steel pin. A coupling-box similar to those used with the pinions fastens the bottom spindle to the bottom roll; seven-eighths of an inch clearance is allowed at each connection between spindle and pinion or roll, respectively. For the top pinion, a light coupling box is used in order that it may act as a safety for the mill by breaking under excessive strain before any other part of the mill is damaged. This box is twenty-two and one-half inches in width, twenty-five and three-fourths inches in outside diameter, and two and one-quarter inches in thickness at the thinnest point. The other boxes are four inches thick. All coupling boxes are held in place by iron or wooden stretcher blocks fastened in place by steel or leather straps.

**Roll Housings:** The roll housing on the engine side of the mill is set with its center-line fourteen feet six and one-quarter inches from the center line of the mill-end pinion housing, a cast iron separator and steel bolt holding these two housings in line. This housing is cast steel but in other respects is the same as the outside housing, which is made of cast iron. Both are bolted to the mill shoes and stand twelve feet three inches high above them; they are set with their center lines seven feet eleven inches apart and are held in line by two cast iron separators and steel bolts, one at the front and one at the back. Besides the mill rolls the housings also support four feed rollers, two on each side of the rolls, sixteen inches in diameter and five feet ten and one-eighth inches long. The windows of the housings are three feet five and one-half inches wide, nine feet deep, and begin two feet ten inches below the top of the housing. In the top of each housing is left a hole for the housing nut, which is made of brass. Through these nuts the housing screws for adjusting the top roll are inserted. The nuts are larger at the bottom than at the top; they are twenty inches in diameter at bottom, sixteen inches at top, and thirty-four inches high. They are shrunk into the housings, and over them are fastened small caps, twenty-seven inches high, on which the screw pinions rest. The housing screws, the bottom ends of which press directly down on the screw brasses in the cast iron breaker blocks on the rider bearing boxes of the top roll, are made of .60% carbon open hearth steel, eight feet three inches long and ten inches in diameter; the threads have a pitch of two inches. They must allow a lift of twenty-five inches. These screws are provided with octagon heads. Fitted about the heads are steel pinions which rest on the top of the screw caps. The pinions have a pitch of two and one-quarter inches, a pitch diameter of fifteen and eighty-two-hundredths inches, a face of eight inches, and twenty-two teeth. The pinions are operated through a gear mounted on a spider which has a pitch diameter of eighty-three and nine-hundredths inches, a pitch of two and one-fourth inches, a face of seven inches, and one hundred sixteen teeth, and is, in turn, operated by means of a pinion fastened to its shaft. This latter pinion has a pitch diameter of twelve and fifty-four-hundredths inches, a pitch of three inches, a face of ten inches, and thirteen teeth, and is operated by a rack with a three inch pitch and a ten inch face. This rack is connected up to the hydraulic cylinder located on the top of the pinion housing. Attached to the rack is the finger, which, moving over a gauge, provides an indicator for the size of the pass. The screws of the mill are required to lift twenty-five inches, but a ten foot stroke of the rack will give the screws a vertical movement of twenty-eight and one-half inches, the extra length of stroke allowing for the wear of the roll necks and bearings. In rolling, this gauge can be set to give correct readings on one pass only, and to gauge the other passes it is necessary to add or subtract a certain quantity from the gauge reading. A cast iron bridge is bolted to the top of the housing and serves both to support the spider and to keep the housings properly spaced. The housings are further supported and kept in line at the top by two cast iron separators and two steel bolts.

**Rolls:** The top and bottom rolls in this mill are alike; there are two in a set, and each roll weighs 26,000 pounds. A typical analysis of the rolls gives the following results: .61% carbon, .75% manganese, .010% phosphorus, .030% sulphur. Their dimensions are: Total length, twelve feet ten inches; length of body, six feet; diameter of wobbler, twenty and one-half inches; diameter of necks, twenty-two inches; diameter of collars, thirty-three and one-eighth inches. They have five passes, the widths and diameters of which are 24″ x 31⅝″, 12″ x 29⅛″, 8″ x 29⅞″, 6″ x 29⅝″, 4″ x 29⅝″. The rolls are ragged only in the twelve inch and eight inch passes, and here the ragging is only one-sixteenth of an inch deep; all passes are roughened slightly with knurling wheels. These rolls are changed every week and dressed in the roll shop. About three-sixteenths of an inch is taken off each time they are dressed, and when the collars have been cut down to thirty and one-half inches, the rolls are scrapped. Four sets are kept on hand, and one set is used once in four weeks, giving a life of about one year per set. The average tonnage is 82,650 tons for each set of rolls.

**Roll Bearings:** The bottom roll rests with each neck on a babbitt lined cast steel bearing, two feet six inches wide, twenty-one and three-fourths inches from front to back, and six and three-fourths inches thick at the base; its bottom is made to fit the sill of the window, and its top is cut out at a twelve inch radius with one and one-quarter inches of babbitt to fit the neck of the bottom roll. Sheet steel shields are placed over the necks of the bottom roll to keep scale from getting between the necks and bearings. The top roll is carried in two cast steel carrier bearings, which in turn are supported each by two three and one-half inch square steelyard rods. These rods are mounted in sockets hung from counterweighted arms underneath the mill, the rods coming up through the housings and bottom bearings on each side of the necks of the bottom roll. The carrier bearings are three feet three inches wide, twenty-three and three-fourths inches from front to back and are six inches thick at the base. They are flat on the bottom and concave at the top with a twelve inch radius and babbitt metal one and one-fourth inches thick. On the engine side of the inner bearings are two lugs for receiving the pin to hold up the spindle carrier. The rider bearing of the top roll is cast steel two feet two and one-half inches wide, twenty-one and three-fourths inches from front to back, and two and one-fourth inches thick, with one inch of babbitt metal. It is concave below at a radius of twelve inches and beveled on top. The bearing box, also of cast steel, is of the same dimensions as the bottom bearing, except that it is seven inches thick. It is beveled underneath to receive the top bearing and is flat on top. On it rests the cast steel breaker block, into which the housing screw fits. The breaker blocks are protected by brasses, which are placed in sockets on the tops of the blocks.

**Hydraulic Shears:** Immediately beyond the forty inch mill delivery table, begins the No. 1 shear table, delivering to a hydraulic bloom shears. This table is thirty-one feet long, and consists of fourteen cast steel rollers, twelve inches in diameter and five feet eleven and one-quarter inches wide. These are driven by a Westinghouse 30 h. p. 220 volt series wound D. C. motor, controlled either at the bloom or the billet shears. At the end of this table is an emergency shear. It is a vertical hydraulic shear, using water at 500 pound pressure to the square inch; the plunger is forty-two inches in diameter with a nineteen inch stroke.. The bottom shear knife is the one actuated by the plunger; the knives are twenty-seven inches wide and four inches thick. As this is an emergency shear, it is rarely used.

**Steam Shears:** No. 2 shear-table is immediately beyond the hydraulic shears and has thirty-six driven rollers, and one idler, all similar to those at No. 1 shear-table, except the last two, which are collared on one end. The rollers are driven by a Westinghouse 50 h. p. 220 volt series wound D. C. motor controlled at the steam shears. This table delivers the blooms and slabs to the steam shears, the center of which is ninety-two feet ten and one-half inches beyond the hydraulic shears. A bloom stamping machine is located on this table midway between the two shears; it is of the idler wheel type and is held in place hydraulically. The steam shears are driven by a MacKintosh-Hemphill 18″ x 20″ simple vertical steam engine, the driving shaft of which is meshed with the shears by a hydraulically operated clutch. These shears are also vertical acting, the top knife blade being driven down to meet the fixed lower one. The knives are twenty-seven and one-half inches wide and three inches thick, and the top one has a ten and three-fourths inch stroke. The steam shears are equipped with a gauge and stopper for cutting a number of pieces the same length; the stopper can be set to cut lengths from twelve inches to one hundred thirty-six inches, inclusive, in quarters of an inch; the piece to be cut is run through the shears onto the rear table, which is sixteen feet long and consists of sixteen hollow cast steel rollers, ten inches in diameter. It is driven through universal joints by a Westinghouse 19 h. p. 220 volt series wound D. C. motor and can be tilted at its receiving end hydraulically to move down with the shear knife. For pieces forty inches long or less, it is moved nearer the shears to prevent the piece from falling into the pit for butt ends. Beyond this table is the loading table for blooms and slabs; it is seventeen feet long and has sixteen hollow cast steel rollers eight inches in diameter. It is driven from a line shaft by the same type of motor as the shears rear table. Halfway down this table on its inner side is a steam kicker with a seven inch by four feet nine inch cylinder, which slides the bloom down a chute to the buggies on the tracks below. A hydraulic stopper is located at the end of this table. Crop ends or scrap can be run over the end of the table to charging boxes below the end of it. Six feet six inches beyond the end of this table begins the receiving table of a fourteen inch continuous mill.

**Manipulator:** All reversing mills are provided with manipulators for turning the ingot as desired between the passes, for moving the piece from groove to groove and for straightening it as it enters the passes of the mill when such straightening is necessary. They are located under the roll table, and near the rolls on the entering side of the mill. They are of various forms. The manipulator for this mill consists of two parallel sets of five fingers each, and has both a vertical and horizontal movement. The frame is beneath the table rolls and rests on a bottom frame which is supported on four heads, connected to the arms of bell cranks. These cranks are supported on a bed plate and are connected up by stretcher rods to a hydraulic lifting cylinder, which has a stroke of fourteen and three-fourths inches. This ratio of the length of the crank arms, however, increases this lift to eighteen inches. On this frame are five rails to form a track for the wheels of the upper frame which is moved horizontally by means of a hydraulic cylinder. In the lowest position, the fingers are five inches below the top level of the roll tables; in the highest, they extend thirteen inches above it.

**Design of the Rolls:** All reversing blooming mill rolls are designed with slight collars between the passes in order to control the spreading of the material under the heavy reduction, as otherwise the material may spread so far at the surface as to cause a protrusion, or fish tailing, of the metal at the edges, which, becoming folded over, would cause laps. To prevent the collars from cutting into the steel and thus forming laps all the passes except the finishing are given a slight belly. A fillet at the base of the collars serves to keep the corners of the piece well rounded. The ragging on the rolls to increase the bite has already been referred to. As to arrangement of the passes, different plans may be pursued, as may be seen from a study of the accompanying drawings. The first two designs

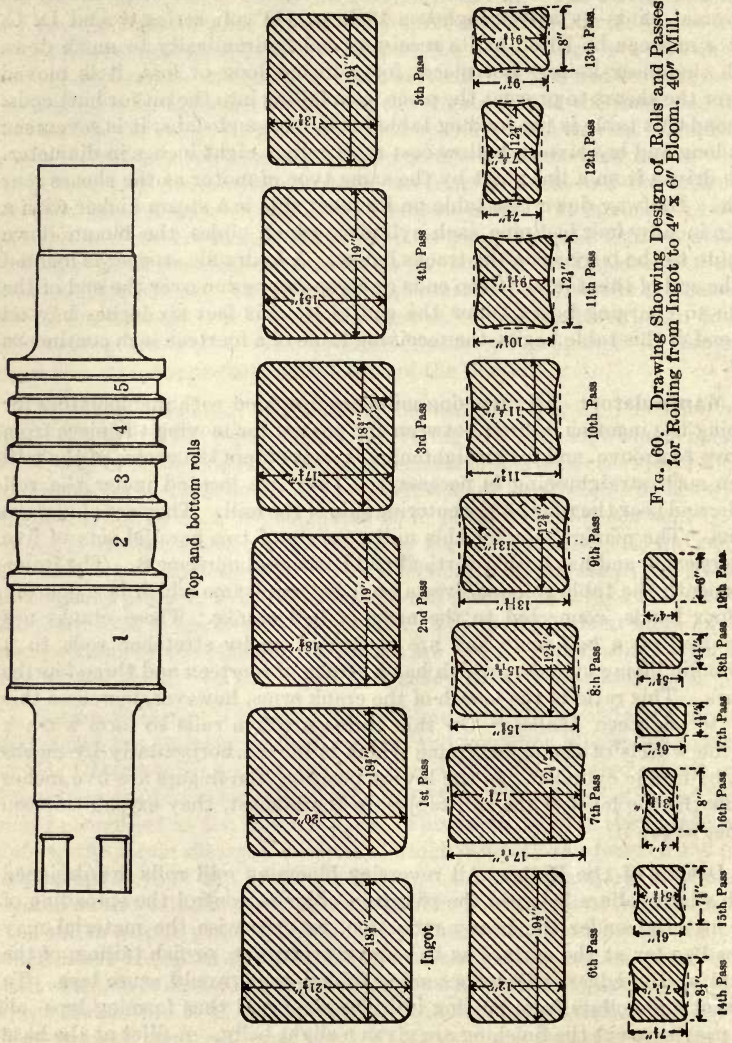


Fig. 60. Drawing Showing Design of Rolls and Passes for Rolling from Ingot to 4" x 6" Bloom. 40" Mill.

are for blooms, billets or slabs, whereas the third design can roll large blooms only and billets only in connection with a roughing mill.

In the method shown in table 53 and fig. 60 the reduction is begun with the ingot on edge, but when rolling soft steel, .08% to .22% carbon, the ingots are sometimes rolled on the flat. This reduces the number of passes to seventeen, the steel receiving only four passes in the first groove. In rolling blooms of other sizes and slabs, about the same procedure is followed out, the steel being given a sufficient number of passes to work it down to the required size. In rolling some of the special steels, such as special drop forgings, etc., it is often the practice to turn the steel after each pass in order to avoid all danger of rolling in laps and seams. Sometimes where fairly sharp corners are desired on the blooms they are given extra passes to hold the edges up. This extra rolling is especially necessary where the blooms are to be reheated in a continuous furnace, since if the corners are very rounded the blooms, instead of sliding down, are liable to roll over the skids in the bottom of the furnace. Furthermore, if the steel shows a tendency to crack, the roller may nurse it along by taking lighter drafts.

**Operation of Rolling:** The sketch referred to above shows how an 18″ x 21″ ingot is broken down to a 6″ x 4″ bloom in nineteen passes. This sketch, combined with the following table, gives about all the information there is to give on this part of the work.

**Table 53. The Rolling of an 18″ x 21″ Ingot.**

| NO. OF GROOVE | SIZE OF GROOVE ON ROLL | NO. OF PASSES AND MANIPULATION | 18″ x 21″ INGOT REDUCED TO |
|---|---|---|---|
| 1 | 24″ | 2<br>—Bloom turned 90° | 18½″ x 19″ Bloom |
| 1 | 24″ | 4<br>—Bloom turned 90° | 12″ x 19½″ “ |
| 2 | 12″ | 4<br>—Bloom turned 90° | 11¾″ x 12½″ “ |
| 2 | 12″ | 2<br>—Bloom turned 90° | 7¾″ x 12½″ “ |
| 3 | 8′ | 2<br>—Bloom turned 90° | 7½″ x 8¼″ “ |
| 3 | 8″ | 2<br>—Bloom turned 90° | 4″ x 8″ “ |
| 5 | 4″ | 1<br>—Bloom turned 90° | 6⅞″ x 4⅛″ “ |
| 4 | 6″ | 1<br>—Bloom turned 90° | 5¾″ x 4¼″ “ |
| 4 | 6″ | 1<br>—Finish | 4″ x 6″ “ |
| | | 19 Passes | |

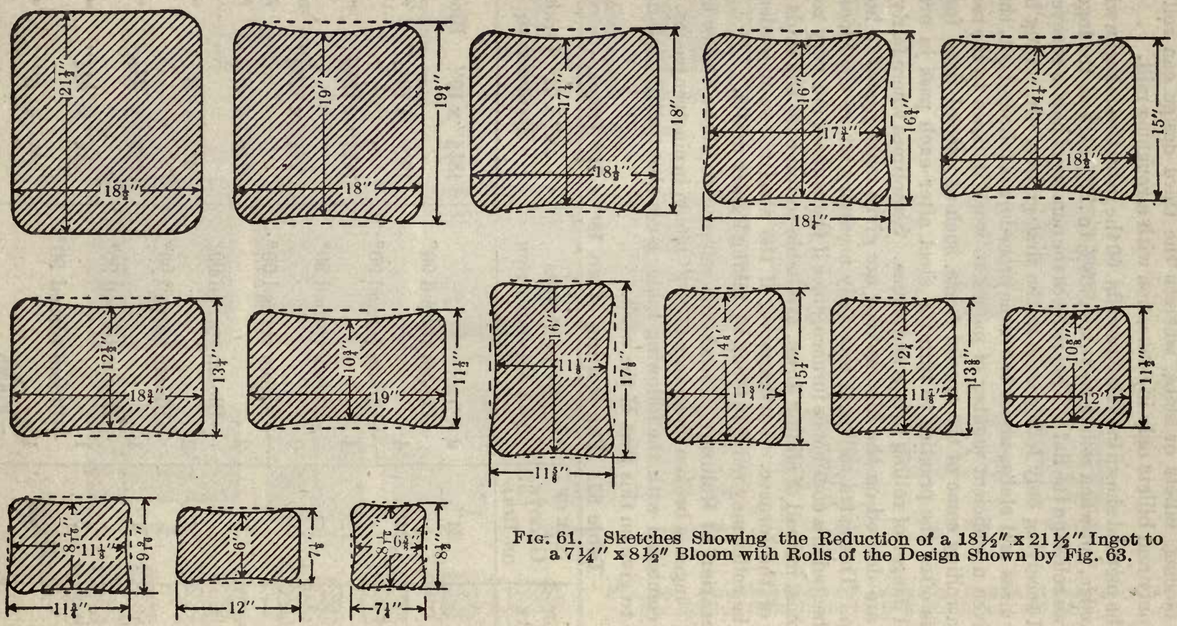


Fig. 61. Sketches Showing the Reduction of a 18½" x 21½" Ingot to a 7¼" x 8½" Bloom with Rolls of the Design Shown by Fig. 63.

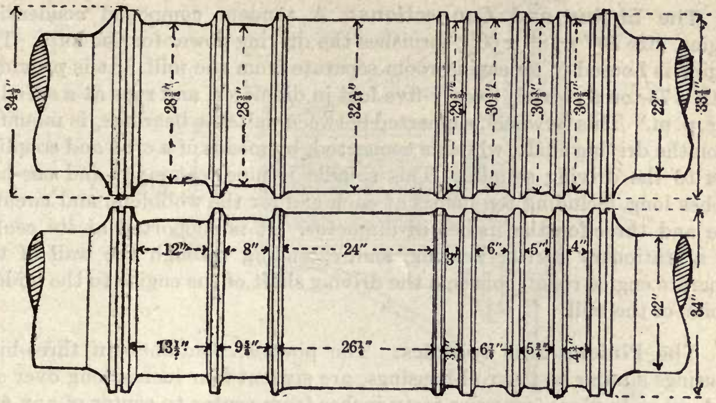
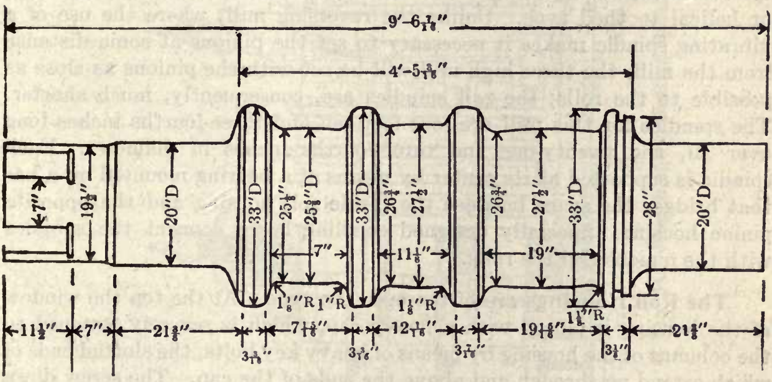


Fig. 62. Another Design for 40-inch Two-High Reversing Blooming Mill Rolls.



Top and bottom rolls have same dimensions

Fig. 63. A 38-Inch Reversing Blooming Mill Designed to Roll a Fixed Size of Bloom.

## SECTION IV.

### EXAMPLES OF THREE-HIGH BLOOMING MILLS.

**Plan of Study:** Since a good idea of the relative dimensions of the different parts of the blooming mill may be gained from the preceding detailed description of the forty inch mill at Duquesne, such details, for the sake of brevity, may now be omitted, and the description of the forty inch three-high mill at Edgar Thomson be made more general with the idea of emphasizing the difference in construction and operation between the two-high and the three-high blooming mills, only.

**The Engine and Connections:** A tandem compound condensing engine, size 50″ x 78″ x 60″, furnishes the driving power for the mill. The engine is housed in an engine room separate from the mill. It is provided with a 75-ton flywheel, twenty-five feet in diameter, and runs at a speed of 54 r. p. m. This flywheel, supported between suitable bearings, is mounted upon the driving shaft, which is connected, by means of a crab and coupling box to the driving spindle. This spindle is nine feet eight and one-half inches long, including ten inches at each end for the wobblers, and twenty-one and three-fourths inches in diameter. It is supported at its center by a stationary carrier bearing, and, extending through the wall of the separate engine room, connects the driving shaft of the engine to the middle pinion of the mill.

**The Pinions and Spindles:** The pinions, contained in three-high housings similar to the roll-housings, are six feet four inches long over all, and, when in place, measure forty inches from center to center of any two adjacent ones. The lengths of the necks are twenty-one inches and their diameters are twenty-two inches. These pinions are of the herring bone, or helical toothed type. Unlike the reversing mill, where the use of a vibrating spindle makes it necessary to set the pinions at some distance from the mill, the three-high mill will be set with the pinions as close as possible to the rolls; the roll spindles are, consequently, much shorter. The spindles for this mill are four feet ten and three-fourths inches long over all, and twenty-one and three-fourths inches in diameter. Each spindle is supported at its center by means of a bearing mounted on a bar that bridges the space between the inside roll housing and the opposite pinion housing. Specially designed coupling boxes connect the spindles with the pinions and the rolls.

**The Roll Housings** are of the open top type. At the top the window of the housing is closed with a heavy cap, which is securely fastened to the columns of the housing by means of heavy key bolts, the slotted ends of which extend up through and above the ends of the cap. The screw down passes downward through the center of the cap and rests on the top of the upper bearing of the top roll, so that the pressure may be applied directly over its center. The rigidity of the housings is increased by the use of brace rods which extend from a height about the center of the top roll, both fore and aft, to an anchorage provided by projections on the shoes. The two housings are tied together by means of separators and bolts on front and back attached just below the caps of the housings, so that they are almost on a level with the upper side of the top roll. In width the housings measure seven feet eight inches from center to center of the shoes, and are approximately fourteen feet high from the lowest point in the base to the top of the cap.

**The Rolls** are all of the same length and diameter of neck. The lengths of the bodies are seventy-six inches, while the dimensions of the necks and

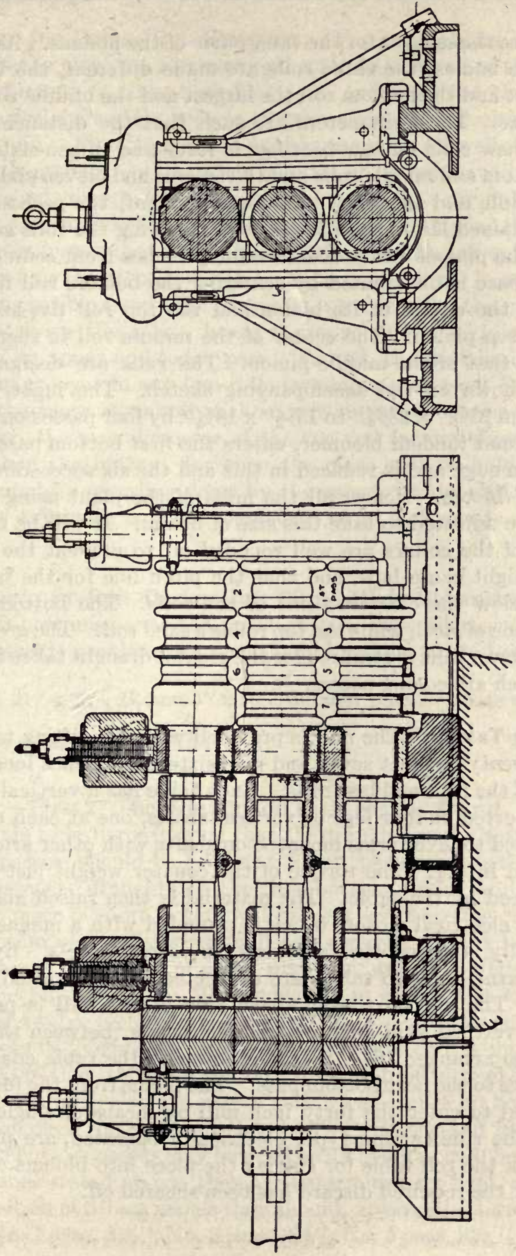


FIG. 64. Sketch of Three-High Blooming Mill.

wobblers are the same as for the same parts of the pinions. As to the diameters of the bodies, the three rolls are made different, the top roll being the smallest and the bottom roll the largest and the middle roll of an intermediate size. These diameters are such that the distance between the centers of new rolls on new bearings is forty and fifteen-sixteenths inches for the bottom and middle rolls and thirty-nine and eleven-sixteenths inches for the middle and top rolls. This arrangement, the necessity for which will be explained later, has the effect of throwing the rolls slightly out of line with the pinions which measure forty inches from centers to centers. This difference is distributed by centering the bottom roll five-sixteenths inch below the center of its pinion and the top roll five-sixteenths inch above the top pinion. The center of the middle roll is then five-eighths inch above that of the middle pinion. The rolls are designed for seven passes as shown on the accompanying sketch. The ingot, having been reduced from 23⅝″ x 23⅝″ to 15½″ x 18¼″ by four passes on a forty-eight inch two-stand tandem bloomer, enters the first bottom pass of the forty-inch mill on edge and is reduced in this and the six succeeding passes to a 9½″ x 9½″ bloom. Hence, all the mills of the plant using blooms from this mill are adjusted to take this size of bloom. It will be observed that the edges of the collars are well rounded off to prevent the formation of fins that might cause laps, and that the pitch line for the bottom passes lies well below the clearance line of the rolls. The bottom and middle rolls are made of steel, while the top roll is a sand roll. The greater strength of the two lower rolls is required for the greater draught taken in the bottom passes, which are edging passes.

**Lifting Tables:** The mill is provided with two lifting tables, each of which is twenty-one feet seven and nine-sixteenths inches long from center to center of the first and last rolls. Each table has a vertical motion only, and is supported on four legs or vertical shafts, one at each corner, which are connected to lever arms mounted on shafts with other arms for counter weights and lifting. The torque of the counter weight just about equals that produced by the table. The material is then raised and lowered by a reversing electrical motor, which is provided with a magnetic brake for automatically stopping the tables at the correct levels. By means of a long lever arm, the two tables are connected and are raised and lowered in unison. The one on the approach side of the mill is provided with stationary vertical skid bars, or transfer fingers, between the table rolls, which are so arranged that the act of lowering the table edges and transfers the piece to the next bottom pass. The bloom from the forty-eight inch mill is edged to enter the forty inch mill by means of single collar rolls. Shears of the side cutting type, electrically operated, are provided fifty-six feet from the roll table for cutting the piece into blooms of the desired length after the required discard has been sheared off.

**Roll Design for Three-High Bloomers:** The peculiarities, previously pointed out, in the size, the arrangement, and the grooves of the rolls for this mill are common to three-high bloomers, and represent the effort on the part of the designers of the rolls to overcome certain difficulties inherent in this type of mill. First, in order to avoid weakening the rolls by increasing their length unduly, only a small number of passes, usually nine, are available. Second, except at rail mills, which are the only mills in existence where any preliminary reduction of the ingots is made, this limited number of passes means that very heavy drafts must be taken in order to reduce the ingot to the more common bloom sizes. Third, in order to get in the greatest possible number of passes on a set of rolls, the passes must be placed one above the other, hence a groove in the middle roll must serve for both an upper and lower pass. Fourth, the peripheral speed at the base of the grooves in any two rolls forming a pass must be equal, or nearly so, if the piece is to roll without curling when coming out of the pass. However, the pass diameter of the top roll for any pass may be a little larger than the bottom, for then the piece will be held down but may be prevented from curling down by the guards on the mill. On forty inch mills this difference is about one-fourth of an inch and is determined by practice.

**An Example of Roll Design for Three-High Blooming Mill** will perhaps be the best answer to the question as to how all these conditions are met. A specific problem and a method of solving it are hereby given:

Given: Ingot 21″ x 23″, Bloom 9″ x 10″, number passes 9, Size of Mill 42″.

Required: To design rolls for the mill.

**Solution:—First: The draught on each pass is found.** In finding the draughts it is to be borne in mind that the draughts on the bottom passes, being edging passes, should be heavier than on the top passes; that it is well to take the heaviest draughts on the first bottom passes while the steel is hot and the piece is short, which will prevent great strains on the engine as the momentum of the fly wheel will carry across a short length; that the top passes are best made of equal draughts; and that little work can be done on the finishing pass. The reduction in size of the ingot to the bloom calls for twelve inches on one side and thirteen inches on the other, or a total of twenty-five inches. Since the reductions on the bottom passes are to be greater than those on the top, let this total draught be apportioned to give ten inches on top passes and fifteen inches on bottom ones. The draught on each top pass will then be two and one-half inches. The draught on the bottom passes may be arbitrarily apportioned, but to accord with the cautions stated above, they are determined by trial, and to give the total reduction of fifteen inches they should, apparently, be apportioned as follows: No. 1 pass, 3½″; No. 3 pass, 3¾″; No. 5 pass, 3½″; No. 7 pass, 3¼″; No. 9 pass, 1″. The complete plan for working the ingot down to size would then be as follows:

Size of the original ingot, 21″ x 23″.

No. 1 Pass, bottom, draught 3½″; size of bloom produced, 21″ x 19½″.
No. 2 " top " 2½″; " " " " 21″ x 17″.
Piece edged.
No. 3 Pass, bottom, draught 3¾″; size of bloom produced, 17¼″ x 17″.
No. 4 " top, " 2½″; " " " " 14¾″ x 17″.
Piece edged.
No. 5 Pass, bottom draught 3½″; size of bloom produced, 14¾″ x 13½″.
No. 6 " top, " 2½″; " " " " 14¾″ x 11″.
Piece edged.
No. 7 Pass, bottom, draught 3¼″; size of bloom produced, 11½″ x 11″.
No. 8 " top, " 2½″; " " " " 9″ x 11″.
Piece edged.
No. 9 Pass, bottom, draught 1″; size of bloom produced, 9″ x 10″.

**Second: The most suitable pitches for the rolls are determined.** By pitch is meant the distance from center to center of a pair of rolls without clearance, or the distance between any two of the pitch lines. These are based on the size of the mill; the average pitch for the top and bottom sets of passes are equal to its size, and should be such, for reasons already noted, that each roll will be approximately one-fourth inch less in diameter than the one above it. The pitch is, therefore, determined by trial as follows: In this case the proper figures appear to be

40⅞″ from center to center of top and middle roll.
43⅛″ " " " " " bottom and middle roll.
(84″÷2=42″=the size of the mill.)

From these figures the working diameter of the passes are found as follows:

43⅛″ pitch of bottom and middle roll.
19½″ height of first pass, (See size of bloom for No. 1 pass.)
2|23⅝″ pass diameter of first pass.

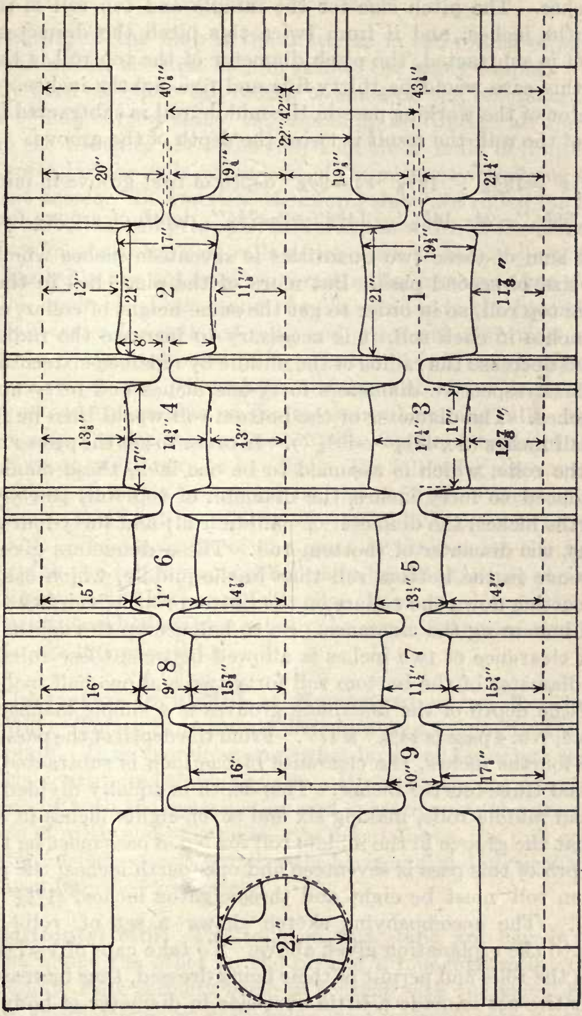
$11\frac{13}{16}''-\frac{1}{16}''=11\frac{3}{4}''$ first pass radius of bottom roll, or first pass working diameter=23½″.

$11\frac{13}{16}''+\frac{1}{16}''=11\frac{7}{8}''$ first pass radius of middle roll, or first pass working diameter=23¾″.

11⅞″+17″ (size of No. 2 pass)=28⅞″.

40⅞″ (pitch of top and middle roll)—28⅞″=12″, first pass radius of the top roll; or first pass working diameter of top roll=2″x12″=24.

As this diameter is a little larger (¼″) than that for the middle roll, the pitches assigned above are assumed to be the proper ones.



Scale 1/16″ = 1″

Fig. 65. Roll Design for 42″ Three-High Mill.

**Third: The size of each roll is determined.** As a preliminary step to finding the size of the rolls, the diameters of the middle and bottom rolls may be assumed to be the same as their pitches, forty-three and one-eighth inches. The pitch size for the middle and top roll is forty and seven-eighths inches, and if from twice this pitch the diameter of the middle roll is subtracted, the pitch diameter of the top roll is the result, which in this case would be thirty-five and five-eighths inches. If, now, the diameter of the working pass in the middle roll is subtracted from this diameter of the roll, the result is twice the depth of the groove.

$43\frac{1}{8}''-23\frac{3}{4}''=19\frac{3}{8}''$. $19\frac{3}{8}''\div 2=9\frac{11}{16}''$ depth of first groove in middle roll.

Similarly, $38\frac{5}{8}''-24=14\frac{5}{8}''$. $14\frac{5}{8}''\div 2=7\frac{5}{16}''$, depth of groove for the top roll. The sum of these two quantities is seventeen inches which checks with the size of second pass. But more of the piece lies in the middle than in the top roll, so in order to get the same height of collar, eight and one-half inches in each roll, it is necessary to increase the radius of the top roll and decrease the radius of the middle by nineteen-sixteenths inches, making their respective diameters forty-one inches and forty and three-fourths inches. The diameter of the bottom roll would then be forty-five and one-half inches ($2\times 43\frac{1}{8}''-40\frac{3}{4}''$). In order to get the proper clearance between the rolls, which is assumed to be one inch, these diameters are further reduced to forty inches, the diameter of top roll; thirty-nine and three-fourths inches, the diameter of middle roll; and forty-four and one-half inches, the diameter of bottom roll. These diameters give a much deeper groove in the bottom roll than in the middle, which can be over come by cutting down the collars on the bottom roll, which has the effect merely of increasing the clearance. So to balance up the depths of these grooves a clearance of two inches is allowed between these rolls, making the final diameter of the bottom roll forty-two and one-half inches. The finding of the depth of the remaining grooves is a simple manner. Thus, for example, No. 4 pass is $14\frac{3}{4}''\times 17''$. From the depth of the pass, fourteen and three-fourths inches, the clearance of one inch is subtracted, leaving thirteen and three-fourths inches. This depth is equally divided between the top and middle rolls, making six and seven-eights inches in each. It follows that the groove in the middle roll for No. 3 pass must be the same. As the depth of this pass is seventeen and one-fourth inches, the groove in the bottom roll must be eight and three-eighths inches, ($17\frac{1}{4}''-6\frac{7}{8}''-2''=8\frac{3}{8}''$). The accompanying sketch shows a set of rolls designed according to the explanation given above. To take care of variations due to wear in the rolls and permit of their being dressed, thus increasing their life, the entire set is made a little over-size in diameter of body, usually about three-fourth of an inch. They are discarded when they have been dressed down to the same amount undersize.

## SECTION V.

### THE ROLLING OF SLABS.

**The Rolling of the Slab** is the first step in the rolling of plates, just as the bloom marks the first step in rolling the many shapes. Attention has already been called to the rolling of slabs on the reversing blooming mill. For rolling narrow slabs, the blooming mill meets all the requirements, but the width of the slabs rolled on these mills is limited to the maximum spread of the rolls on account of the necessity of edging the piece near the last passes. In America, therefore, slabs are rolled for the most part on the universal mill principle, in which the width of the slab is partly controlled by means of vertical rolls which work on the edges of the slab. The slabbing mills are not true universal mills, however, but double or duplex mills, made up of one stand of rolls, similar to the blooming mills but with plain instead of collared rolls, and one stand of vertical rolls near to and in front of the horizontal rolls. Each mill is driven independently, and both are reversing. By such an arrangement larger ingots may be rolled than would be possible on the reversing blooming mill. Since the piece is not edged under the horizontal rolls, ingots varying in thickness and slabs of great width may be handled. The following sizes as to thickness and widths of ingots are rolled by the thirty-two inch mill to be described later, 23⅝″ x 23⅝″; 26″ x 40″, 26″ x 45″, 26″ x 48″; 26″ x 53″ and 27″ x 57″. The thickness of the ingot is limited by the maximum height to which the top horizontal roll may be lifted, while the width is controlled by the spread of the vertical rolls. In preparation for the rolling, the ingots are treated in soaking pits in the same manner as that already described for the blooming mills.

**The Thirty-two Inch Mill at Homestead as an Example of a Slabbing Mill:** This mill is an old mill and was originally designed to roll armor plate. It is, therefore, somewhat larger and stronger than some more recently constructed slabbing mills. However, the main features and the principles of both the construction and operation are the same on this mill as those of other slabbing mills. As noted above, the mill consists of two separately driven stands of rolls—the horizontal and vertical stands,—which are best described separately.

**The Horizontal Mill:** The rolls on this stand are four in number, arranged one above the other on the plan of a four-high mill. Only the two intermediate rolls actually come in contact with the ingot, however, the topmost and bottommost rolls being used as reinforcing or stiffening rolls to the two intermediate ones. All these rolls are nine feet two inches long in the body, but the re-enforcing rolls are thirty-two inches in diameter, while the intermediate ones are twenty-six inches in diameter. This arrangement permits a more rapid reduction of the ingot and with less power than would be possible with only two rolls, which would have to be of large diameters to give the great strength required. The smaller roll, exposing little surface to the steel, sinks into the metal with less pressure and is turned with less power. The four rolls are held in place by a cast steel housing. The necks of the bottom re-enforcing roll rest on bearings fitted into the bottom of the housing; this roll then supports the lower intermediate roll, the contact being made the entire length of their bodies. Lateral displacement of this lower intermediate roll is prevented by babbitted side bearing boxes at either end. The two upper rolls are held in two steel frames, one at each end, each of which is fitted with a brass top bearing for the re-enforcing roll and a box fitted with bottom and side bearings for the top intermediate roll. As these frames move up and down with the adjustment of the top rolls, guide bars bolted to the outer edges of the windows are provided to hold them in place, while liners inserted between the frames and the sides of the windows prevent the wearing away of the housings. The ends of two plunger rods rest against the bottom of this frame while the rods extend to hydraulic cylinders which, located beneath the mill and acting under a pressure of 600 lbs. per sq. in., are used for raising the top rolls. The rolls are lowered by means of screws similar to those in the blooming mill, but in this case the power for the screw down is obtained from a 60 h. p. motor mounted on a platform a little above the top of the housing. The screws rest on breaker blocks which serve as a safety to prevent the breaking of the rolls. The maximum lift of the mill is nearly forty inches. For indicating the distance between the rolls a gauge pole and disc are provided. The disc is mounted on top of one of the screws with the marking pole adjacent to it. The circumference of the disc is divided into 100 equal parts, while the pole is divided into spaces of one inch each. These divisions on pole and disc are plainly marked and permit the opening of the mill to be read to within 1-100 of an inch. **The Drive** for the horizontal mill is connected to the intermediate rolls, the re-enforcing rolls being friction driven. The motive power is furnished by a 40″ x 54″ horizontal reversing engine, which is indirectly connected to the leading or driving spindle of the mill.

**The Vertical Mill** is located about ten feet in front of the horizontal mill, measuring from center to center of the rolls. Like the horizontal mill the vertical mill has four rolls, two of which are re-enforcing; but these rolls are much smaller than the horizontal ones, being only eighteen inches in diameter and about forty-four inches in length, or a little longer than the lift of the horizontal mill. The rolls are supported vertically in the housings by means of bearing boxes at both the tops and bottoms. These boxes are held in place by heavy rest bars which extend across the mill at top and bottom and from housing to housing, between the windows of which they are securely fastened. For adjusting the spread of the rolls inwardly two screws, acting horizontally through the sides of the housings instead of through the top as for horizontal rolls, are provided. They bear on a frame that extends from the top to the bottom bearings, and are operated by a 50 h. p. motor through a system of gears. For spreading the rolls apart hydraulic jacks are used. In operating the mill, all four of the rolls are driven. Starting with the engine, the connections are made as follows: The engine, a 36″ x 57″ horizontal reversing steam engine, is mounted upon a concrete foundation a little above the level of the bottom of the housings and on the opposite side of the mill from that on which the engine for the horizontal rolls is placed. The power is indirectly transmitted through two gears, one above the other, to the driving shaft, which extends from the upper gear to the farther side of the mill. To this shaft, the two outside rolls are connected by means of bevelled crown and sleeve gears, while a second set of gears connecting the inside and outside rolls in pairs furnish the means by which the driving of the inside rolls is effected. The horizontal rolls are run at full speed, while the speed of the vertical rolls is controlled by the engineer to suit that of the horizontal mill. While the maximum spread of the vertical rolls is about sixty-five inches, the widest slabs rolled are only fifty-four inches wide, because this is the greatest width the mill shears are built to cut. The excessive length of the horizontal rolls (one hundred ten inches in the body, as previously given) is explained by the fact that this mill was formerly used for rolling armor plate.

**Precautions to be Observed in Rolling Slabs:** The essential part of the rolling is the determination of the draughts to be taken on each pass through the mill. This determination is made by the roller from the dimensions of the ingot to be rolled, the slabs desired as given on the rolling order sheets, the temperature of the ingot as it comes to the rolls and the steam pressure available for the engines. The temperature controls the draught in that the hotter the steel the less the pull on the mill and the greater is the possible draught. Uniform temperature throughout the ingot is also necessary to insure good rolling, as steel hotter on one side than the other causes curling of the slabs, due to the fact that steel always curls towards the cold side, because the elongation is less on that side. To assist in rolling, ingots are fed to the rolls with the hot side up and the small end first, thus affording a better grip by the rolls and preventing or lessening the tendency for the slab to curl up when leaving the mill as they do when the cold side is turned up. Slabs are often hotter on one side than the other, which condition also causes curling, due to the greater spreading or flowing of the steel on the hot side. Indirectly, the chemical composition of the ingot regulates the possible draught; high carbon steel, for example, cannot be heated as hot as common plate steel, hence longer time and smaller draughts must be taken in the rolling. The total vertical draught, which in all cases, except 27″ x 57″ ingots, amounts to about one inch, is taken during the first few passes. From then on, the vertical rolls are kept in contact with the steel at a pressure only sufficient to prevent tearing of the edges which results when no pressure is applied on the sides of the slab. With small ingots tearing of the steel is also caused when the ingots are not hot enough for good rolling but still capable of being passed through the rolls. In the case of large ingots that are cold, there is little danger of injuring them, because there is not sufficient power to roll them, as in the case of smaller ingots. Correct lining of the rolls is necessary to make good slabs, since if the rolls are crossed or are higher on one end than on the other the slabs curl. At the thirty-two inch mill the driving end of the rolls is always kept slightly higher than the other end to allow for the more rapid wearing of the bearings due to the extra weight on that side of the mill. Above ⅛″ the slabs will curl in passing through the mill. The maximum draught, i. e., reduction in sectional area, that can be taken by the horizontal rolls with the steel at a good rolling temperature is approximately thirty square inches on the entering pass and forty square inches on the return pass. The difference in reduction possible on the entering and return passes is due to the fact that, on the return pass, the vertical rolls aid in pulling the slab through the mill, while they cannot effect any power by pushing the slab when going in the opposite direction. For the entering pass thirty divided by the ingot width gives the approximate draught, or bite, and forty divided by the ingot width, the return pass bite. The last pass taken is entering, and is a pass in which very little pressure is used in order to straighten the plate, roll down the top ends, and remove the convex surface due to the spring from the rolls.

**Removal of Scale:** During the rolling of an ingot the scale must be removed from the surface to prevent the slab, and resulting plates, from being pitted. The process employed in removing the scale depends upon the kind of steel being rolled. For removing scale on low carbon steel salt and water, the latter being sprayed on the slab at high pressure and the former thrown on with scoops, are very effective. In case of high carbon steel the scale sticks more firmly to the slab, and burlap sacks are used, as necessary, in addition to salt and water. When nickel steel is rolled, coal is used in place of salt, and burlap is also thrown under the rolls. Brush or green twigs are often employed to serve the same purpose as burlap. The actions of all these substances are somewhat similar. In each case the substance is drawn under the rolls, which tend to bring it rapidly into close contact with the hot metal. The material thus caught by the rolls is gassified by the heat, and, in an effort to escape, the gases get beneath the scale and carry it off with them. Coal and burlap, being less volatile than salt or water, are carried a little farther beneath the rolls and give a more violent action. Nickel scale is the most difficult of all to remove, and if the first scale is melted off in the soaking pits and a second formed, it is almost impossible to clean it off. All nickel bearing slabs are cleaned first on one side, then turned over by cranes and cleaned on the other side.

**Shearing Slabs at the Thirty-two Inch Mill:** From the rolls the slabs pass by means of motor driven roll tables to a hydraulic shear. Two plungers are used to operate the knife, a small one on top for lifting the blade and a large one on the bottom for pulling the knife down against the steel, thus effecting the cutting. Two Wilson and Snyder pumps, an accumulator and steam intensifiers comprise the operating equipment. The slabs are cut to length by means of a scale of marks placed on a steel slab in front and to one side of the shears. Graduations on this marker indicate the distance from the shear-blade, so by running the slab out to any certain mark the length of slab is indicated by the graduation. The roll table approaching the shear-blade is also graduated in inches of distance from the blade. By fixing the eye on any spot or mark on the slab at any distance from the knife as shown by position on scale and watching this mark until it is moved beneath the knife, the length of slab can be obtained. The size (total weight) of the slab is determined by the dimensions and gauge of the plate into which it is to be rolled. Since the width of the ingot limits the width of the slab, planning the size of the slab starts with the selection of an ingot of the proper size. Next, the thickness of the slab must be determined, and then the length. It is evident that very careful work is necessary in making up the mill schedule, if the steel is to be rolled to best advantage. All this planning is done in the mill office, and the shearman is generally given the lengths into which the slabs are to be cut, though occasionally he may be ordered to cut to best advantage. The first cut made on the slab is to remove the piped end. After the discard is sheared off, a few slabs are cut, when the piece is turned around with a manipulator, the bottom crops taken off, and the remainder cut into slabs. From the rolling sheets, the shearman gets the length of slabs ordered and the amount of discard that is to be taken before slabs can be cut. Cuts are usually made up to the center of the slab before turning it around. By turning the slab the shearman can tell how much steel will remain after taking off the bottom crop and better decide as to how he shall cut the remainder. Slabs are cut as ordered if possible, and if a piece is left over that is too large, or heavy, for any slab ordered, it is marked as an "odd" cut. For example, a 5000 pound slab is ordered, and, after the first slabs have been cut, the remaining piece is 7000 pounds, or 2000 pounds over the weight desired. Were this 7000 pounds to be used on a slab calling for only 5000 pounds, 2000 pounds would be scrapped in the plate mill. This system is too expensive, so the slab is marked as an odd cut and placed on some other order. The limits as to width and thickness of slab that may be sheared on this shear are fifty-four inches and twenty inches, respectively. The percentage of discard varies from about 15% on plain steel to 35% on some special orders; the larger portion of the discard is taken from the top of the ingot on account of the segregation and piping being mostly confined to this section. All discarded steel is placed in open hearth charging buggies and shipped to the open hearth, note being taken of the special alloy steel scrap, which is kept separate from the plain steel scrap. As the slabs are cut, they are stamped with a serial number, beginning with one from the first of the year. A recorder takes down the slabs made, size, number, cut, etc., and enters it on the product side of the rolling order sheet. The weight of ingot, weight of slabs made, and weight of scrap is noted, and the information sent to the product department. From this data the practice of the mill is figured.

# CHAPTER VI.

## THE ROLLING OF BILLETS AND OTHER SEMI-FINISHED PRODUCTS.

### SECTION I.

### THE THREE-HIGH BILLET MILL.

**General Features of Rolling Billets:** A large percentage (over 50%) of the steel produced is rolled into material of very small section. In order to finish their product in one heat, the mills rolling such sections must start with small billets. While many blooming mills of the reversing type are able to roll billets as small as 4″ x 4″ or less, which is a size much too large for the majority of the smaller mills, the inadvisability of employing these large mills for rolling billets is at once evident, and accounts for the existence of the billet mill. In order to reduce the cost of the billet, the billet mill will be placed just after the blooming mill so as to effect the reduction from ingot to billet on the original heat of the former. As to the kinds of mills used for rolling billets, almost any mill of medium size may be adapted to the work. Since the section is a very simple one and so little in the way of accuracy as to form of section or of finish is necessary, about the only requirements of the billet mill is that it be heavy enough to handle fairly large blooms and speedy enough to reduce the piece to the desired size before it becomes too cold. For the larger sized billets, a single stand of three-high rolls placed after the bloomer serves very well, but for small billets that are not intended for certain special purposes, like forgings, for example, the continuous mill is the best mill for the purpose.

**Example of Three-high Billet Mill—The Twenty-eight Inch Mill at Duquesne:** As an example of the former type of mill the twenty-eight inch mill at Duquesne will be described, because every device is employed to increase the out-put, and it also is an example of how the mills are compelled to adapt themselves to change in conditions. This mill was originally designed as a rougher for a rail mill, but was rebuilt in 1907. The mill is fed by a thirty-eight inch two-high bloomer which reduces an 18½″ x 20½″ ingot to a 7¼″ x 8½″ bloom. The twenty-eight inch mill at Clairton placed after the forty-inch bloomer is very similar to the Duquesne twenty-eight-inch mill.

**Engine:** The mill is direct driven by a Cooper Corlise tandem compound horizontal condensing engine, 44″ x 74″ x 54″, designed to develop 2500 h. p. at 75 r. p. m. and 25% cut-off and to run at 80 r. p. m.

at 120 to 125 pounds steam pressure. The engine is capable of developing 4500 to 5000 h. p. The ordinary speed is about 62 r. p. m. and the normal load about 1200 h. p., the maximum being about 3500 i. h. p. per pass. The steam consumption is about 300 pounds per ton of steel rolled. The exhaust from the low pressure cylinder is taken to a central condensing plant near the engine house; this plant is of the Weiss barometric type and is equipped with the following apparatus: One 20″ x 42″ x 24″ air pump and two Wilson-Snyder 18″ x 30″ x 26″ x 36″ 8,000,000 gallon duplex compound-plunger water pumps. The engine is controlled in the engine house by a sixteen inch throttle valve and may be shut down quickly in an emergency by a sixteen inch quick-closing valve just above the throttle.

**Drive:** The crank shaft is connected through a flexible coupling to the spindle shaft. The cast steel coupling, five feet six inches in diameter is keyed tight to the crank shaft of the engine with a bronze half thrust collar over the half coupling; a .80% carbon steel wearing plate is screwed to the outboard bearing support of the engine and separates the collar from it. Eight two and three-fourths inch bolts hold a second half coupling to the first one. The former fits over a cast steel hub keyed to the engine end of a cast steel spindle shaft, twenty inches in diameter. The engine end of the spindle shaft is slightly curved to promote flexibility. The spindle shaft is seventeen feet eight and one-half inches long and twenty inches in diameter, and three feet seven and one-half inches from its end is the center line of a 20″ x 48″ ring oil bearing, which supports the mill end of the spindle shaft. The oil bearing is held in a cast iron yoke and base, mounted on a cast iron hot plate. The bearing is lined with babbitt and is provided with small oil grooves for lubricating. A tight crab, four feet in diameter, of cast steel is keyed to the mill end of the spindle shaft; two and one-half inch bolts hold a four foot cast steel loose crab to the tight crab. A cast steel compound coupling fits over the mill end of the loose crab and the adjacent wobbler of the leading spindle. The cast steel leading spindle is three feet ten and one-half inches long and sixteen inches in diameter. A plain cast steel coupling box joins the leading spindle to the middle of the mill, fitting over the adjacent wobblers of each.

**Pinions and Their Housings:** The pinion housings for the twenty-eight inch mill are steel castings bolted to the mill shoes; the housing windows are seven feet three inches deep from the top to the sill and twenty-six inches wide; one forged steel liner one inch thick is used on each sill, and each window is faced on each side with a one inch forged steel liner. These are all bolted to the housings. All these liners are forged steel of .40% to .50% carbon. The pinions are steel castings of the helical tooth type. They measure thirty-six inches in length of face, and have thirteen teeth with a pitch diameter of twenty-nine inches. Their diameter at the shrouds is twenty-seven inches, and the necks taper from seventeen and three-eighths to seventeen inches in diameter; the wobblers are sixteen inches in diameter. The total length of the pinions is nine feet two inches. All six pinion bearings are of the same pattern, being made of cast steel with three-fourths inch babbitt and four narrow brass plates set 90° apart. The bottom bearings rest flat on the housing sill liners, no beveling being required; the bearings are twenty-three inches wide, twenty-eight inches high, and twenty-three and one-half inches through. The cap for the pinion housings is a solid steel casting fitting over both housings; it has slots at its four corners for key bolts to hold down the pinions tightly beneath it. Steel eye bolts are set in the caps, so that they can be lifted easily. The housings are held in line also by steel separator rods on each side, top and bottom. The bottom and top pinions are driven by the middle pinion and all three are connected to their respective rolls by cast steel coupling boxes and cast steel spindles, unsupported.

**Housings and Roll Bearings:** The roll housings are cast steel, closed at the top with a cast steel cap; the housings are bolted to cast iron mill shoes. The windows of the housings are nine feet two inches deep and two feet nine inches wide. Three feet one and one-fourth inches above the sill is a ledge on which rests the bearing for the middle roll; this roll is held stationary, the others being adjusted to it. Bearings for this mill are as follows: Bottom roll: two steel carrier bearings with babbitt and brasses. Middle roll: same, and two rider bearings with similar babbitt and brasses. Top roll: two forged steel babbitted saddles for carrying the roll; two cast steel rider bearings with babbitt and brasses. The middle roll is held down on its ledge by three and three-quarter inch rods, which are in turn held down by two five inch set screws of one and three-quarter inch pitch through the caps; the rods press on the rider bearings of the middle roll. The screws are adjusted by means of wrenches which fit over nuts at the top of the screws. The carrier bearing of the bottom roll rests on a seat which is fastened to a seven-inch screw running up from below the housing through its center; this screw turns in a charcoal iron nut shrunk in the mill housing, and is regulated by a gear and pinion connection from outside the housing. The gear is moved by a vertical rod with a slotted wheel in the top; a hand lever is used to turn this wheel, and thus the bottom roll is raised or lowered. The top roll is held up by two counterweights through steelyard rods in each housing reaching up to the top roll's carrier bearing; the roll is held down at each end by a single seven-inch screw of one inch pitch reaching through the cap to the breaker block on the rider bearing. The screw is adjusted like a bolt, with a short wrench usually turned by a crane.

**Rolls:** In this mill the top and bottom rolls are similar and interchangeable, while the middle roll differs in that the barrel of the roll has larger diameters than the bottom roll in those passes in which it acts as the top roll, and smaller diameters where it acts as the bottom roll when paired with the top roll. In passes Nos. 1, 3, 5 and 7 the diameters are

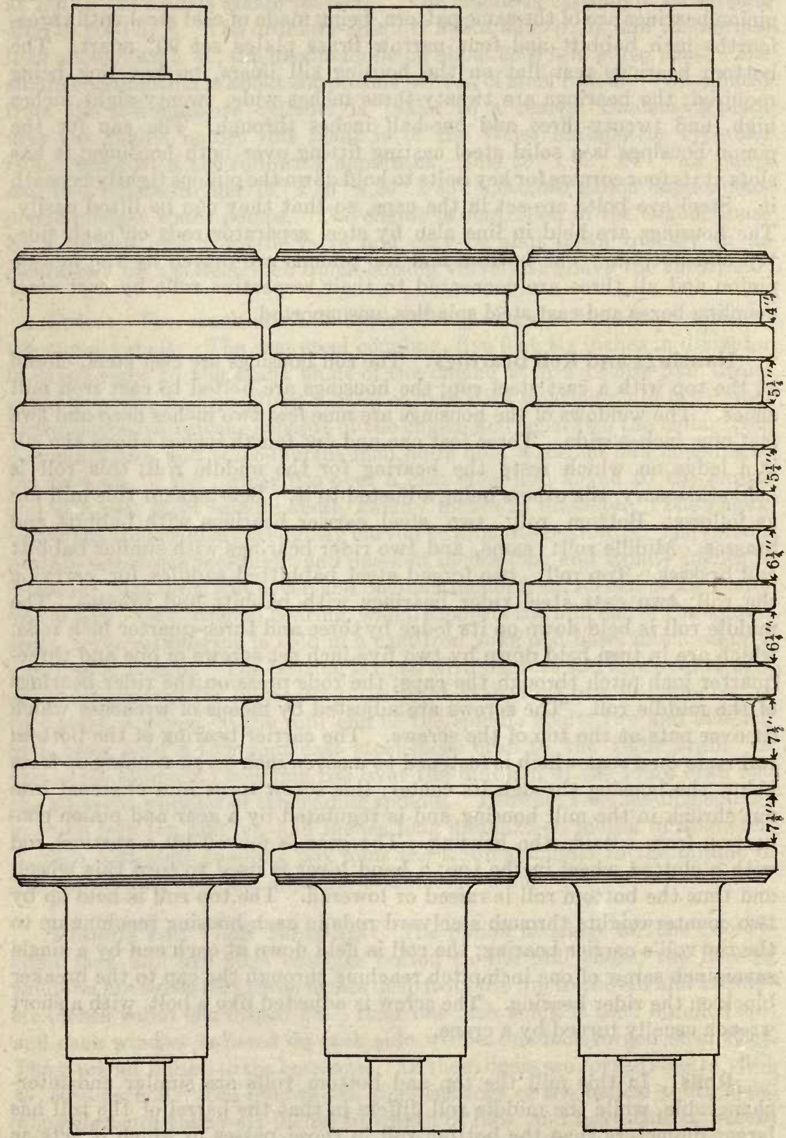


**Fig. 66.** Three-High Billet or Roughing Mill.

larger in the middle roll than in the top and bottom and in Nos. 2, 4 and 6 they are smaller. The rolls are thirty and three-eighths inches in diameter, eleven feet four inches long over all and six feet four and one-half inches long in the body; the passes are shown in the accompanying sketch. One-sixteenth inch ragging is used. The rolls are made up in sets of four,—two middle rolls, one top, and one bottom roll making up the set. The rolls are changed every two weeks, when a new middle roll is inserted and the bottom and top interchanged, as only passes Nos. 1, 3, 5 and 7 have been used in the bottom roll and passes Nos. 2, 4 and 6 in the top roll; all seven passes have, of course, been used in the middle roll. At the end of a four weeks' period, the entire set is returned to the roll shop for dressing. About five sets are kept in stock. Recently the diameter of the rolls have been increased, which permits more dressings and gives longer life. Both adamite and sand cast iron rolls are used here, as the reductions of the piece are small and no great strength is required. Adamite rolls are annealed and are very hard. The sand cast rolls are ordinary cast iron of the following composition, approximately: 1.87% total carbon, 1.22% graphitic carbon, .65% combined carbon, .37% manganese, .070% sulphur, .920% phosphorus, .70% silicon. The rolls weigh 18,000 to 19,000 pounds each. The passes are 7⅛″, 7½″, 6¼″, 6¼″, 5¼″, 5¼″ and 4″ wide. The sketch, (Fig. 66) shows the relative dimensions. When new, the rolls have a collar of thirty and three-eighths inches diameter and three-fourths inch is taken off at each dressing of the cast iron rolls and one-fourth inch for the adamite rolls; the rolls are scrapped when the collars have been turned down to a diameter of twenty-eight and one-fourth inches.

**Guide Cages:** Two inches above the center line of the bottom roll, lugs are attached to front and rear of the roll housings to support guide cages. These cages are cast steel frames for holding up the guides used on all passes of this mill. They are bolted to the housings. The front guide cage is six feet six and three-fourths inches long, reaching almost to the face of the housing, and is about five feet high. It contains closed holes in front of all passes using the bottom roll and in front of No. 6 pass of the top roll; slots are provided in front of Nos. 2 and 4 passes. The rear guide cage is practically the same as the front but has all open slots in front of the top roll passes. Cast steel guides and side guards are bolted to these guide cages.

**Tables:** The bloom from the thirty-eight inch mill comes from the shear tables to the engine side of the roll table for the twenty-eight inch mill. This table, together with the rear table, is of the lifting type and is raised and lowered as a unit with the rear table. The front table contains twelve cast steel rollers, each of which has five collars for turning the billets. The size of these collars, beginning at the engine side, are: 16″ x 2″, 14″ x 12½″, 15″ x 12½″, 16″ x 12½″, and 16″ x 1½″. This arrangement allows four grooves, 9½″, 8½″, 7¼″ and 6″ from end to end. The diameters of the rollers at these grooves are 9″, 10″, 11″ and 12″, respectively. The rollers are driven by a Crocker-Wheeler 75 h. p., 220 volt series wound D. C. Motor. There are side guards on the edges of the table and at the front end are side guards for putting the bloom from the thirty-eight inch mill into the proper pass and for protecting the other grooves. The table is thirty-four feet ten inches from center-line to center-line of the end rollers and is about six feet wide, inside. Coupled to the front of the table at the last groove is an extension table consisting of four dead rollers protected by side guards; it is fifteen feet long and fourteen inches wide and is used as an extension for the bar when ready for the seventh pass of the mill. Both front and rear tables are raised and lowered by means of fourteen and twenty-one inch plungers operated by a hydraulic cylinder; the hydraulic apparatus is located under one end of the front table and is connected to each table by bell-cranks from a main shaft attached to the cross-heads. The front table is equipped with a stationary manipulator for advancing the bars from pass to pass; it consists of four sets of three and one set of two cast steel fingers bolted to pedestals on the foundation of the mill. The fingers are set between rollers Nos. 1 and 2, 4 and 5, 7 and 8, 9 and 10, and 11 and 12, in line with the wide collars; they are flat cast steel plates mounted vertically and with their tops bent at an angle giving a 45° slope in the direction it is desired to move the piece. The fingers do not reach above the level of the pass when the table is elevated and the bars run out on the collars of the rollers; as the table sinks, the bars encounter the stationary fingers and slide down into the next groove. The rear table, as mentioned, is operated through the same shaft as the front table, but owing to the fact that it must raise the bars from the lower roll to the middle one and advance them one pass, it has to travel through an arc in rising to bring its grooves in line with the next passes. This is done by causing the table to slide toward the next pass as it is raised by the use of pull-over rods attached to pedestals on the proper side of the bottom of the scale pit; when lowered, the table slides back into place again. The table consists of twelve cast steel rollers, fourteen inches in diameter, and six feet wide, set three feet two inches apart, making a table thirty-seven feet long; the rollers are driven by a motor similar to the one used on the front table. Rollers Nos. 2, 3, 4, 5, 6, 8, 10, and 12 have 19″x 4″ collars on their ends for turning the piece, which should tumble off them as it comes from the seventh pass. In addition there is a manipulator in the first groove; this consists of five forged steel fingers two and one-fourth inches wide mounted on rocker arms attached through a shaft to a plunger in a cylinder pivoted to a support on the floor of the scale pit. The upward motion of the table draws the fingers with it and, when the plunger stops rising in the cylinder, causes them to turn the piece and advance it for the second pass. This manipulator lies below the table when material is delivered from the bottom roll and acts only to turn bars 90° from the first pass to the second. The table is equipped with three heavy cast steel side guards between the four passes which the material uses in the bottom roll. These reach back nine feet from the front to the table; there are also light side-guards at each end of the rollers reaching the length of the table. These tables make the operation of the mill practically automatic, and make it possible to roll four pieces at the same time.

## SECTION II.

### THE CONTINUOUS BILLET MILL.

**General Features of the Continuous Mill:** The continuous mill, often called a Morgan mill after the inventor, Chas. H. Morgan, consists of a series of horizontal roll stands arranged one after the other, so that the piece to be rolled enters the first stand and travels in a straight line through the mill to the last stand where it issues as a finished bar, thus making but one pass through each stand of rolls. In such a mill, where the piece is being rolled in several different stands at the same time, it is necessary that the surface speed of the different sets of rolls be so proportioned that each set will travel at a speed as much greater than the preceding one as the lengthening of the piece requires. With new rolls and perfect adjustment to produce the proper reduction, this relation of speed of the different stands is easily provided for by a system of driving gears. To care for the wearing down of the rolls, the bottom roll is made adjustable, and as a further precaution against little irregularities that can't be overcome by adjustments, each set of rolls is purposely set to run at a slightly greater speed than that required to conform to the speed of the preceding set, so as to put the piece under tension at all times. For turning the piece between passes twisting guides are employed.

**Advantages and Disadvantages of Continuous Mills:** High out-put and low labor costs are the two chief advantages of this type of mill. In addition, the mills roll the metal down very rapidly, thus giving less time for oxidation and permitting more working in one heat, and yet the speed of the roll is low, so that comparatively little power is required to run them. Besides, the scrap losses are low, due to the fact that they can roll from blooms of any length, which fact makes it unnecessary to cut the bloom after leaving the bloomer, except to discard for pipe or other flaws that occasionally occur. Finally, the rolls are so short as to be almost unbreakable, and, therefore, very light rolls may be used for comparatively heavy work with entire safety. As to the disadvantages, the great number of rolls not only makes the first cost of the mill very high but adds immensely to the cost of rolls for different sections. For the same reason, much time is required for roll changes. Hence, the mill is best adapted to roll large amounts of one section continuously. It is obvious that complicated sections or those requiring great accuracy cannot be rolled on such a mill. These characteristics of the continuous mill, however, make it particularly well suited for rolling billets, strips, such as hoop and cotton ties, and skelp. They are also employed as roughing rolls for the various combination mills.

**Example of Continuous Billet Mill:** As an example of the continuous billet mill the fourteen inch number one mill at Duquesne has been selected, because it is fed by the forty inch blooming mill, previously described. By this combination the ingot is rolled down to a bloom approximately 6″ x 4″ in the forty inch mill from which it is delivered on roll tables, after the proper discard at the shears, to the continuous mill, where, without reheating, the bloom is reduced to billets ranging in size from three and one-quarter inches to one and three-eighth inches square. The mill consists of ten stands of rolls, and is set in line with the bloomer. The distance from the blooming mill shears to the first stand of rolls is eighty-four feet eight inches.

**Drive:** This mill is driven by gears from a line shaft from an Allis Chalmers horizontal vertical compound condensing Corliss valve steam engine, size 44″ x 78″ x 60″, with an indicated horse power of 3500. This engine is opposite the shears and is set so its driving shaft extends in a direction parallel to the mill line. The engine is designed to run at a speed of 75 r. p. m. at a steam pressure of 130 lbs. The maximum torque the engine is designed to give at the roll circumference is 450,000 inch pounds. The exhaust of this engine is taken to a central condensing plant. The line shaft is coupled to the crank-shaft of the engine as follows: A cast steel hub is forced on and held by keys to the end of the crank-shaft. A phosphor-bronze thrust collar is bolted in halves over this joint. The outer end of the hub, three feet ten inches in diameter, is bolted to a short steel hub having wobblers twenty inches in diameter on its other end. A cast iron coupling six feet ten inches long fits over this wobbler and that of a similar but longer hub at its outer end. This hub is two feet seven inches long, of cast steel, and its large end, three feet ten inches in diameter is bolted to a short hub, twenty-one inches wide, which is keyed onto the seventeen inch end of the line shaft. The line shaft of forged steel, is made in two pieces, nine to thirteen inches diameter, and is seventy-two feet six and three-fourths inches long. At ten points on the line shaft, beginning at the engine end of the shaft are mitre gears respectively 4′ 6″, 4′ 0″, 3′ 4½″, 3′ 11¼″, 5′ 2½″, 5′ 5″, 7′ 0″, 5′ 5¾″ and 7′ 11″ apart; these mesh with mitre gears keyed on cross over shafts that lead to their respective roll stands. These gears are supported by bearing stands along the line shaft. The crossover shafts drive the mill pinions, and give to each set of rolls, beginning after No. 1 stand, a higher speed than that of the one preceding, in order to take care of the increased length of the bar. The mill ends of the crossover shafts are carried in bearings supported on pedestals; the ends of the crossover shafts have cast iron half couplings keyed to them, and these are bolted to other half couplings which are connected to the leading spindles by coupling boxes twelve and one-half inches long and twelve inches in diameter. All spindles, pinions and coupling boxes on the mill are cast steel. The pods on the spindles extend along their entire length. The spindles, top and bottom, are all of the same dimensions: two feet long, nine inches neck diameter, and nine and one-half inches body diameter. The leading spindles are cast hollow so that they will break under excessive strain before any other part of the mill, and are connected by plain coupling boxes, each twelve and one-half inches long and twelve inches in diameter, to the top pinions of the roll stands.

**Pinions and Housings:** The pinions are of the staggered tooth type with three pods. They are four feet eight inches in total length, fourteen and three-fourths inches wide across the face of the teeth, nine inches in diameter at the wobblers, nine and one-half inches in diameter at the necks, and fourteen and one-fourth inches in pitch diameter of the teeth, of which there are fourteen. The pinion housings are cast iron, in one piece, and are bolted to the pinion shoes, which run the length of the mill; each pair is bolted together at the top as caps are not necessary. The windows are cast to shape to receive the pinion bearing boxes, which are bolted to them. The pinion bearing boxes are solid cast steel boxes, round in shape and with lugs on the outer ends for bolting to the housings. They are babbitted one-half inch deep; their dimensions are thirteen inches wide in the windows and eleven and three-fourths inches long. The pinions are joined to the rolls by solid spindles and coupling boxes already described.

**Rolls and Housings:** The roll housings are charcoal cast iron about four and one-half feet high, bolted to the cast mill shoes; the mill shoes run at right angles to the rolls through the length of the ten stands. The housings have charcoal cast iron caps, one fitting over each. The caps are notched at the four corners to receive the bolts to hold them fast to the housings, and in the center of each side is bored a five inch hole for the phosphor-bronze housing nuts, in which turn the housing screws; the housing screws are of tool steel, twenty-four inches long, with one and one-half threads per inch. Each housing has a window three feet seven and three-fourths inches deep and thirteen inches wide, with a beveled sill at the bottom and a ledge, twenty-one and one-quarter inches above the sill, for resting the carrier bearing for the top roll. Each pair of housings is held in line at the top by means of cast iron separators. The necessary holes for set-pins and stud-bolts are drilled into the housings. The liners used are the ordinary steel plates of varying thicknesses.

**Adjustment of the Rolls:** The method of adjusting rolls in mills of this type is nearly always that of lining the bottom roll up or down to the top roll. A cast steel screw box, therefore, is placed on the sill of each housing and bolted to the housing; it is 16¾″ x 10″ and is threaded with nine half inch grooves, babbitted to prevent excessive wear. In each of these is placed a special screw bolt, left-hand thread for the outside housing and right-hand thread for the inside housing. These bolts have short square ends on the outer ends but longer squares on the inner ends; the latter may be coupled together by a cast iron coupling. Above the screw bolts and resting on them and the screw boxes are placed cast steel wedges fourteen inches long and eight inches wide, with nine half inch grooves, babbitted. The threads are, of course, the same as for the screw boxes. On the wedges are rested the bottom bearings; these are steel castings. On the bottom they are provided with a wedge which fits against the screw wedge. The bearings have one inch of babbitt metal lining and two bronze bearing pieces. No top bearing is necessary for the bottom roll, as there is no upward pressure on it and it has no other piece to support, as the carrier bearing for the top roll rests on the ledge mentioned in the preceding paragraph. The breaker blocks are cast iron, the bottom ends of the set screws resting directly on them. These screws are squared off above the threads for adjustment by wrenches, and are provided with lock nuts.

**Arrangement of Roll Stands and Guides:** Owing to the fact that the speed of travel of the bar and hence the speed of the rolls is greater in each successive pass, the housings are placed closer and closer together as the bar is reduced to avoid danger of buckling. In order from No. 1 stand, the center lines of the rolls are at the following intervals: 10′ 0″, 9′ 0″, 8′ 0″, 7′ 0″, 6′ 6″, 6′ 0″, 5′ 6″, 5′ 6″, 5′ 6″. For the purpose of obtaining work on all sides of the bar and as the most convenient method of rolling, the bar is twisted between every other pair of rolls, and for this reason special guides have to be used. They are of cast steel made up especially for these stands, so that they will give the bar just the proper twist or keep it headed right to enter the next pair of the rolls. These guides are set usually in cast steel guide boxes bolted to rest bars that are fastened in ledges in the housings; where necessary, saddle bars are used to hold down the guides and guide boxes. All guides are wedged tightly in place with either steel or wooden wedges. The following is the arrangement of the guides on this mill: No. 1 receiving guide is a combination straight guide and crop shear bumper; all the rest of the receiving guides are straight; but the delivery guides are alternated thus: No. 1, straight; No. 2, twisting; No. 3, twisting; No. 4, straight; No. 5, twisting; No. 6, straight; No. 7, twisting; No. 8, straight; No. 9, twisting; No. 10, straight. Where the stands are far apart or the section is light, the bar is supported from below by narrow plates reaching from one delivery guide to the next receiving guide or else by light steel side guards.

**The Rolls:** The rolls for this mill are of the following dimensions: Total length, four feet six inches; length of barrel, sixteen inches; diameter of wobbler (3-pod), nine inches; diameter neck, ten inches; weight, 1500 to 1600 pounds.

### Table 54. Data Pertaining to Rolls for a 14″ Continuous Billet Mill.

| Stand | Composition | No. Grooves | Body Diameter Before Turning | |
|---|---|---|---|---|
| | | | Top | Bottom |
| 1 | Steel | 1 | 13 5/8″ | 13 5/16″ |
| 2 | " | 1 | 13 3/4″ | 13 7/16″ |
| 3 | " | 2 | 13 5/8″ | 13 5/16″ |
| 4 | Adamite | 2 | 13 1/2″ | 13 3/16″ |
| 5 | " | 2 | 14 1/4″ | 13 3/4″ |
| 6 | " | 2 | 14 1/4″ | 13 7/8″ |
| 7 | Chill Iron | 4 | 13 5/8″ | 13 5/16″ |
| 8 | " | 4 | 13 3/4″ | 13 7/16″ |
| 9 | " | 4 | 14 3/8″ | 14″ |
| 10 | " | 4 | 14 3/8″ | 14 1/16″ |

Six inches is allowed between the centers of the grooves when only two grooves are cut, but only three and three-fourths inches is allowed in the case of four-groove rolls. Following is a table of the speed of the rolls of each successive stand and the observed delivery speed of the bar coming out of it with the engine at normal speed of 75 r. p. m.

### Table 55. Speed Ratios on Fourteen Inch Continuous Billet Mill.

| Stand | Speed of Rolls—Revolutions Per Minute | Delivery Speed of Bar Feet Per Minute |
|---|---|---|
| 1 | 17 | 46.7 |
| 2 | 21.4 | 54.5 |
| 3 | 24.55 | 67.1 |
| 4 | 30.9 | 99.2 |
| 5 | 36.6 | 126.3 |
| 6 | 44.6 | 156. |
| 7 | 57.6 | 188. |
| 8 | 68.7 | 242. |
| 9 | 89.1 | 326. |
| 10 | 117.9 | 417. |

**Cropping Shears:** Between the receiving table to the mill and the first stand of rolls are hydraulic shears, pressure 450 lbs. per square inch; through these shears all blooms for the fourteen inch No. 1 mill pass. They are capable of cutting blooms up to 7″x11″ in size, but their usual work is on 6″ x 4″ blooms. They are used to cut crops from the front end of the bloom so it will enter No. 1 stand easily. When necessary they may be used for shearing off pipes and bad pieces that have escaped discard at the

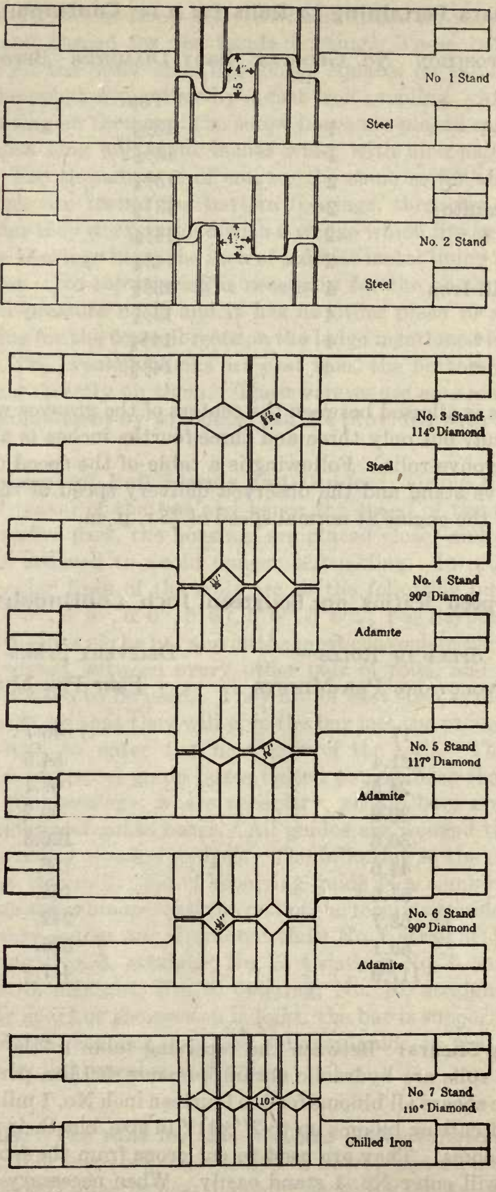
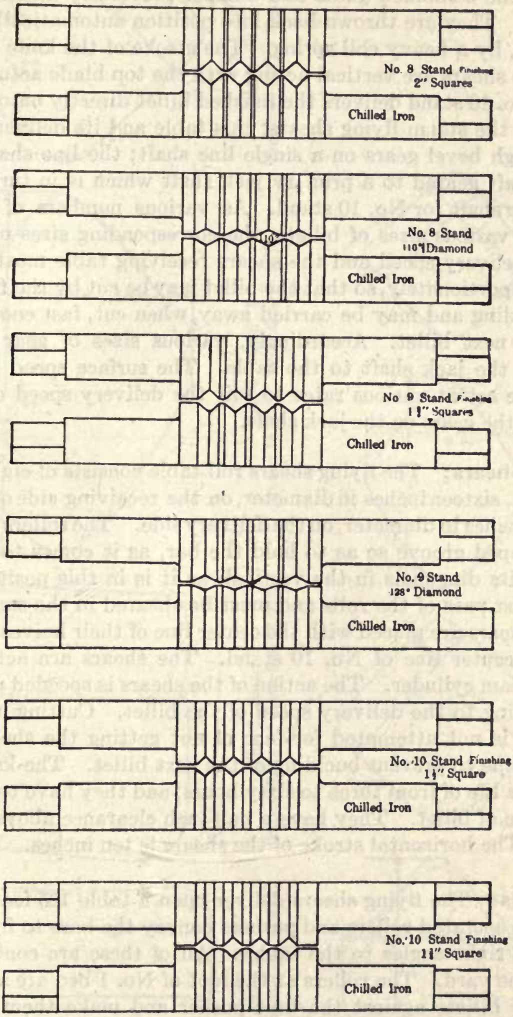


FIG. 67. Rolls and Passes for



**the Continuous Billet Mill.**

blooming mill shears, and for severing the bloom in case of a cobble. They are capable of a ten inch swing from the base, and at the end of their stroke they strike the combined guide and bumper previously mentioned as the No. 1 guide. They are thrown back into position automatically, when the bloom is cut, by a heavy coil spring. The stroke of the knife blade is ten inches. The shears are vertical acting with the top blade actuated by the cylinder. No. 10 stand delivers the finished billet directly onto the receiving table for the steam flying shears; this table and its delivery table are driven through bevel gears on a single line shaft; the line shaft is driven by a jack shaft geared to a primary jack shaft which is in turn geared to the crossover shaft for No. 10 stand. As various numbers of stands are used for the various sizes of billets, the corresponding sizes of bars have a different delivery speed and the shears receiving table must, therefore, be driven proportionately, so that the billet may be cut by the flying shears without buckling and may be carried away, when cut, fast enough to keep clear of the next billet. Accordingly, various sizes of gear wheels are provided for the jack shaft to the table. The surface speed of the roll table may be set at various rates to suit the delivery speed of the billet by changing the gears on the jack shaft.

**Flying Shears:** The flying shears roll-table consists of eight cast steel rollers,—two, sixteen inches in diameter, on the receiving side of the shears and six, ten inches in diameter, on the delivery side. The rollers are notched with a V-shaped groove so as to hold the bar, as it comes to the shears, with one of its diagonals in the vertical, as it is in this position when it leaves the last pass of the rolls and must be sheared in the same position. The flying shears are placed with the center line of their knives twenty feet beyond the center line of No. 10 stand. The shears are actuated by a 30″ x 20″ steam cylinder. The action of the shears is speeded up or slowed down according to the delivery speed of the billet. Cutting under fifteen foot lengths is not attempted for fear of not getting the shears back to position in time to prevent buckling of the next billet. The knives on the shears have a life of from three to sixty hours; and they have to be changed for every size of billet. They have a half inch clearance above the square being cut. The horizontal stroke of the shears is ten inches.

**Hot Beds:** The flying shears deliver upon a table 125 feet long, from which steam operated rollers and pushers convey the bars to four hot beds extending at right angles to the tables. All of these are controlled from a pulpit in the yard. The rollers at the foot of No. 1 bed are skewed so as to bring the billets against the first pusher and make them lie parallel with it; all the other rollers are, as usual, set at right angles to the pieces. At four points on the table are hydraulically operated stoppers for stopping the bars at the hot bed desired or allowing them to pass to the horizontal scrap bed beyond the last hot bed. The hot beds are sloped up at a slight angle and are each thirty-one feet wide by fifty-three feet six inches

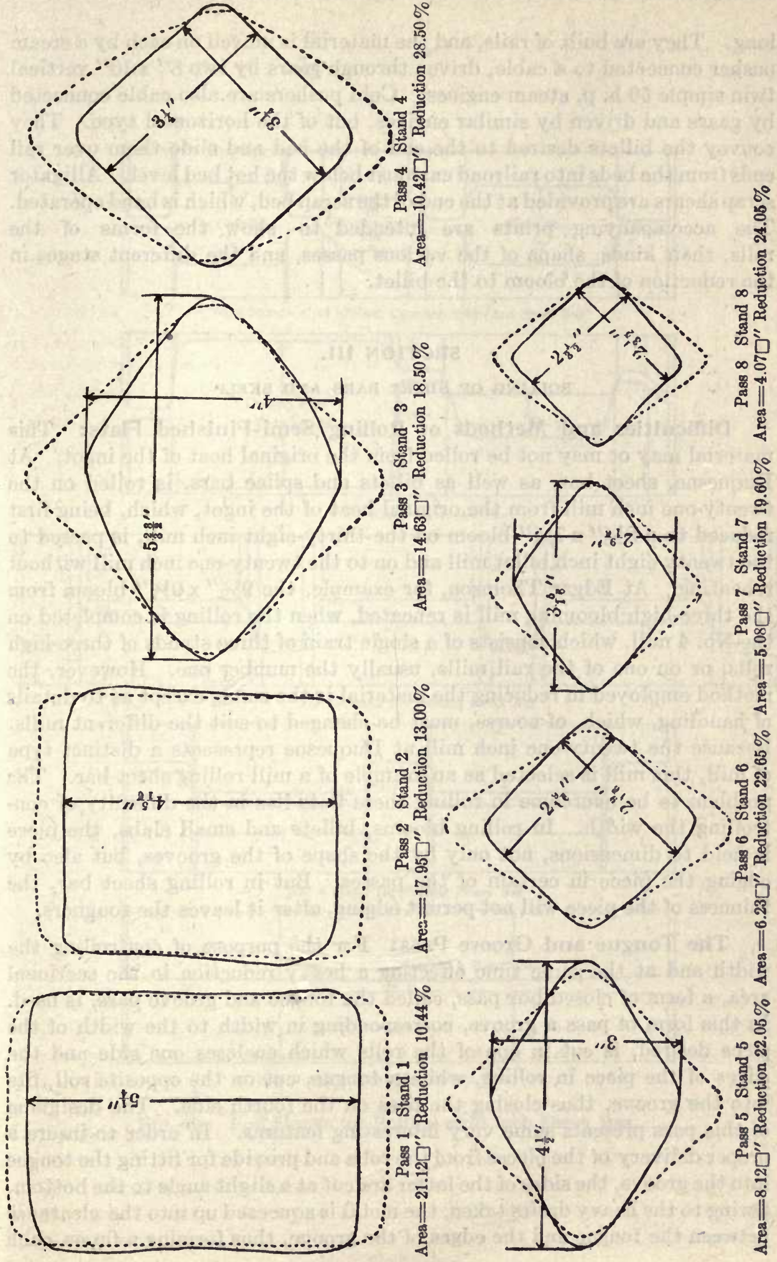


Fig. 68. 14″ Continuous Mill—4″ x 6″ Blooms to 2″ Billets.
Drawings from Actual Sections.

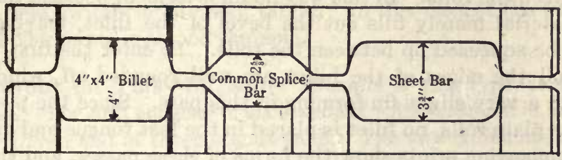
long. They are built of rails, and the material is moved on each by a steam pusher connected to a cable, driven through gears by two 8″ x 10″ vertical twin simple 50 h. p. steam engines. Cold pushers are also cable connected by gears and driven by similar engines, but of the horizontal type. They convey the billets desired to the end of the bed and slide them over rail ends from the beds into railroad cars just below the hot bed level. Alligator scrap shears are provided at the end of the scrap bed, which is hand operated. The accompanying prints are intended to show the forms of the rolls, their kinds, shape of the various passes, and the different stages in the reduction of the bloom to the billet.

## SECTION III.

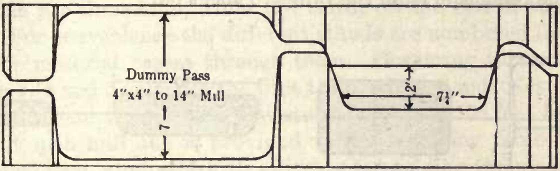
### ROLLING OF SHEET BARS AND SKELP

**Difficulties and Methods of Rolling Semi-Finished Flats:** This material may or may not be rolled from the original heat of the ingot. At Duquesne, sheet bar, as well as billets and splice bars, is rolled on the twenty-one inch mill from the original heat of the ingot, which, being first reduced to a 8½″ x 7¼″ bloom on the thirty-eight inch mill, is passed to the twenty-eight inch billet mill and on to the twenty-one inch mill without reheating. At Edgar Thomson, for example, the 9½″ x 9½″ bloom from the three-high blooming mill is reheated, when the rolling is completed on the No. 4 mill, which consists of a single train of three stands of three-high rolls, or on one of the rail mills, usually the number one. However, the method employed in reducing the material is the same, except as to details of handling, which, of course, must be changed to suit the different mills. Because the twenty-one inch mill at Duquesne represents a distinct type of mill, this mill is selected as an example of a mill rolling sheet bar. The problem to be overcome in rolling these flats lies in the difficulty of controlling the width. In rolling blooms, billets and small slabs, the piece is held to dimensions, not only by the shape of the grooves, but also by edging the piece in certain of the passes. But in rolling sheet bar, the thinness of the piece will not permit edging, after it leaves the roughers.

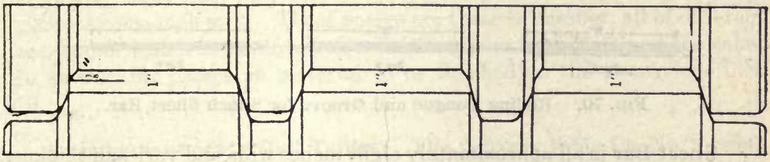
**The Tongue and Groove Pass:** For the purpose of controlling the width and at the same time effecting a heavy reduction in the sectional area, a form of closed box pass, called the tongue and groove pass, is used. In this form of pass a groove, corresponding in width to the width of the piece desired, is cut in one of the rolls which encloses one side and the edges of the piece in rolling, while a tongue, cut on the opposite roll, fits into the groove, thus closing the pass on the fourth side. The designing of this pass presents some very interesting features. In order to insure a proper delivery of the pieces from the rolls and provide for fitting the tongue into the groove, the sides of the latter are cut at a slight angle to the bottom. Owing to the heavy drafts taken, the metal is squeezed up into the clearance between the tongue and the edges of the groove, thus forming a fin on each



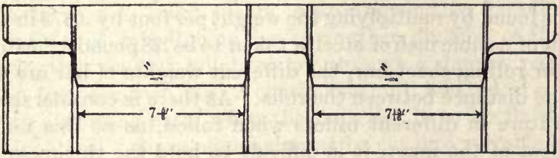
No. 1 Stand—4"x4" Billet, Common Splice and Sheet Bar



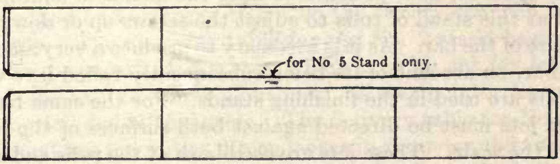
No. 2 Stand for Sheet Bar



No 3 Stand for Rolling Sheet Bar



No. 4 Stand for Rolling Sheet Bar



Nos. 5 and 6 Stands for Rolling Sheet Bar

Fig. 69. **Roll Stands for Rolling eight inch Sheet Bar.**

side of the piece, unless precautions are taken to prevent it. These fins are prevented from forming by cutting the groove with fillets at the edges, and arranging them so that the bevelled edges of the piece formed by the fillets enter the succeeding pass opposite the openings formed by the clearance between the rolls. In this way no fin is formed, because the spreading of the material merely fills out the bevel of the fillet, leaving no excess metal to be squeezed up between the rolls. To enter the first tongue and groove roll the edges of the billet are well rounded off, which prevents more than a very slight fin forming in this pass. Since the piece is to be finished in plain rolls, no fillet is placed in the last tongue and groove pass. The accompanying prints show the forms of these passes, and the different steps in the reduction from the billet to sheet bar.

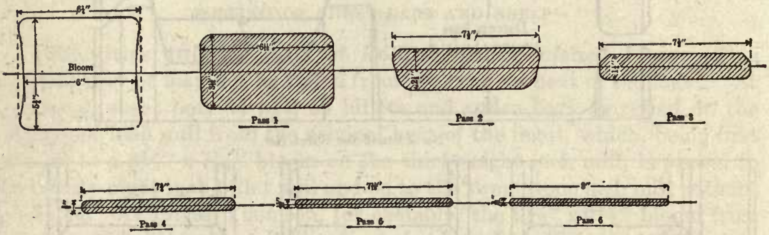


FIG. 70. Rolling Tongue and Groove for 8 inch Sheet Bar.

**Sheet Bar** is all approximately eight inches wide and varies in thickness to give weights, per linear foot, from seven to forty-three pounds. The gauge in inches is found by multiplying the weight per foot by .0372 in which factor the weight of a cubic inch of steel is taken to be .28 pounds. After the mill is once set for rolling sheet bar, the different weights of bar are obtained by varying the distance between the rolls. As there is considerable difference in temperature in different billets when rolled, as at this mill, from the original heat of the ingot, it is difficult to hold the thickness constant at the finishing stand, and, in order to keep the thickness uniform, a man is stationed at this stand of rolls to adjust the screws up or down to suit the temperature of the bar. As it is necessary to produce a very smooth surface on sheet bar, on account of its being subsequently rolled into thin sheets, chilled rolls are used in the finishing stands. For the same reason, water and steam jets must be directed against both surfaces of the bar in order to remove the scale. These jets are used both at the rolls and at the saws.

**Example of a Mill Rolling Sheet Bar—The Twenty-one Inch Mill at Duquesne:** As previously stated, this mill represents a distinct type. The design aims to secure the advantages of the continuous mill and eliminate the disadvantages. So, while it is practically continuous in action the different stands of rolls are placed so far apart that the piece clears one stand before it enters the next. As a tandem arrangement alone would spread the mill out over a too great length, the various stands of rolls are usually arranged in trains that are in tandem. Such a layout requires long roll tables for carrying the piece forward and suitable apparatuses for transferring the piece transversely, such as lifting cradles, skids, diagonal roll tables, and switch, or divided, tables. In this respect the twenty-one inch mill at Duquesne is a good example.

**The Layout for This Mill,** as for all mills of this type, is somewhat complicated. The mill consists of six stands of rolls arranged in two trains, separately driven and of three stands each. The two trains are separated by a distance of 119 feet. In each train the first and second stands next to the engine are three-high, while the third, on the end of the train, is two-high. For convenience the different stands are numbered in the order in which the material passes through them. Observing this order, then, stands Nos. 1, 4 and 5 compose the first train, while stands Nos. 2, 3 and 6 make up the second train. The first stand is located 105 feet beyond the twenty-eight inch mill and is provided with a receiving table fifty-three feet six inches long, equipped with switches for guiding the material from the twenty-eight inch mill into the different passes in the first stand of the twenty-one inch mill. These passes are three in number, all of different sizes, one of which is employed as a finishing pass for billets and the other two as working passes on material to be finished on the twenty-one inch mill.

**Arrangement of the Roll Tables:** The delivery table for No. 1 stand is provided with a center guard for diverting material to the billet table that leads to the 4″ x 4″ billet shears, located beyond No. 2 stand. Further along, by means of a switching device another division of the material may be made, thus sending billets either through a dummy pass in No. 2 stand to the fourteen inch No. 2 continuous mill, located about 100 feet beyond, or to a working pass, when the material is to be finished at the twenty-one inch mill. Since material must be cut into suitable lengths for rolling on the twenty-one inch mill, a hydraulic shear is located 77 feet from No. 1 stand and arranged to cut on the twenty-one inch mill-half of the table only. The receiving table for the No. 2 stand begins at these shears. It is provided with a stop which may be set for lengths from twelve and one-half to thirty-eight feet. A manipulator for turning the piece is also provided in this table. The delivery table for No. 2 stand is 65 feet long and has ten rollers fifteen inches in diameter and twenty inches long; these rollers are separated by a side-guard from the rollers leading to the fourteen inch mill No. 2. In connection with this table is a transfer skid table for moving the piece to the receiving table for No. 3 stand. It consists essentially of a frame of rails bolted together and hinged to the table, onto which they are to deliver the steel. The frame, when in its lowest position, lies below the roller tables, so that when the transfer is raised, it picks up the steel, which slides down the rail skids onto the table.

The skids are greased so that the steel will slide more easily. The frame is raised and lowered by means of links keyed to a line shaft which is in turn operated by a hydraulic cylinder. The transfer raises the bars twenty inches from the top of the delivery table No. 2 to the top of the rollers of the receiving table of No. 3 stand, the distance between the two tables being eight feet three inches. As No. 3 stand is often used as a three-high stand this table is of the tilting type, and operated by an hydraulic cylinder placed near the stand. The delivery table of No. 3 stand is 109 feet long and serves also as a receiving table for No. 4 stand. It is stationary and, in order to receive the material when No. 3 stand is operated two-high as well as three-high, it is inclined, extending from the top of the bottom roll of No. 3 stand to the top of the middle roll in No. 4 stand. Collars on its rolls serve to turn the piece between the stands, and its side guards are adjustable so that they may be used to guide the piece into different passes on No. 4 stand. The delivery table for No. 4 stand is 79 feet long, and has guards on the side next to the engine only, in order that the piece may be transferred by means of a skid table to the receiving table for No. 5 stand. This transfer table is similar to that between No. 2 and No. 3 stands except that the piece here slides to a lower level, where it is stopped by the guards on the receiving table for No. 5 stand. Connecting No. 5 and No. 6 stands is a stationary table provided with adjustable side guards and vertical rollers for edging the piece as required.

**Hot Saws and Shears:** The delivery table of the last, or No. 6, stand is about 104 feet long, and at its farther end are located two electrically driven hot saws set thirty feet six inches apart. These saws, made of .80% carbon steel, are forty-two inches in diameter and one-fourth inch thick. This table feeds into a shear table, one hundred three feet nine inches long, along which are situated seven electrically operated shears. These shears are adjusted to cut at any lengths up to ninety-seven feet six inches, which is the maximum distance between the first and last shears. They may be made to cut in unison or separately, as desired. From the shear table the piece may take a straight course to the sheet bar shears and bundling cradle, or be diverted to the hot beds which are used for billets and splice bars. Returning now to the billets from No. 1 stand, it was mentioned that 4″ x 4″ billets could be diverted to a shear. This shear, of the duplex type, is located several feet beyond No. 2 stand and is provided with a bisected table of which each part leads to one of the two blades of the shears. A gauge and automatic stopper, mounted on a gauge beam about two feet above the delivery tables for the shears, can be set at one-quarter inch intervals for any lengths from twenty-three and one-half inches to twenty feet. From these shears, an elevated inclined roller conveyor carries the short billets to eight bins, each of which has a capacity of 30 tons and is located so as to empty directly into railroad cars by gravity.

**Drive:** Each train is direct driven by a William Tod Co. 34″ x 58″ x 60″ tandem compound horizontal condensing engine of 3500 h. p. The usual speed of these engines is 67 r. p. m. but they can be run as high as 82 r. p. m. Both trains are direct driven through a pinion shaft from the crank-shaft of the engine. The connections between engine and mill and between the stands of rolls are made in a manner exactly similar for both trains, so that one description will suffice for both. To the end of the engine crank shaft is keyed a half coupling of cast steel, and over it is bolted a thrust collar. A second half coupling is bolted to the one next the engine. A compound coupling box—two feet two and one-half inches in diameter on the engine end and nineteen and one-half inches on the mill end and nineteen and one-half inches long for No. 1 train of rolls, and a similar box but two feet two and one-half inches in diameter on the engine end and twenty-three and one-half inches in diameter on the mill end and nineteen and one-half inches long for No. 2 train of rolls—fits over the wobbler of the second half-coupling and the mill end wobbler of the leading spindle. The leading spindle for No. 1 train is three feet four and three-fourths inches long, and twelve inches in diameter, and has three pods on the engine and four on the mill end. For No. 2 train the leading spindle is four feet one and one-half inches long, sixteen inches in diameter on the engine end, where it has three pods, and twelve inches in diameter on the mill end, which has four pods; this spindle has twelve and one-half inches near the center turned smooth to a fifteen inch diameter for a rider bearing. A coupling box of cast steel, fifteen inches long and seventeen and one-half inches in diameter, connects the leading spindle to the center pinion of the three in the pinion housings.

**Pinions and Housings:** These pinions are plain steel castings, six feet three inches long, with a pitch diameter of twenty-one inches, a neck diameter of thirteen inches, a wobbler diameter of twelve inches, and a width of twenty-four inches across the face of the teeth. There are eleven teeth, of six inches pitch, cut in the helical manner. There are three pinions, set one above the other in their proper bearings in cast steel pinion housings. These housings stand about five feet eight inches above the mill floor and are bolted to the mill shoes; their windows are twenty-two and one-half inches wide and five feet eight inches deep, beveled at the bottom, and are provided with forged steel side liners, five feet four and seven-sixteenths inches long and two and three-fourths inches thick, and cast steel bottom liners, 35″ x 12″ x 2″. The housings are drilled for the necessary holes for set pins, stud bolts, cap bolts, etc. One steel cast pinion housing cap covers the housings; at its four corners are drilled four inch holes for the cap bolts which are three feet five inches long, and are held in by a nut at the bottom and a key at the top. In the middle are fastened two hooked lifting bolts, for enabling the crane to get hold when the caps are to be removed. The bearings are all of the solid type, of cast steel, and babbitted. Coupling boxes, similar to the one connecting the leading spindle to the middle pinion, connect the three pinions to their respective spindles. The spindles are steel castings with wobblers of four pods each, extending from end to end;

they are three feet six inches long and twelve inches in diameter. They are supported on the mill end by another set of similar coupling boxes which connect them to the rolls.

**Rolls and Roll Housings:** The rolls on this mill are twenty-six inches long on the body for all stands except No. 3 which is thirty-six inches, because, being a three-high stand, it contains a greater number of passes than the two-high stands. The collars are usually twenty-two and one-half inches in diameter; the body diameters range from fifteen to twenty-seven inches; the diameter of the necks is thirteen inches, and of the wobblers twelve inches. The total length is six feet ten inches for the rolls on No. 3 stand and six feet for the rest. The rolls range in weight from 3800 pounds to 7000 pounds. The rolls are cut down each time they are dressed one-eighth to three-eighths of an inch until a collar diameter of nineteen inches is reached, when they are scrapped. The rolls are of the following materials for the various products rolled:

No. 1 Stand—Usually sand roll; rarely steel.

No. 2 Stand—Sand Roll for billets and common splice bars; steel in majority of cases for Duquesne and continuous rail joint; always steel for sheet bar.

No. 3 Stand—Sand Roll for billets and common splice bar; sometimes the top roll for common splice bar is steel. Steel always for sheet bar and nearly always for Duquesne and continuous rail joint; otherwise cast iron.

No. 4 Stand—Sand Rolls always for everything.

Nos. 5 and 6 Stands—Always sand rolls except for sheet bar; sheet bar requires chilled iron rolls.

About three sets of billet rolls, about three sets of cast iron rolls for sheet bar and five sets of chilled rolls, two sets of common splice bar rolls for No. 6 stand and one set of other rolls are carried on hand. For rail joints rolls are turned up as needed, and all splice bar rolls are ordered new when specifications for a new section come in. The roll housings for the twenty-one inch mill are similar for stands Nos. 1, 2, 3, and 4, which can be used as three-high, and for Nos. 5 and 6 which are only two-high. In No. 1 train, the rolls in No. 1 stand are connected by spindle and coupling boxes to those in No. 4 stand and the bottom two of No. 4 are connected to No. 5 rolls. No. 2 train is similarly connected; the top roll of Nos. 1 and 2 stands is a dummy acting as a spindle and the bottom rolls in Nos. 1 and 4 stands act the same way. The spindles, except those between No. 3 and No. 4 stands, are two feet nine inches long and twelve inches in diameter; the latter are three feet six inches long and twelve inches in diameter. The coupling boxes are all fifteen inches long and seventeen and one-half inches in diameter. The roll housings are cast iron, held in line, top and bottom, by cast iron separators. For Nos. 1, 2, 3, and 4 stands the housings stand five feet eight and one-half inches above the mill shoes and have twenty-two and one-half inch windows; those for Nos. 5 and 6 stands rise three feet eleven and three-fourths inches above the shoes and have twenty-two and one-half inch windows. From each housing there are two cast iron caps, held down by square key bolts, fitting through five inch square holes in the caps. In the center of each cap is cast a hole for receiving a phosphor bronze housing-nut, which is pressed into the cap and threaded for receiving the housing screw. This screw, which is made of open hearth steel of .36% to .40% carbon, is five and three-eighths inches in diameter at the base and is threaded at a one inch pitch. On all stands but No. 6, a cast steel rosette is fastened on top of the housing screws to provide means for turning them. They thus hold the top rolls tightly down. On No. 6 stand a cast steel disc is used instead of a rosette, and a long lever is attached to it, which in turn is held in place by means of bolts through slots in the outer edge of the disc. The bottom bearings for Nos. 1, 2, and 3 stands, as well as all the riders and the carrier bearings are of cast steel. Brass bearing pieces are used in some, but not in all, of the housings. The preceding prints show how the mill may be used for rolling billets as well as sheet bar. The rolling of rail joints, to be described later, is gradually being discontinued on this mill, the intention being to transfer this business to Edgar Thomson Works.

## SECTION IV.

### SOME GENERAL PRECAUTIONS TO BE OBSERVED IN ROLLING SEMI-FINISHED PRODUCTS.

**Reasons for Studying Defects:** A great many of the precautions necessary to observe in rolling the semi-finished products have been mentioned at various times in preceding pages. However, as failure to observe the proper precautions in rolling gives rise to defects in the material which may show up in the finished article and as the reader may be particularly interested in this phase of the business, it is thought that a list of rolling defects and their causes may be found useful and interesting. By giving the cause for each, it will be shown that many defects are unavoidable, and that even the most rigid inspection will not suffice to eliminate some defects which are a common annoyance to the manufacturer and consumer alike.

**Rough Surface Due to Scale:** One of the defects common to semi-finished material and one that often shows up in the finished article is a very rough or pitted surface. That this roughness most often is due to the adherence of scale on the surface of the ingot during the rolling there can be little doubt, because a careful examination of such defects will generally reveal its presence in these pits. At first thought this defect is likely to be attributed to a rolling of the scale into the surface, and the remedy at once suggested is to clean the ingot of scale during rolling. But failure to remove the scale from the ingot will not always account for this roughness. In such cases the blame for the defect is to be laid to the presence of blow holes near the surface, which in the heating of the ingot in the soaking pit become filled with molten oxides. The presence of the oxide may be attributed to two causes, namely, to the oxidation of the surface of the blow holes or to its introduction through small openings which lead from the blow holes to the surface of the ingot. Thus, if the ingot is subject to a temperature sufficiently high to fuse the oxides, the oxide in the hole will melt, or the liquid oxide on the surface will flow through these openings to the blow holes beneath and partially or completely fill these small cavities. This oxide cannot be removed, and when the ingot is rolled, it becomes so firmly embedded in the surface that even subsequent pickling will not remove it. The only correction remaining for such defects, then, is the very expensive one of chipping or grinding. Low carbon chrome-nickel steel is very susceptible to this fault, and it is very difficult to clean the scale from its surface. While this peculiarity of nickel steel may be attributed to the same cause as that just cited for plain steels, there is much evidence to show that scale pitting in this case is partly due to an entirely different cause, namely, the reduction of the oxide of nickel by metallic iron at the rolling temperature of this steel. Thus, as fast as this alloying element is oxidized on the surface, its oxide is reduced by the free iron beneath, the result being the formation of iron oxide under the surface of the metal. This condition gives rise to an outer layer composed of metallic alloy mingled with oxide, in which the oxide acts as a binder between metal and surface scale. It can readily be seen that this layer may vary in thickness, and the merging from all metal to all oxide is gradual, resulting in what may be termed an interpenetration of metal and oxides, which causes the scale to adhere most firmly to the surface.

**Cobbling:** The most frequent failure in rolling is cobbling. It occurs at the bloomers as a turn down or twisting of the piece in the rolls, at the rougher in the same way or by catching and buckling on the roll table, and at the other mills as a roll table or mill accident. The piece may catch on a table and buckle up and be prevented from coming through the rolls; it may catch against a guide and buckle; or it may buckle against the rolls, if delivered to them too fast. In such cases, practically all of the piece has to be scrapped; the uninjured sections of partially cobbled blooms can usually be finished and be made use of.

**Laps:** An over filling of a pass causes the steel to spread between the collars of the rolls and causes a lap; this is usually rolled down into the surface, partially or altogether, if the steel is turned for the next pass, and the place between the lap and the rest of the piece is left as a surface crack, or seam. A lap may result from a crack in the rolls into which the steel flows.

**Collar Marks:** Owing to overdraft or possibly defective heating, or, in the blooming mill, to too infrequent turning of the piece, the steel will overfill the groove, causing collar marks. Lack of alignment or proper adjustment of the rolls or any other incident that gives an unequal draught will cause the collars to bite into the bloom and injure it. Collaring leaves deep cuts that can seldom be rolled out, hence the injured portion of the bloom is discarded at the shears.

**Guide Marks:** Guides, if they are too deep, out of line, or required to do too heavy duty will score the surface of the steel, usually, in fine lines, or else may tear its edges.

**Ragging Marks:** Ragging leaves protrusions on the surface of the steel, and sometimes these are lapped over, showing in the finished steel in irregular seams and cracks. On mills rolling steel that is to be rolled to small section or a fine finish, only light ragging is used.

**Off Size:** If a bloom, slab, or billet is off size, it makes the weight of the predetermined cut different from the actual cut and will prevent an order from being accurately filled, or may even cause a deficit of steel to apply on the order. On mills of the class in question it is difficult to work to absolutely correct sizes, hence, a tolerance for weight as well as for size should be given.

**Unequal Draughts:** These defects are due to the rolls being out of parallel with each other, causing one side to be rolled light and the other heavy. This condition may result also in a turning down of a lap in the next pass in the case of a bloom, or a cobble in the case of a billet.

**Seams:** Seams may be caused by blow holes, by laps, or by tearing of the steel due to causes which will be explained in a succeeding paragraph. Slivers or scale, first rolled into the surface, and then torn out, may leave cracks that will roll down to form seams. Seams may also be caused by too much belly in the roll, or by not turning the piece often enough during the rolling of the bloom, as illustrated in Fig. 71. Seams are especially injurious in steels for forgings and for heat treatment. They seldom fail to cause the steel to crack in quenching, particularly if the steel is quenched in water.

**Slivers:** Slivers are due to defective teeming of the molten steel and to a tearing of the corners of the steel in blooming, roughing, or finishing. Tearing is attributed to many things, such as over oxidation in the open hearth, burning, twisting in the rolls, and improperly adjusted guides. Soft steels and high sulphur screw stock are especially subject to these defects.

**Scabs:** Scabs are found on steel if it is burned or if scale is rolled into it.

**Shearing Defects:** Failure to discard properly at the shears may result in rejection of product. Aside from this neglect, other defects may be produced by the shearing. Thus, a dull shear knife or one with too great clearance will not make a clean cut and will leave a lip on the side of the steel where its stroke ends. An unavoidable effect of shearing is to produce what may be termed a mechanical or manufactured pipe. In the shearing of billets and slabs, especially in the case of 4″ x 4″ billets and larger, it frequently occurs that the sheared end shows a pulled-out con-

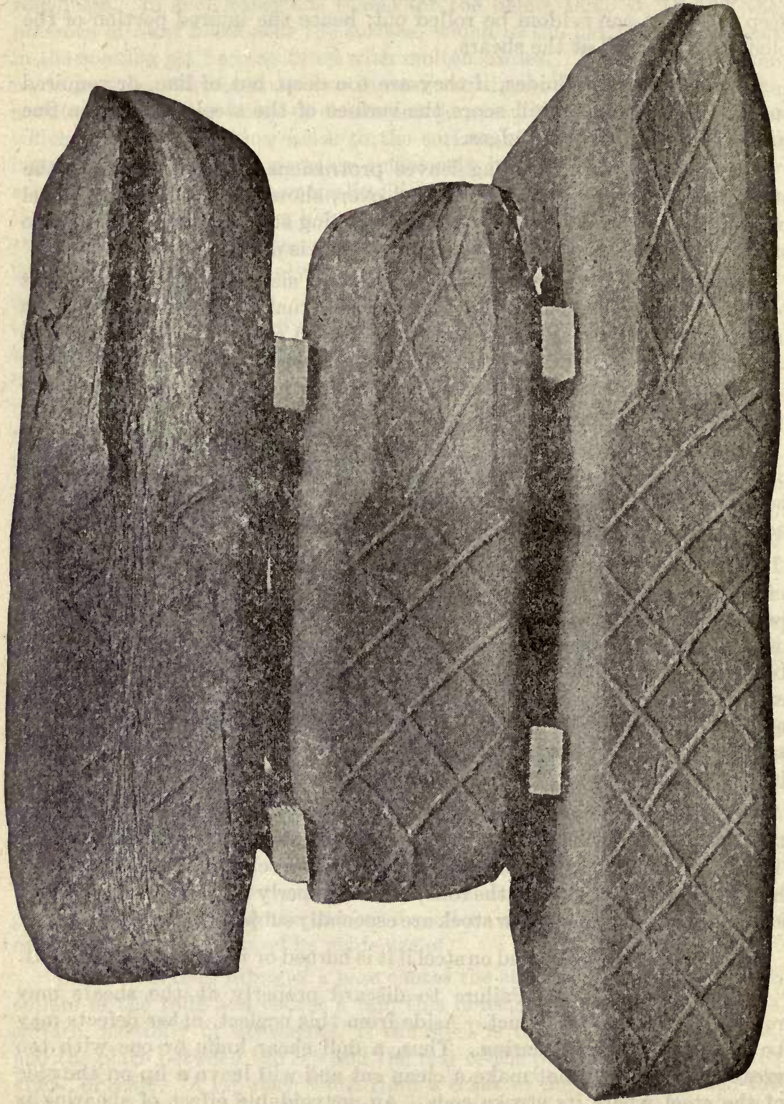


FIG. 71. Good and Bad Practice in Rolling Blooms.
Top bloom shows effect of not turning the bloom often enough.

dition. There are a number of things responsible for this condition on the sheared ends. Thus, highly segregated steel will not shear uniformly and often results in a pulled-out condition, and the same thing is almost sure to happen in case the billet or bloom has a spongy center. The temperature at which the billets are sheared plays a very important part, also. These pulled-out cavities on the sheared end may have a depth of more than one inch. It is readily seen what happens when such billets are reheated and rolled into small sizes. The pull-out is closed up and elongated with the rolling, and when rolled into a small rod or any other smaller shape the effect of this pull-out condition may extend far back into the finished material. Very often this manufactured pipe is mistaken for a genuine metallurgical pipe, since in most cases it is centrally located. The injurious effect of a manufactured pipe on the physical properties of steel is similar to that of a metallurgical pipe.

**Splits or Cracks in Billets and Blooms:** In breaking down ingots it often happens that the metal does not yield properly to the draught, and the surface structure is cracked or torn at a number of places, and sometimes to a depth of two or three inches. As the rolling is continued, these torn surfaces are gradually closed, but not perfectly welded, and become much elongated, so that it is not easy to detect them in the finished article, not only because they are completely closed but because of the new scale, which, forming after the rolling is finished, totally covers up all signs of their presence. This feature makes their occurrence all the more serious, because, though their dangerous character is recognized by the manufacturer, and every attempt is made to eliminate them, the inability to detect them often leads to their passing the inspection. These cracks are attributed to many causes. In the first place, certain grades of steel, more particularly those in which the carbon content lies between .18% and .22%, are more susceptible to this defect than others. The sulphur and manganese content also appears to affect the tendency of ingots to crack. Hence, many steel men are inclined to lay most of the blame to chemical composition, while others hold that the fault lies in improper treatment in manufacture. It is a fact that steel not properly made may be red short, and that the steel can be injured through too heavy draught and too much reduction without turning, or poorly designed passes in rolling cannot be denied. It also appears that the heating of the ingot in the pits may exert an important influence upon the rolling properties of the steel.

**Inspection:** Blooms, billets, and slabs are inspected on the mill yard, and when defects are not very deep, they are chipped out with chipping hammers, if so ordered, before the steel is shipped. All inspection is directed to the elimination of the defects listed above, and rejection is according to the strictness of the order in respect to this requirement. Billets and sheet bars are hot bed inspected, and in addition to inspection for surface defects sheet bar is also tested for exactness of weight.

## CHAPTER VII.

## THE ROLLING OF THE HEAVIER FINISHED PRODUCTS—PLATES.

### SECTION I.

### PREPARATION OF THE STEEL FOR ROLLING FINISHED PRODUCTS.

**Reheating:** While a few finished steel articles, such as plates, large rails and heavy shapes, which on account of their large mass retain their heat for a considerable length of time, may be rolled by rapid methods directly from the ingot without reheating, the majority of articles are so small that their temperature would fall far below the rolling range before the great amount of reduction required could be accomplished. For all such articles a reheating of the bloom, billet, or slab is a necessary step preliminary to rolling. Needless to say, this reheating of the steel is a matter of great importance and requires even more care than the heating of ingots. Compared with hot ingots the nature of heating is very different, for here all the heat is conducted toward the center from the surfaces exposed to it; and since in practice it is well nigh impossible to expose all surfaces equally to the heating medium, uneven heating is likely to occur, the result of which is a variation in the dimensions of the finished section. Here, too, as with ingots, the danger of burning or overheating is ever present. As the temperatures attained are far above the critical range, the reheating tends to undo the refining of the previous rolling. Since the extent of this obliteration of the original structure is about in proportion to the temperature above the critical attained it is desirable to keep the reheating temperature as low as possible, and to finish the rolling as near the critical range as practicable. However, some finished materials are so light that the highest temperatures attainable without injury to the steel is barely sufficient to complete the rolling, and in addition the wear-and-tear on the mills incident to rolling at the lower temperatures increases so rapidly as to add very much to the expense of rolling. Again, the surface of the metal is oxidized very rapidly in a flame or a hot atmosphere even slightly oxidizing, and this oxidation results in the formation of an insulating coat of scale that retards the heating. This scale may cause trouble in other ways, also, because, at the temperature which it is often necessary to maintain in the furnace in order to heat the steel to the proper temperature for rolling, it becomes pasty or quite fluid, and blooms or billets in contact in the furnace are often cemented together by it. Besides, the surface of the piece, being covered with this pasty scale, is liable to cause pieces of brick, sand, or other foreign substances to adhere to it, and these, being rolled into the steel, produce serious surface defects in the finished material, some of which are known as scabs, brick spots, pitted surfaces, etc. The loss of metal due to the formation of scale will sometimes amount to as much as 5% and is seldom under 2%.

**Types of Reheating Furnaces:** Reheating furnaces cannot as yet be said to have reached a standard in design and construction. They are, therefore, of various forms and types, and each furnace is constructed along lines which were thought to be the best suited to the local conditions at the time of its erection. Most of these furnaces are, however, of the reverberatory type, and may be fired with either coal or gas for fuel, though the gaseous fuels are much preferred for this purpose on account of the ease with which the temperature may be regulated. In order to conserve the heat as much as possible, they may be provided with waste heat boilers or be constructed on the regenerative or recuperative principles. New mills, however, the majority of which are being electrically driven, cannot employ the waste heat boilers. The more modern furnaces are, then, built either on the regenerative or the recuperative principle, in both of which gaseous or liquid fuels or pulverized coal are used.

**The Regenerative Reheating Furnace** is similar in working principle to an open hearth steel furnace. Gas and air ports at each end of the furnace are connected by flues that lead to checker chambers, made of the proper refractory materials for retaining the heat from waste gases and giving up the same to ingoing air, or air and gas if producer gas is used, the current being reversed at certain intervals of time. Unlike the open hearth furnace, however, the checker work for these furnaces is usually placed under the furnace, and, instead of the basin-like hearth, the reheating furnace is provided with a floor practically on a level with the door sills. A low bridge wall, which separates this floor from the up-and-down takes, forms a kind of combustion chamber and prevents the flame from impinging directly upon the steel. Above this combustion chamber the roof of the furnace slopes downward toward the middle of the furnace and reverberates the heat of the flame upon the floor. The steel is charged through lifting doors in one side of the furnace, and it may be drawn either through these same doors or through doors in the opposite side. Originally, it was the general practice to line the bottom of these furnaces with refractory siliceous sand, hence they are often called sand bottom furnaces. As the scale in melting unites with this sand to form a slag of a too high per cent. of silica to be used economically, these furnaces are now made up of magnesite or cinder, which, melted into place, makes it possible to use the resulting cinder in the open-hearth or blast furnace. These furnaces are used mainly

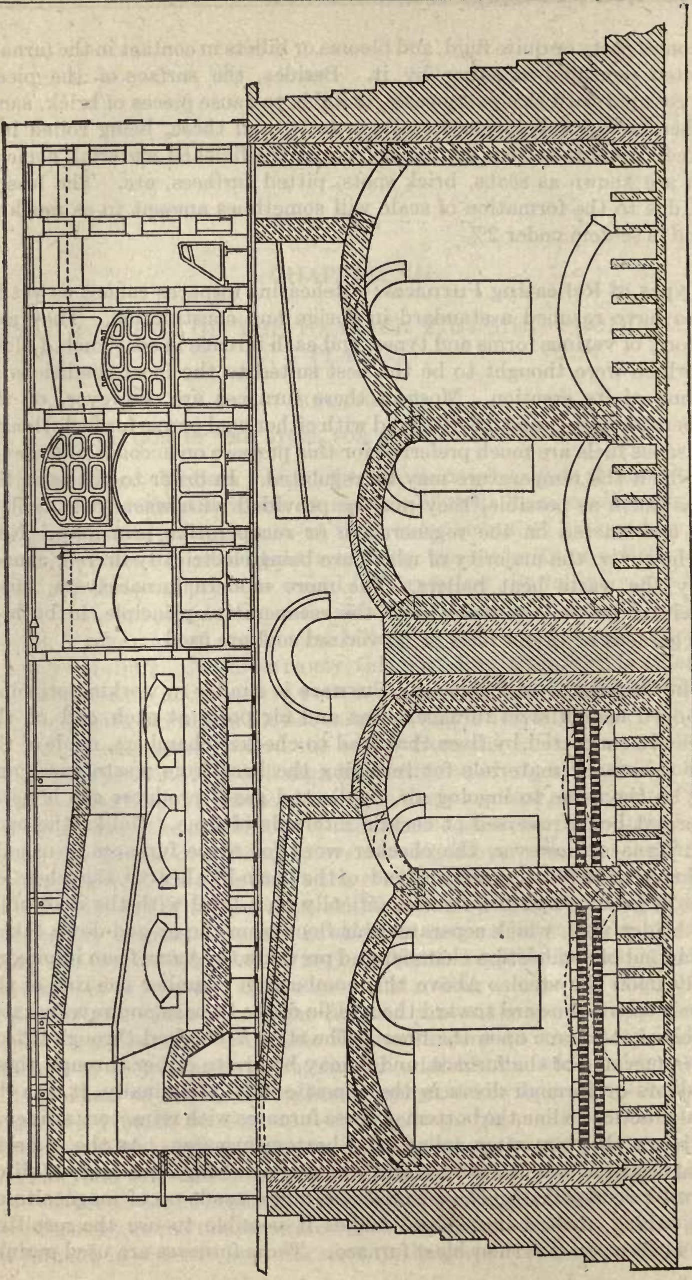


FIG. 72. Regenerative Reheating Furnace.

for reheating heavy material, such as blooms, slabs, and the larger billets, for which purpose they are very well adapted.

**The Recuperative or "Continuous" Furnace** works upon the principle of counter-currents throughout. The combustion chamber is located at one end of the furnace, where the heated steel is drawn, while the chamber for recovery of the waste heat is located at the opposite end, which is always nearest the stack and where the steel is charged. In one current, the hot gases and flame from the combustion chamber are drawn by the chimney draft over the floor, which is separated from the combustion chamber by a bridge wall, and then downward through a series of spaced iron pipes to the stack flue. In the other current the course of the steel and the air for combustion run counter-current to the heat, the steel over the floor of the furnace, the air through the enclosed space about the hot pipes and a flue under the floor to the combustion chamber. The passage of all may, therefore, be made continuous, hence the name, continuous furnace. It will be observed that the billets move from the coldest part of the furnace to the hottest part, hence they are heated very gradually, reaching the rolling temperature just prior to drawing. The scale, therefore, does not melt, and no slag is formed in the continuous furnace if it is fired with gas, oil or tar. When powdered coal is used for fuel, the silicious ash unites with the scale to form an easily fused slag that collects at the discharge end of the furnace. In order to push the billets through the furnace suitable pushing devices must be provided, and to aid in this work the floor of the furnace is sometimes inclined, sloping downward from the charging to the drawing end. To prevent the tearing up of the floor, skids for supporting the billets are provided, built into the bottom. These skids are generally made of heavy pipe through which a stream of water flows to keep them cool. An objectionable feature in the use of the skids is that they cause cold spots in the steel where the billets rest upon them. To overcome this defect the pipes are bent or off-set at the lower ends, or the billets may be delivered from the skids to a section of the bottom lined with magnesite. In this way the temperature of the cold spots is restored to near that of the rest of the billet.

**The Advantages of Continuous Reheating Furnaces** are numerous. In the first place, they are the best type of furnace to precede a continuous mill. The use of complicated charging and drawing machines is avoided. The heating, being confined to one end of the furnace, makes it easy to regulate the temperature to suit the different grades of steel, and to heat to the rolling temperature only those billets that are to be used at once. Where the billets used are of constant length, the width of the furnace is so proportioned to the length of billet that the entire bottom is covered with the steel to be heated. Thus, there are no vacant areas on the bottom to decrease the heating efficiency of the furnace. The accompanying prints are intended to show the chief features in the modern construction of these two types of furnaces.

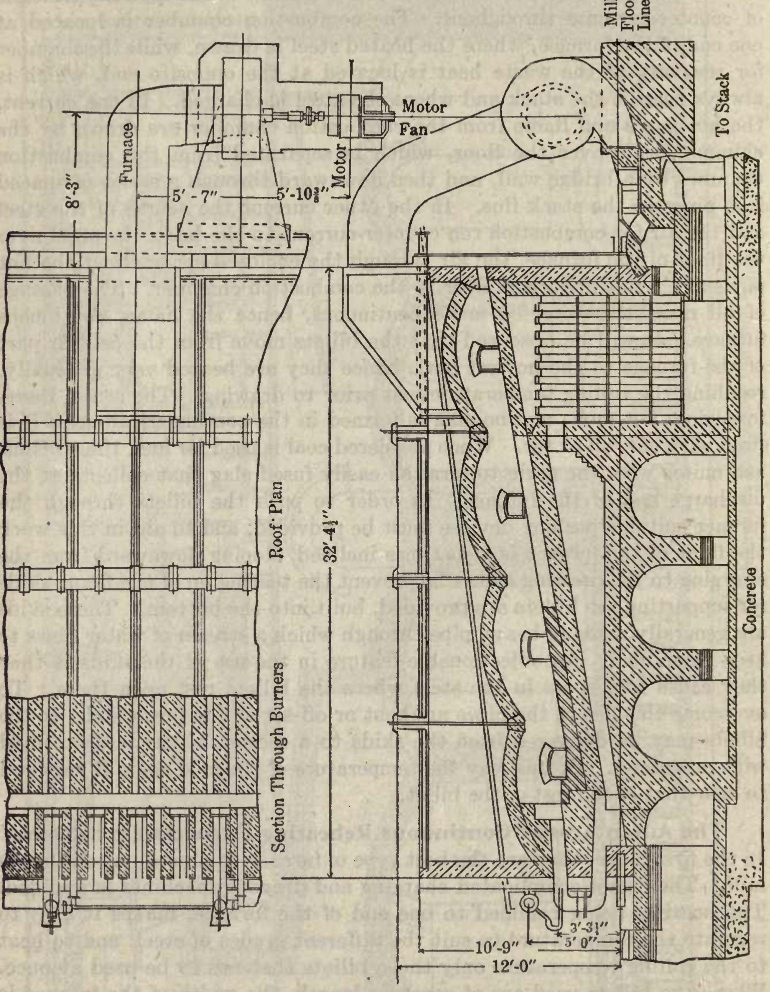


Fig. 73 **Continuous Heating Furnace.**

## SECTION II.

### THE ROLLING OF SHEARED PLATES.

**Methods of Rolling Plates:** As previously indicated, plates may be rolled either from ingots or from slabs, and on several different types of mills. Thus, in England, and a few places in this country, Birmingham, for example, plates are rolled on a two-high reversing mill consisting of a train of two stands of plain rolls. In these mills, the stand nearer the engine has both rolls driven and is used for roughing, while the second stand is used for finishing and has, therefore, only the bottom roll driven. In the majority of these mills the rolls are run hot, that is, no attempt is made to cool the rolls during the rolling. In America the practice for rolling plates is entirely different. In all cases the rolls are kept cold by directing streams or sprays of water upon them during the rolling, and two types of mill, neither of which is like the English mills, are used. One of these, the universal mill, has already been mentioned, and will be described more in detail later, while the other, the invention of Mr. B. C. Lauth, of Pittsburgh, is a kind of three-high mill. In this mill the top and bottom rolls are driven, are of the same size, and of large diameters, while the middle roll is friction driven and, in diameter, is usually about two-thirds the size of the other two rolls. The maximum size of the middle roll is determined by the width of the housing windows, as the roll is removed by passing it endways through this opening. The top roll can be raised and lowered in the housing, and the middle roll, through suitable levers hydraulically or electrically operated, can be brought into contact alternately with the top and bottom rolls, which then play the part of re-enforcing rolls. Thus, in making the bottom pass, the plate passes between this middle roll and the bottom roll, while the top roll is used as a re-enforcing roll. On the return pass, the middle roll is dropped down upon the bottom roll, and the piece, having been raised to the proper level by a tilting table, passes between the top and middle rolls. In either case, the amount of draught is controlled by screw downs acting against the top roll in a manner somewhat like that of the blooming mill. The advantage of this construction will become apparent as this study advances. Plates rolled on this mill must be sheared on all edges, hence they are called "sheared plates" to distinguish them from universal mill plates which are sheared only on the ends to obtain the lengths required. The size of the sheared plate mill is determined by the length of the bodies of its rolls, while universal mills are distinguished by the maximum spread of the vertical rolls.

**The One Hundred Forty Inch Mill at Homestead as an Example of a Sheared Plate Mill:** In this mill the top and bottom rolls, which must be carefully matched and of exactly the same diameter, are each approximately thirty-eight and three-fourths inches in diameter when new, and the middle roll twenty-two inches. All three are chilled rolls, the depth of the chill being between one and one and one-half inches. The bottom roll is held in place by bottom and side bearings of brass, which are fitted into the bottom of the cast steel housings. For the top roll, which requires both top and bottom as well as side bearings, riders for containing the brasses are provided. This roll is supported from below by steel-yard rods which extend from the bottom rider to the shorter arms of counterbalanced levers in the pits beneath the mill. In this respect as well as in the method of screwing down the top roll, the construction of the mill resembles the forty-inch mill at Duquesne. For driving the screws, however, a 60 h. p. motor is provided, instead of the hydraulic cylinder, and is connected to the screws through a worm shaft and crown gear. For indicating the draught on the mill a large drum or cylinder, about four feet in diameter and with an altitude equal to the total lift of the mill, is mounted on the top of one of the screws. The surface of this cylinder is divided vertically into parallel spaces, the width of which equals the pitch of the screws, one and one-quarter inches. The circumference of each circle separating a pair of spaces is then divided by vertical lines into a number of equal parts. By means of this arrangement and a stationary pointer, mounted on the housing beside the cylinder and set to point at zero on the drum when all the rolls are in contact and screwed down tight, the distance between the rolls may be read off direct and with great accuracy. For holding the middle roll in place, bearing boxes with side bearings which fit into chocks placed on the side of the housing windows are provided. For keeping this roll in line, liners are employed, and for raising and lowering it, a rest bar built on the plan of a swinging lever is fitted over each neck outside of the housing and across the window. One end of each rest bar is supported at an almost constant level by means of a turn buckle rod hung from the top of the housing, while the opposite end is connected to the plunger of a hydraulic cylinder which, located in the pit beneath the housings, furnishes the power for raising and lowering the roll. In many cases this cylinder is located on top of the housings, and in the most recently constructed mills, electric motors are employed instead of the hydraulic cylinder.

**The Drive and Connections:** The top and bottom rolls are connected to the pinions through coupling boxes and spindles similar to those in the blooming mill. The spindles are eleven feet long, and both are supported at their centers by suitable bearings. The saddle box for the vibrating spindle is attached at one end to the pinion housing and at the other to the roll bearing box, thus keeping the motion of the saddle and spindle co-incident with that of the top roll. Since the middle roll of the mill is friction driven, the middle pinion is used as a driving pinion only, and is smaller than the top and bottom ones, the speed ratio being 11 to 19. The pinions are of the helical toothed type and are held in cast steel housings. A short spindle, four feet eleven inches long, connects the middle pinion to the driving shaft of the engine on which is mounted the fly wheel. This mill is driven by a 42″ x 66″ x 60″ tandem compound engine, capable of giving 3500 h. p. at the speed of 64 r. p. m. Nearly all the new mills built since 1916 are electrically driven. The new one hundred ten inch mill at Homestead, otherwise known as the Liberty mill, is so driven. This motor was built and installed by the General Electric Co. It is designed to develop 4000 h. p. and to give a speed of 82 r. p. m. on full load. It uses alternating 3-phase current with a frequency of 25 cycles per second and a pressure of 6600 volts. The installation is marked for its simplicity; the peak loads are taken care of by means of a 55-ton fly wheel mounted on the same shaft with the motor.

**Difficulties in Rolling Sheared Plates:** While the rolling of plate may appear to the novice as one of the simplest of rolling operations, yet there are problems connected with the rolling of wide plate that require the combined skill and experience of the heater, the millwright, the roller, and roll designer to overcome. If the slabs are not heated uniformly in all parts, the plates will curl and buckle in rolling, while a similar effect is produced if the rolls are even slightly out of alignment. The stretch of the housings and the stoving up of the screw are minor considerations in overcoming the difficulties of rolling exactly to gauge. The wearing away of the rolls, which in actual operation, takes place faster in the middle portions than at the ends, causes them to become hollow in a short time so that the plate is thicker in the middle than at the edges. Since the pressure for rolling must be applied at the ends of the rolls, this effect is increased by the bending of the rolls. The opposite effect would be produced if the rolls should become hot in the middle, the expansion causing an increase in their diameters. This last complication is avoided by keeping the rolls cold with water sprays above them. This water, running down upon the plate, has a tendency to cool it faster, but this cooling is not as rapid as might be expected, because the water assumes the spheroidal state on striking the very hot plate and glides off without being vaporized to any great extent. At the one hundred forty inch mill, the spring and wear in the rolls are provided for in the following manner: To remove the effects of wear the top and bottom rolls are dressed down every Saturday, either in position by attaching an electrically driven reduction gear to the driving pinion, which virtually converts the mill into a lathe, or by removing them and sending them to be lathe turned in the machine shop. To neutralize the spring in the rolls the middle roll is turned so that its diameter at the middle is a little greater than that at the ends. If this swell or belly in the roll were made to fit the top and bottom rolls it would almost represent an arc of a very large circle, but as it is impossible to dress the roll in this way, the lines are cut only approximately correct by tapering the ends and leaving the central portion of the roll cylindrical in form. The amount of the taper will vary with the hollowness of the mill, but is never less than one sixty-fourth nor greater than three sixty-fourths of an inch, thus making the difference in diameter between the ends and the center vary from one-thirty-second to three-thirty-seconds of an inch. The distance from the end of the roll to which the taper extends may vary from forty-six to fifty-six inches, thus making the central cylindrical portion twenty-eight to forty-eight inches long, and depends upon the width of plate being rolled. It is the practice, when advantageous, to roll the wide plates at the beginning of the week, while the mill is full, and to roll the narrower plates at the end of the week when the rolls have been worn down, and the hollowness of the mill is more pronounced. Even with these changes the mill will often become so hollow that it is necessary to roll the edges a little below gauge in order to get the weight correct. Hollowness in the mill tends to make the edges of the plate dovetail or buckle. During the week the middle roll will be changed four to six times.

**The Rolling Process** on this mill, as on the English mill, may be looked upon as being performed in two steps or stages, namely, a roughing or breaking down stage and a finishing stage. In the breaking down of the slab the most important feature of the rolling is the determination of the draughts, the size of slab and the spring of the rolls being the controlling factors in this regard. With a heavy slab, that is, one six to ten inches thick, a maximum draft, or bite, of about three-fourths inch is possible. The amount of bite decreases as the slab thickness decreases and the width increases. The greater the surface the less the possible draught on account of the greater amount of work necessary in rolling. Following the first few passes the draughts become smaller and smaller because of the increased work required and also to allow material for the finishing. At least one-fourth inch is allowed for the finishing passes, as this amount is required to give sufficient material with which to remove the effect produced by the spring of the rolls. Were the spring not removed, that is if the plates were finished by a continuance of passes carrying the heavy draughts, the middle of the resulting plates would be much heavier than the sides. By decreasing the draughts the "spring" is removed, and the plate approaches nearer the desired weight and gauge. Blind passes, that is, passes in which no additional pressure is applied to the rolls, are also used in finishing for the same reason. The heavier gauge plates cause less spring in the roll and fewer finishing passes are necessary, while with light gauge plates, especially on a full mill, it is necessary to start the finishing when about one-half inch above the final gauge, since a bigger draught is necessary to hold the plate and prevent buckling. Near the beginning of the rolling, the slabs are passed through the mill transversely a few times to obtain the desired width and are then rolled longitudinally. In gauging the width six inches are allowed for shrinkage, shearing, etc., on plate not over eighty-five inches wide, while seven to eight inches are allowed on plate from ninety inches to the maximum of a hundred thirty-two inches. Extra allowance on the wide plates is necessary to take care of the overlap, or lamination, of the top and bottom sides due to the greater flowing of the metal on these faces during rolling. Any large variation in the distance between the rolls from end to end shows up in the plate at once, since under such conditions it will curve to the side on which there is the less draught. If the variation is small it may not show up in this way. The plates are gauged four times daily at the edges and in the middle to determine the hollowness and variation. Excessive hollowness is corrected by putting in a new middle roll, while variations are overcome by inserting or removing liners under the bearing boxes. During the rolling, scale is removed with salt on common steels or with burlap and coal on nickel steel, as in the rolling of slabs.

**Cooling and Straightening:** In order to keep the cooling of plate uniform, the roll tables are preferably provided with collared, or disc rolls instead of plain ones, which cause black streaks to appear across the plate. Disc rollers in the tilting tables of the mill also make it possible to roll very narrow slabs. These slabs are difficult to handle on plain rolls, because they do not ride these rolls in a horizontal position, but tend to fall down between them edgewise. This difficulty is overcome with the disc rollers, for by alternating the discs the bearing surface from roll to roll is brought nearer together than is possible with plain rolls, and there is no straight line of separation between rollers. After the rolling is completed, the plate is passed by roll tables to a Hilles & Jones cold roll straightener. This straightener is constructed of two rows, one above the other, of small rolls, five in the top and four in the bottom row. The centers of the rolls in the top and bottom rows are alternated, so that the piece, on entering between the rolls, is given a long bend or sweep which is then removed by smaller sweeps until the piece, on passing out of the rolls is quite or nearly straight. Two or more passes may be required to straighten some plates. The best work is done on plates about one-half inch thick, as they still retain enough heat when arriving at the cold rolls to be well and easily straightened. The rolls are operated by motors, and the draught is set on the mill by gears connected to a motor. From the rolling order sheets, the cold roller obtains the gauge of the plate when finished and then sets the cold rolls to take a plate of that gauge.

**Laying-out and Stamping:** After being straightened, the plates pass to the cooling bed and then to the marking tables. Here the heat number, slab number, customer's name, or mark, and plate dimensions are written on the plate by the marker. The plate is now ready to be laid out by the gauger. Laying out consists of drawing out in chalk the plate or plates as they are to be sheared, it being remembered that the plate as rolled from a slab may be made up so as to give material for two or more plates, in which case the plate as rolled is called a **combination.** As the plates are still hot when gauged, allowance must be made for shrinkage, this allowance amounting to one-fourth inch in width and length for each hundred inches on plates up to one-fourth inch in thickness, and three-eighth inch for each hundred inches of length or width on gauges over one-fourth inch. This difference is necessary on account of the higher finishing temperature of the thicker plates. In case plates come to the marking table that will not make the plates ordered, on account of being too short or too narrow, the material must either be applied on another order or put in stock. Any plates with objectionable surface defects are rejected at the marking table and stocked. Plates stocked at the table are treated in the same manner as rejections, although they are not listed as such, because they have not been finished at the time of stocking. If a plate has a snake or is pitted on one end, this part may be sheared off and the remainder used on a different order than that for which it was intended. Plates that are too narrow to make the ordered plates are held until an order can be found calling for such a gauge, width and length as can be cut from them. It is a duty of the stock marker to replace such plates as are taken from the marking table. A report is made on the rolling order sheet, by the marker, of the number of plates made on an order, and the stock marker informs the office of all plates made from stocked material. While plates are being laid out they are stamped, giving heat number or slab number as is desired, and any other stamp that may be called for on the order by the purchaser. Heat number, slab number and size is also painted on the plates with white lead after they are marked. Some orders require that heat numbers, etc., are to be painted instead of being stamped, this being more generally the case on very light gauge plates. The method used in laying out a plate can be described from sketches, such as those shown in Fig. 74.

First, the width of the plate is taken at AB to determine the amount of stock over that of the ordered width plus allowance for shrinkage. The stock is then divided so as to give one-half to each side. Point C is set leaving the distance BC as excess stock. Point O is now set along XY in the same manner as point C. Line CO is drawn with a chalked string or a straight edge. Widths OM—EN—CP and others, if needed, are measured using line CO as a base. Line PM is then drawn by "the line drawer." A right angled square is now used to draw line CP at right angles to CO, thus squaring up the plate. The true length of the plate is taken along CO, using C as a starting point, and OM is likewise drawn at right angles to CO.

In case the plate is curved, the base lines must take the direction indicated in Sketch II in order to avoid scrap, and in case the length of the plate ordered is such as X′Y′ the plate cannot be made on account of the curve. This plate must be applied on orders that require lengths of approximately XI and QR, with widths and gauge such as can be obtained on the given plate. Whenever the number of plates ordered to the same dimensions will justify the expense, patterns of wood are made for laying out. Sketch plates are always marked out to a templet, or pattern.

**Test Pieces:** In laying out the plate sufficient material must be given to allow for the test pieces that are required. On sheared plates both longitudinal and transverse test pieces are often taken.

**Shearing:** Three shears, one end and two side shears, are used on the one hundred forty inch mill, and are so arranged that the plate does not require turning to shear the sides. The ends are sheared first, and the plate is then passed over castors to the side shears. This mill is also equipped with a rotary shear for heads and other circular plates, an alligator shear and a scrap shear.

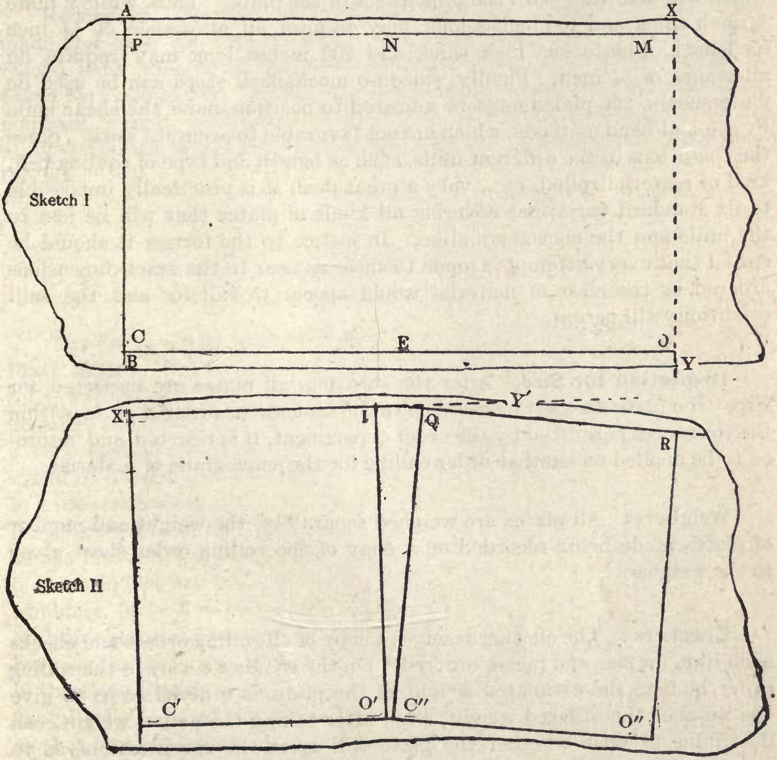


Fig. 74. Sketches Illustrating the Laying Out of Plates.

**Shearing Tolerances:** It is evident, even to the casual observer, that conditions at the mills are such that shearing to exact dimensions is impossible. Observations made on any one mill will reveal many of these unfavorable conditions and also show that it is impossible to remedy them. The plates must be sheared in the order they are rolled, and, to keep up with the mill, rapid working is required, a condition that makes it difficult to lay out or shear accurately. Owing to variations in the thickness of the plates and in the time required for rolling them, they leave the cooling beds at widely varying temperatures. Since there is no way of knowing accurately just what this temperature is at the time of laying out the plate, proper allowance cannot be made for the shrinkage, the total amount of which will also vary with the dimensions of the plate. Thus, while a plate ¼ inch thick and 100 inches long may require an allowance of ¼ inch for length, a plate one inch thick and 200 inches long may require an allowance of ⅞ inch. Finally, since no mechanical stops can be used on plate shears, the plates must be adjusted to position under the shear knife by eye-and-hand methods, which are not favorable to accurate work. Since the conditions in the different mills, such as length and type of cooling bed, kind of material rolled, etc., vary a great deal, it is practically impossible to fix standard variations covering all kinds of plates that will be just to the mills and the consumers alike. In justice to the former it should be stated that every attempt is made to shear as near to the exact dimensions ordered as the class of material would appear to call for and the mill conditions will permit.

**Inspection for Size:** After the shearing, all plates are inspected for size. If a plate does not measure up to the dimensions ordered or to within the tolerances permitted by the order department, it is rejected and returned to be applied on another order calling for the same grade of material.

**Weighers:** All plates are weighed separately, the weight and number of plates made being recorded on a copy of the rolling order sheet given to the weigher.

**Checkers:** The checker receives a copy of all rolling orders and checks each item for size and pieces ordered. On the weigher's copy of the rolling order, he lists the estimated weight of the plate as ordered so as to give the weigher the ordered weight, who, after taking the actual weight, can determine at once whether the plate will meet the specifications as to weight. The checker lists all plates ordered in the order book, and receives a copy of all orders to be rolled on the mill, so as to avoid the making of duplicates in case a plate is ordered twice. In case error is found in dimensions of plates listed on the rolling order, the checker informs the roller and marker. The checker also lists all plates made in the order book, thus keeping a record of the plates still on order.

**Slip Maker:** The slip-maker's duty is to make a form giving the following information: mill, slip number, customer's name, Carnegie order number, sheet number of order, heat number, number pieces made, dimensions, marks and actual weight. The dimensions, etc., are to be taken from the plate, formerly painted on by the painter at the marking table. A copy of the rolling order is at the disposal of the slipmaker to aid in identifying plates, but data cannot be taken from the order without seeing the marks on the plate, in as much as certain plates may, at the marking tables, be applied on orders different from those they were originally intended for. A new or separate slip is made out for each order number. The signature of the slipmaker is required on each slip for identification.

**Recorder:** The duty of the recorder is to test the weights of all plates made and note the turn on which they were rolled and sheared. The record here taken is the final record of the product made and must be taken very accurately. Special forms are used for recording, showing turn, numbers, weight, descriptions of plates, etc. Special sheets are made for alloy steels and small pieces that are inspected at the time of measuring for size.

## SECTION III.

### UNIVERSAL MILL PLATES.

**The Forty-eight Inch Mill at Homestead as an Example of Universal Plate Mills:** This mill consists of two horizontal rolls and four vertical rolls, two on each side of the horizontal ones, all contained in the same housings and driven by the same engine. This construction makes the mill a very complicated piece of machinery, a detailed description of which would be too lengthy to attempt here, so only such matters as are necessary to an understanding of the working of the mill will be discussed. While the working surface of the horizontal rolls is only four feet, which is the same as the maximum spread of the vertical rolls, the total length of the rolls is thirteen feet one inch, of which length twenty-four inches makes up the wobblers, forty-five inches the necks, and forty inches, twenty inches on each side, crosses the spaces in front of the vertical rolls, which must stand between the housings. These rolls are connected to the engine and are driven in the same way as the ordinary reversing mill. The total lift of the horizontal rolls is twenty inches. The screw down on these rolls is the same as that on the sheared plate mill, and the same form of graduated drum is used to indicate the lift of the rolls, or the gauge of the plate. The vertical rolls, whose centers are located three feet one inch from the centers of the horizontal rolls, are seventeen and one-half inches in diameter at the body, and the height of their rolling surface is two feet four and one-eighth inches. They are provided with bearing boxes at both their tops and bottoms. A five inch collar on the upper end of the lower neck rides on a side bearing in the bottom box which furnishes the vertical support for the roll. A screw, bearing on a frame attached to the bearing boxes and actuated by an electric motor, furnishes the means by which the pressure for rolling is applied to these rolls; for spreading them hydraulic jacks are used. Large discs, graduated on their circumferences and mounted on the screws, indicate the spread of the vertical rolls. As already stated, these rolls are driven through a system of gears by the same engine that drives the horizontal rolls. Beginning with the engine, the power is transmitted to the horizontal rolls in the usual manner for reversing mills, while the drive for the vertical rolls is taken off the upper pinion. Upon the prolongation of the outside bearing of this pinion, a second gear is keyed. This gear meshes with two idlers, one on either side, which in turn mesh with gears mounted on the ends of the two drive shafts for the vertical rolls. These shafts then extend to and across the roll housings, where they are supported by suitable bearings. On the section of these shafts included between the roll housings are mounted four sliding miter gears which mesh into similar crown gears keyed to the tops of the rolls. Through these gears the peripheral speed of the vertical rolls is adjusted to equal the speed of the horizontal rolls, and never more. Hence, the vertical rolls may be used on the piece only on the entering side of the passes, because if the vertical rolls were used on the delivery of the plate the greater speed of the piece due to the elongation produced by the horizontal rolls would jam the material between the two sets of rolls. The rolling of the piece on the entering side is preferable to rolling on the delivery side, as then thin plates would tend to buckle or bow up in the center on applying pressure from the vertical rolls. These rolls cannot be brought closer together than twenty inches. Hence, the mill has a range in width of plates from twenty to forty-six inches.

**The Operation of Rolling:** Rolling universal mill plates involves most of the difficulties of rolling sheared plates, and in addition there are several features, due to the vertical rolls, that are not peculiar to sheared plate mills. Thus the piece must always enter the mill at right angles to the horizontal rolls, as otherwise the action of the vertical rolls will cause the plate to buckle or curl or jam between the rolls. As the plates rolled on this mill are in very long lengths, the slightest variation in the spacing of the horizontal rolls shows up as a decided camber in the plate as it runs out on the table. To correct this defect, which is prone to occur on universal mills, a spanner block is placed under the screw down on the roller's side of the mill. By means of a spanner bar and a sledge hammer, this block may be turned and the proper adjustment made on this end of the upper horizontal roll to cause the plate to roll straight. As to the draught and manipulation of the horizontal rolls, the plate is reduced in the same way as on the sheared plate mill. On the vertical rolls the greatest draughts are taken in the first few passes, the object being to reduce the piece to the desired width as quickly as possible, after which the pressure on the vertical rolls is just sufficient to hold the piece to width. This mill rolls many plates directly from the ingot. Ingots intended for this purpose are rectangular in section, being from one to two inches wider at the smaller end than the width of the plate desired. In beginning the rolling of these slab ingots the rollers prefer to have the small end enter the mill first, as in this way the suddenness of the pull on the mill is avoided and the draught can be more easily adjusted, but many plates are rolled with the butt end of the ingot entering first. The chief objection to rolling plates directly from ingots is that the pipe and central line of segregation is rolled into the plate, and in order to avoid it the scrapping of a large amount of finished material is necessary.

**Straightening, Marking and Shearing U. M. Plate:** From the rolls, the plate is carried on live roller tables to the two cooling beds, which extend in opposite directions from both sides of the receiving table. Here any curve or camber is removed from the plates by clamping them tightly to a straight edge. The buckles thus produced on the edges of the plate are then flattened out with wooden mallets. While the mill is provided with a machine straightener, similar to the one employed at the one hundred forty inch mill, it is seldom used, the general practice at universal plate mills being to straighten the plates in the manner described above. Every plate rolled on this mill has the name and letters "Carnegie, U. S. A." rolled into it at intervening spaces of seven feet. While on the cooling beds the plates are marked off for length, the heat number is stamped on, and the slab number, size of plate, order number and the customer's name is marked on with white paint. The plates then move on to the receiving tables, which carry them to shears, where the plates are cut to length. A large shear used for splitting plates is also provided. Unless otherwise specified, two longitudinal tests for the physical laboratory are taken for each order or on each heat of steel; one test is taken from the top of the ingot, and the other from the bottom. The weighing, recording, and inspection of the plates are then conducted as for sheared plates.

**Advantages of Universal Mill Plates:** While the effect of the one way rolling on Universal mill plates, as will be explained shortly, is such as to require care and discrimination in their use, they, nevertheless, possess certain advantages over sheared plates that make them more desirable for some purposes. First, the possibility of producing plates of great length with a rolled edge makes them available for many purposes, such as girder construction, for which sheared plates are not suitable. Second, the ability to roll to fairly exact widths reduces shearing costs to a minimum. Third, the rolled edge eliminates all costs to the purchaser for machining. As a fourth advantage the greater tonnages that these mills are capable of producing may be cited, because this tends to keep the first cost to the customer low.

**Physical Properties of Plates:** The effect of rolling on the physical properties of steel is now generally recognized by the users of plates, and specifications are usually written accordingly. In a previous discussion of this subject it was made plain that the controlling factors during rolling are the amount of work done and the temperature above the critical at which the rolling is completed. To these there should now be added the manner in which the rolling is performed. Attention has been called to the different methods of rolling plates in the preceding description. It will be recalled that the plate may be rolled from the slab with one reheating or from the ingot direct without reheating. As to the difference in effect produced by these two methods, there is little data on the subject, but reasoning from the theoretical standpoint, there should be no difference. The abandonment of the method of rolling from the ingot is probably due to economic considerations rather than to any tendency of the method to produce defective material. Again, in the rolling of the slab or ingot it was pointed out that all the rolling may be in one direction only, or the plate may be rolled both transversely and longitudinally. Here a marked difference is observed to result from the two methods of rolling. For example, if a slab or ingot be rolled in one direction only and a longitudinal and transverse test piece be cut from the resulting plate, little difference in tensile strength will be observed in pulling the two tests, but a marked difference in ductility will be found. Thus, the longitudinal piece will give from 4% to 7% greater elongation than the transverse piece, and 10% to 15% greater reduction in area. Concerning the amount of work and finishing temperature, the ductility is affected in a somewhat erratic way, while the tensile strength is increased by increased work and lower finishing temperatures. Thus, a thin plate will show a very appreciable increase in tensile strength over a thick one rolled from the same slab or ingot, and to obtain the same strength in plates of different thicknesses it is necessary to employ chemical control. The following table is intended to show approximately the variations in the carbon content, other metalloids being constant, that should be made to produce plates of uniform strength when varying in thickness as indicated.

**Table 57. Showing Variation of Carbon Content with the Thickness of Plates to Give the Same Strength.**

| THICKNESS OF PLATE | CARBON REQUIRED |
|---|---|
| 3/16″ | .12% |
| 7/16″ | .15% |
| ½″ | .17% |
| ¾″ | .18% |
| 1″ | .19% |
| 1½″ | .20% |

**Inspection of Plates** for size and weight is made by mill inspectors, while inspection for surface and other defects are made either by mill or customer's inspectors. Certain surface defects, as snakes and surface marks, may do the plate no harm if they do not extend too deep into the metal, and may be ground out with any suitable device. For this purpose a movable electrical grinding wheel is employed. The rigidness of the inspection may be surmised from a glance at the inspector's list of causes for rejection, which is here appended. Most of these reasons are self-explanatory, while others have already been discussed, so that no further explanation is required.

**Table 58. Defects for Which Plates are Rejected.**

| Defects Acquired or Caused From | | | | | |
|---|---|---|---|---|---|
| The Ingot | In Heating | In Rolling | In Laying Out | In Shearing | From Many Sources |
| Blister<br>Pipe<br>Slivers<br>Seams | Burnt<br>Bricked<br>Scabby<br>Cinder spot | Split<br>Slivers<br>Dished<br>Pitted<br>Scored<br>Buckled<br>Over weight<br>Under weight<br>Over and under gauge<br>Scale<br>Cambered<br>Laminated<br>Roll marked<br>Bad edge (Universal Mill Plates only) | Wrong Dimensions<br>Made wrong | Scant<br>Bad Edge<br>Crop end<br>Test piece cut<br>Knifed | Snake<br>Seams<br>Test lost<br>Duplicate<br>Broken<br>Ground too deep<br>Cracked<br>Tests are not within specification |

# CHAPTER VIII.

## THE ROLLING OF LARGE SECTIONS.

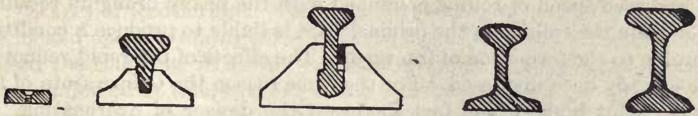
### SECTION I.

### RAILROAD RAILS.

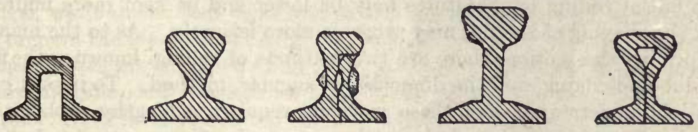
**Development of Rail Manufacture:** Dating from the invention of the steam locomotive, the railroad rail represents one of the first sections with which the rolling mill operators had to deal, as well as one of the most difficult and certainly the most important. The importance of the railroad as a factor in modern civilization and progress is recognized by all, and that the rail is a most vital part in railroad operations is just as evident. With the advancement in speed of travel and weight of loads carried, more and more has been required of the rail, until to-day no material is subjected to more severe punishment in service than the railroad rail. Exposed to the weather at all times, it is subjected, under constantly varying conditions, to immense compression and bending stresses, shocks, vibrations, friction and wear. The form of the rail, then, should be such as will give the greatest transverse strength, provide abundance of metal for wear, present a wide base for fastening to the cross tie, and still, for the sake of economy, be of the lightest section possible. Now, it so happens, that the form that best meets all these requirements is the section known as the American Tee Rail. It also happens that this section was, in the early days of rolling mills, one of the most difficult sections to roll, mainly on account of the wide flange. The history of rail development as indicated in the sketches of Fig. 75 gives evidence of this fact.

Thus, the first real departure made from the original strap rail of 1808 was the chair rail of 1820. As the chair of this rail was expensive, an attempt was made in the section of 1831 to roll a rail with a wide and relatively heavy flange on the bottom to replace this chair. The difficulty of rolling the flange led to the better balanced bull head of 1837, the U-shape of 1844 and the pear head rail of 1845. Then came the compound rail of 1856 and the form of 1860, which is the U-shape of 1844 with the lower parts closed in and welded to form the web. As neither of these forms proved serviceable, a demand for more metal in the head for wear forced a final return in 1865-8 to the tee shape with wide thin flange. From this date the design of rolls, quality of material, and lay-out of the mills has gradually been improved until at the present time the American rail mills are not only producing the largest tonnage of the world but also rails of the best possible grade.

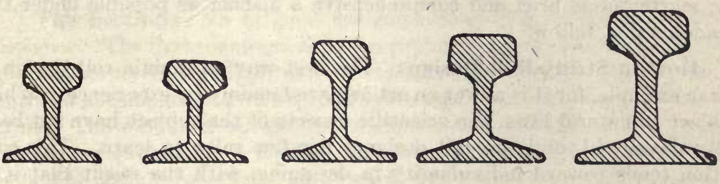
**Methods of Rolling Rails:** Rails were originally rolled on the pull-over mill, and then on the reversing mill, which in England is the type of mill still employed for this purpose. But in this country all rails are rolled on the three-high mill, which formerly was usually made up of a single train of three stands driven with one engine. With the increase in the size of the section, which has almost doubled in weight within the last quarter century, and the growing demand for larger quantities and better quality in the product, a more advantageous lay-out of the mills for handling this material became necessary. The more modern rail mills will, therefore, consist of two or three trains, each separately driven and made up of one or more stands of rolls, all so arranged that the rolling of the piece in any one stand is complete before it is passed to the next succeeding one. With this arrangement the output of the mill is greatly increased without much increase in the speed of the rolls, because different pieces may be rolling at different stages at the same time, and the turning of the piece between passes is avoided. As to the heating of the steel, rails may, as previously



1808 Strap Rail 19 lbs. per yd.
1820 Birkenshaw Chair Rail 25.8 lbs. per yd.
1830 Clarence Chair Rail 33 lbs. per yd.
1831 Stevens', (the 1st. T-rail) 40.8 lbs. per yd.
1837 Lock's (Bull Head) Rail, 58 lbs. per yd



1844 Evans' 40 lb. U-Rail First Rail Rolled in United States.
1845 58 lb. Pear Head Rail, First T-rail Rolled in U. S.
1856 Compound Type of Rail, 60 lbs. per yd.
1858 P. R. R. Standard 85 lbs. per yd.
1860 Closed-U Rail



1868 Welch Design 67 lbs. per yd. First Bess, Rail Rolled in U. S. (1865) similar to this
1874 Chanute Design 60.3 lbs. per yd.
1883 P. H. Dudley Design 80.2 lbs. per yd.
1892 P. R. R. Standard 100 lbs. per yd.
1910 C. R. R. of N. J. 135 lbs. per yd.

Fig. 75. Sketches of Rail Sections Illustrating the Evolution of the Railroad Rail in America.

stated, be rolled either from blooms that have been reheated after having been rolled from the ingot, or on the original heat of the ingot. The latter method, which was introduced a few years ago mainly to save the extra cost of reheating, was until very recently looked upon with favor both by the manufacturer and the consumer, who believed that the scheme would have a beneficial effect upon the quality of rail produced, due to the fact that the material was necessarily finished at a low temperature. Within the last two years, however, sentiment appears to have taken a swing in favor of reheating, because, as is claimed by the advocates of reheating, the increased speed of rolling combined with the heavy draughts required to complete the rolling on the original heat is liable to produce a condition favorable to the formation of fractures. The effects of too rapid reduction have already been discussed. For the same reason the temperature of the ingot is kept high, which fact increases the danger of overheating. In addition, the difficulty of keeping the finishing temperature constant, presents a serious problem. On the other hand, by reheating the bloom the two initial rolling temperatures may be lower and be kept more uniform, and the shaping of the rail may progress more leisurely. As to the manner of forming the section, there are two methods of rolling, known as the flat, or slab-and-edging, and the diagonal, or angular, method. To impart even a slight understanding of these methods requires a lengthy explanation; but in the proper design of the various passes for the progressive forming of the rail, as for any section, lies the crux of the rolling process. Therefore, as the subject is one of great interest, an attempt is to be made to discuss the matter in as brief and comprehensive a manner as possible under the headings that follow.

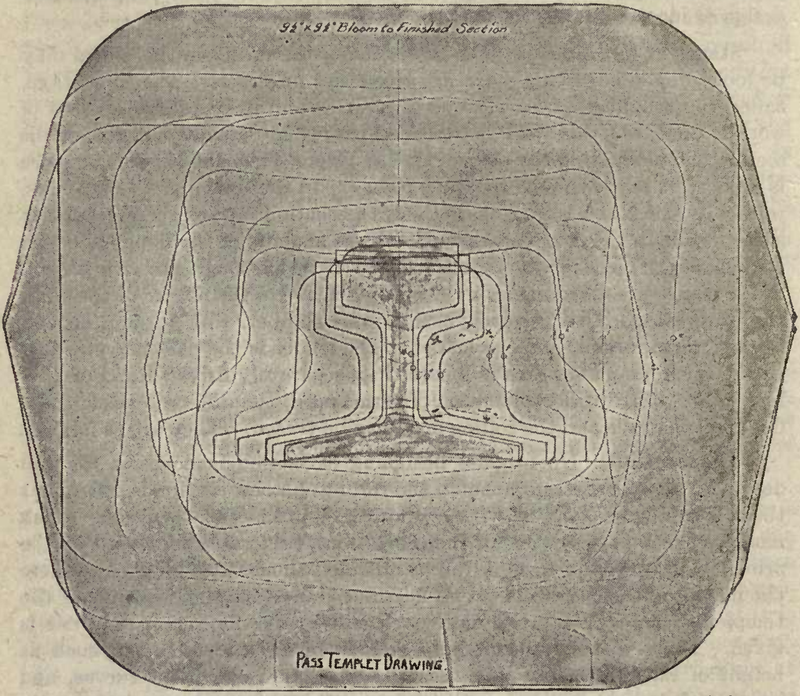
**How to Study Roll Design:** The best way to explain roll design is by an example, for it is as yet an art acquired mainly by experience. While subject to natural laws, the scientific aspects of the subject have not been fully developed, and the roll designer has few rules to learn. This condition tends toward individuality in designing, with the result that it is seldom two designers will be found to do the same thing in the same way. To serve as such an example the flat method of rolling as carried out at the Edgar Thomson Works will be described, because, of the two methods of rolling, this is the older and the one more generally employed. Before beginning with the example, however, some preliminary explanations are required.

**Precautions to be Observed in Designing the Rolls:** Of course the first consideration in roll designing is to produce a finished piece of the correct size and form, and this must be done by spreading, bending and directing the flow of the steel. The ease with which this forming is done depends on the plasticity of the metal, which in turn is affected by the kind of steel, whether open-hearth or Bessemer; the grade, whether high or low carbon; and the temperature. With the speed of the rolls fixed, the temperature confined to a very narrow range, and the kind and grade of steel given, the only instrumentality remaining in the hands of the roll designer is the size and shape of the passes, and in part of these, at least, the size will be governed by the size of the bloom. In designing the passes, a good designer will endeavor to work the steel in such a manner that the quality of the product will be benefited, and no defects will be developed. The defects that require constant care are fins, laps, overfills and underfills Laps may result from fins or a collaring of the piece in the rolls; overfills, from worn rolls, bad or improper design; and underfills either from bad design or incorrect adjustment of the rolls.

**Stages of Reduction:** The formation of the rail from the bloom may be looked upon as taking place in three steps or stages. The first stage, called the roughing, is merely one of preparation; in it a large amount of work is done, but this work is expended mainly in reducing the size of the section and elongating the piece. At the Edgar Thomson Works the piece is reduced in seven to nine roughing passes. In the first four to six passes, rolling by the slab-and-edging method, the section retains the rectangular shape, while in the next three passes a little shaping of the flange is begun to prepare the piece for the first finishers, in which there are five passes. These passes are given names in order, indicative of the nature of the work they are intended to perform, as follows: slabber, first former, second former, third former, and the leader. The leader is the pass just previous to the finishing pass, which is located in a separately driven stand of two-high rolls. With this explanation of terms used, the different steps in the design of the rolls and the rolling may now be traced. They are as follows:

**The Section:** No original designing of section is done by the roll designer. The first requirement in the rolling of a new section is, then, that the roll turner be supplied with a drawing or print of the section, which must be accompanied with all the dimensions, preferably indicated on the print. The weight of rail desired or expected should also be given. Here the matter of dimensions is of extreme importance, for the designing of the templets cannot be started until each and every dimension required is given. These dimensions not only include linear measurements, such as height of rail, width and thickness of parts, but radii of all curves, and amount of slope on inclined surfaces expressed in degrees or percentages.

**The Cold Templet:** With all the necessary information before him, the first step taken by the roll designer is to prepare a drawing for the cold templet. This templet is made of brass and represents an exact section of the rail when cold. This drawing is constructed on the axis of symmetry of the rail, which is the vertical line drawn through the center of the head, of the web, and of the flange. On this line the section of rail is symmetrically constructed to the dimensions given on the drawing, all the dimensions being made with extreme care and accuracy. All measurements are made with micrometers or steel rules. If a rule is used a magnifying glass is employed to take the readings. The construction lines are made as fine as possible. Even the contraction and expansion of the drawing paper, due to the varying humidity of the atmosphere, is taken into consideration, and the proper allowances are made. With this very accurate drawing completed, the area of the section is measured with a planimeter in order to check up the weight of the section.If this weight should differ from that given on the original print or drawing, the templet drawing is checked and, if correct, the customer is notified that the actual weight will not be as specified. No further work may then be done till this question of weight is settled, when the brass templet will be made from the drawing.



| PASS | HEAD | WEB | BASE | TOTAL | % RED. | SPREAD |
|---|---|---|---|---|---|---|
| FINISHING | 14.4 | 5 4 | 12.1 | 31.9 | 5% | ⅛" |
| LEADER | 15.2 | 5.7 | 12.7 | 33.6 | 15% | 3/32" |
| 3RD FORM. | 17.9 | 6.7 | 14.9 | 39.5 | 20% | 3/32" |
| 2nd FORM. | 22.4 | 8.4 | 18.6 | 49.4 | 24% | 3/32" |
| 1ST FORM. | 29.5 | 11.1 | 24.3 | 64.9 | 22% | 3/32" |
| SLABBER | 37.8 | 14 2 | 31.2 | 83.2 | | |

%Reduction in Passes.

| | No. | Pass | % Red. |
|---|---|---|---|
| 2nd. Rough | A | Finishing Pass | 5. % |
| | B | Leader | 15. % |
| | C | 3rd. Forming | 20. % |
| | D | 2nd. Forming | 24. % |
| | E | 1st. Forming | 22. % |
| | F | Slabber | 23. % |
| 1st. Rough | G | 9th. Pass | 24.5 % |
| | H | 8th. " | 24.5 % |
| | I | 7th. " | 22. % |
| | J | 6th. " | 27. % |
| | K | 5th. " | 22.8 % |
| | L | 4th. " | 17.7 % |
| | M | 3rd. " | 28.8 % |
| | N | 2nd. " | 17. % |
| | O | 1st. " | 14.5 % |
| | P | Bloom | |

FIG. 76. Pass Template Drawing—Slab-and-Edging Method of Rolling Rails.

**The Hot Templet:** The next step, which is really the first step in designing the roll passes, is the making of the hot templet. This templet is exactly like the cold templet, but larger in size to allow for contraction, as it represents the section of the rail at the finishing temperature of rolling. The co-efficient of contraction, or exact amount to allow here, is determined by experience. From this hot templet the various passes are designed successively as the experience and judgment of the designer dictates.

**The Pass Templet:** In designing these templets, the designer constructs each in a drawing showing the different passes superimposed upon each other as in the accompanying illustration. In actual practice these drawings are constructed full size, but for convenience in printing this photograph is three-eighths natural size. This illustration represents the passes for a light rail rolled by the slab-and-edging method. In this method, the axis of symmetry of the rail coincides with the pitch line and is parallel to the train line of the rolls, as can be seen from the print. The more darkly shaded area in the photograph represents the hot templet, with the pitch line or axis of symmetry drawn through it, and from it the grooves in the finishing pass are cut. From this pass the roll designer works back to the bloom. As a preliminary step toward designing these passes, a table like that shown attached to the photograph is prepared. In a vertical column, headed **pass,** are placed the names of the various passes from slabber to finishing, while the figures in the columns designated as **head, web,** and **base** represent the sectional area of the different passes for these parts expressed in pounds per yard, which is directly proportional to the area in square inches. This table is prepared as follows: The areas of the different parts of the rail are fixed by the hot templet. In this section the metal was proportioned in the design so as to give 14.4 pounds per yard in the head, 5.4 pounds per yard in the web and 12.1 pounds per yard in the flange, the total being 31.9 pounds per yard, which is heavier than the cold section by 1.4 pounds per yard. This difference is due to the fact that the weight of the hot section is calculated as if it were cold, a correction for difference in gravity not being necessary for this purpose. Next will be put down under the column headed **per cent. reduction,** the amount of reduction expressed in per cent., which from experience and judgment, the designer thinks will be best. In this case these amounts are as follows: In the finishing pass one-thirty-second of an inch reduction on each side of the web is allowed for the marking; in the leader, 15%; in the third former, 20%; in the second former, 24%; in the first former, 22%; and in the slabber, 23%. From these figures the areas of the different parts of each pass are calculated, and the blanks in the table filled in as shown. Next, the amount to allow for spread of the piece from one pass to the other is decided upon and placed in the column headed **spread.** This allowance is expressed in fractions of an inch and is measured and allowed for along the axis of symmetry as shown by the positions of the rail heads in the photograph. With the reduction for the various passes and their parts thus apportioned, the designer then proceeds to draw in the passes, as designated in the photograph by the letters a to p, and in doing so he keeps the following points constantly in mind. First, is the danger of forming fins. As an aid in avoiding these defects the piece is passed through the mill so that each side of the pass alternately enters an open and closed side of the groove. How this is done on the three-high mill without turning the piece can be seen from a study of Fig. 78. Even

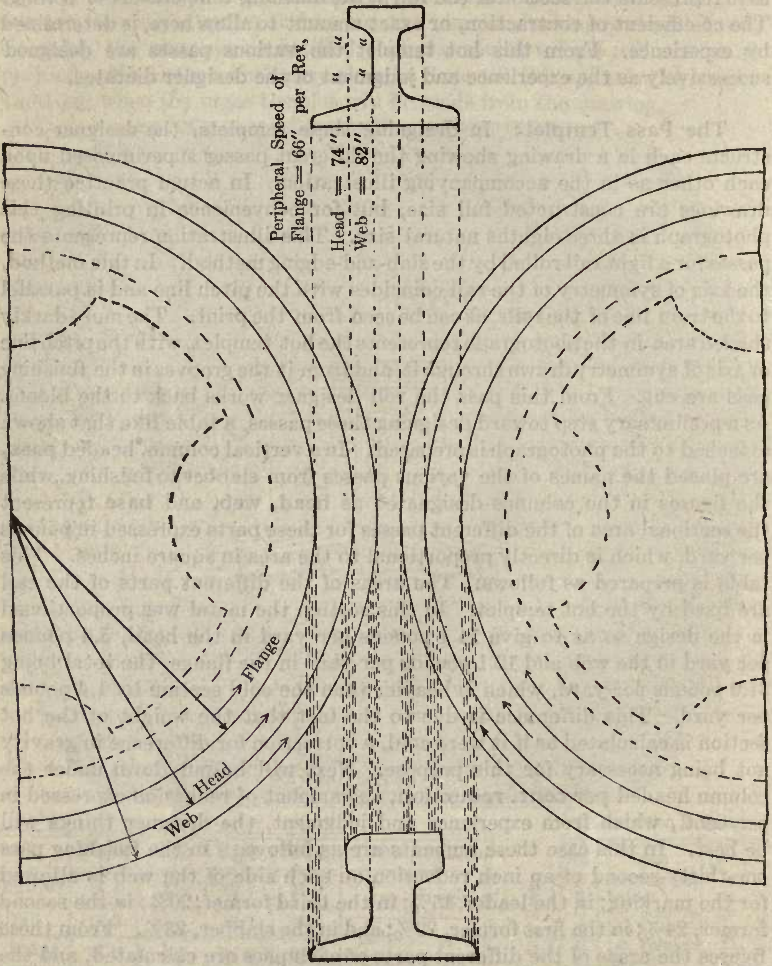


**Fig. 77.** Showing Difference in Peripheral Speed of the Rolls at Web, Head, and Flange.

with this arrangement fins would still be formed if the passes were not properly designed. To avoid all danger of fins two tricks of design are here resorted to. Thus, in the leader, or pass a, the corner of the head, which is to come opposite the openings between the rolls in the finishing pass, is well rounded off, so that the spread or flow of the metal will be taken up in filling out this rounded corner and none will remain to be forced into the clearance. For the same reason, that half of the flange on the same side of the rail is left much shorter. It will be observed that this provision is made in all the passes down to the slabber. From the photograph it will be noticed that most of the work from the slabber is done along the fishing of the rail, the metal being forced horizontally from the central portion of the slab toward the head and flange and vertically into the web. This is done by holding the working surface under the head and on top of the flange at the angles shown. In designing this part of these passes care must be taken to see that the line XY at the bottom of pass *d*, for example, is not greater than X′Y′ at the top of its preceding pass *c*, as otherwise the piece would be collared when it entered *d*. Great care is necessary in distributing the reduction of each part to prevent the metal flowing away from parts where it is needed. Thus, for example, if a too great reduction in the web takes place in one pass, it will produce a flow of metal away from the head, causing the latter to be underfilled. The cause for much of the trouble of this kind lies in the different diameters of the pass, which causes a different roll speed for head, web and flange, and hence different rates of elongation. If the elongation at one point due to increased speed of the rolls, is not balanced by elongation produced through compression at the point of less speed, the section will be imperfectly formed, or cracks will result. The accompanying illustration (Fig. 77) will help in understanding this point. In all reduction, it is a good plan to keep the angle of bite well below the limiting angle of 30°. In the first roughers the difficulties of design are approximately the same as those of the three-high bloomer, and no further explanation of these passes is required.

**Preparation for the Rolling:** After the passes have all been constructed properly in the drawing, a set of working templets, including both male and female for the cold templet, is made from the drawings. The working templets may be of steel. These templets may number from the slabber down only, as the roll designer strives to keep the roughing passes of such shapes and sizes that the same set may be used for a large number of different sections of the same general design. When completed they go to the tool shop, where they are used as patterns in making a set of tools for turning the rolls for the section. For the last six passes, that is, numbering from the slabber to the finishing, inclusive, twenty-two different tools are required for each type and size of rail. After shaping these tools to a little over size, they are tempered and then redressed to exact size before they can be used to turn the rolls. When ready, templets and tools pass to the roll shop, where the work of turning the rolls is done. Here the templets

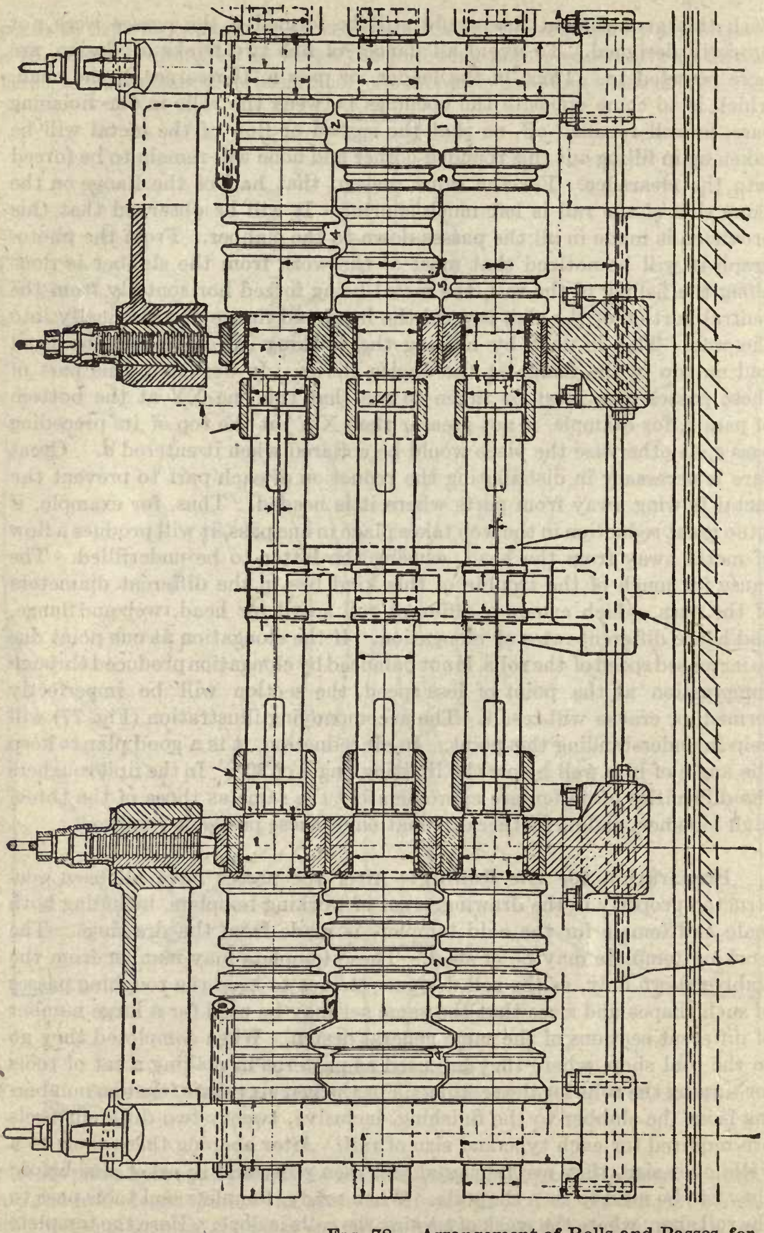
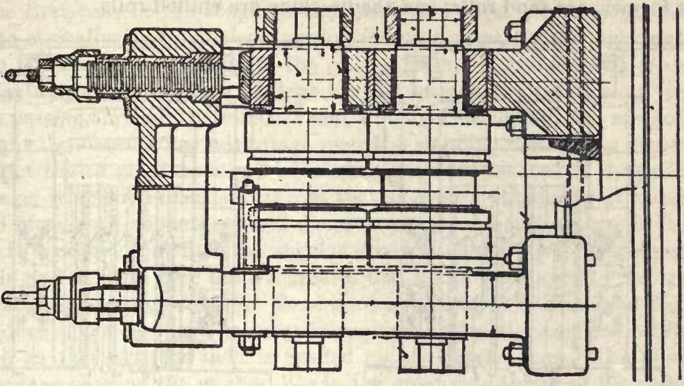
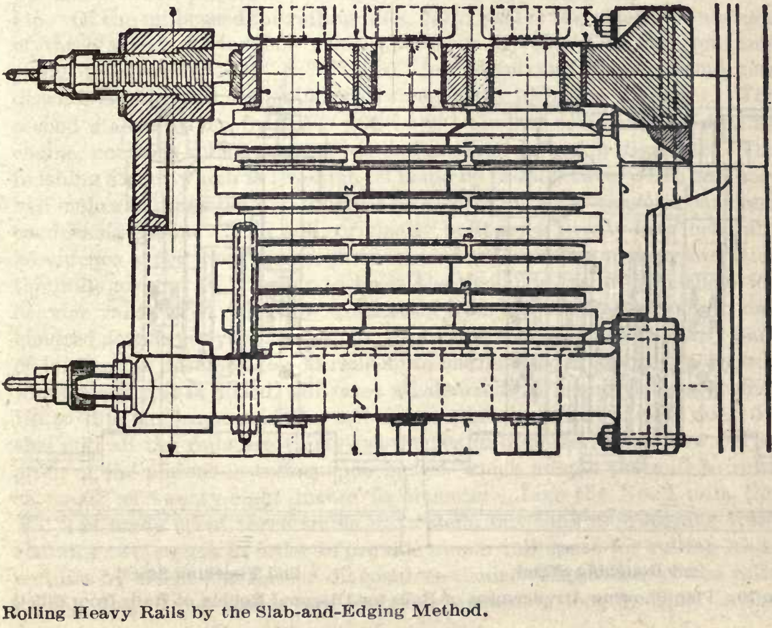


FIG. 78. Arrangement of Rolls and Passes for Roughing Stands.



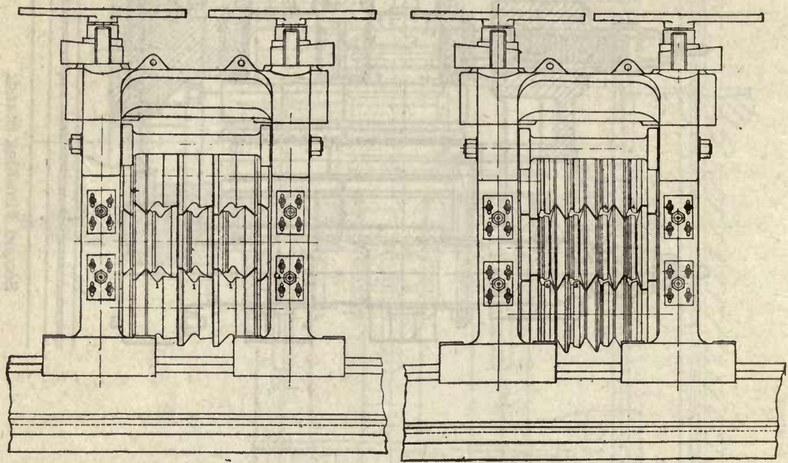
Second Finishing Stand.



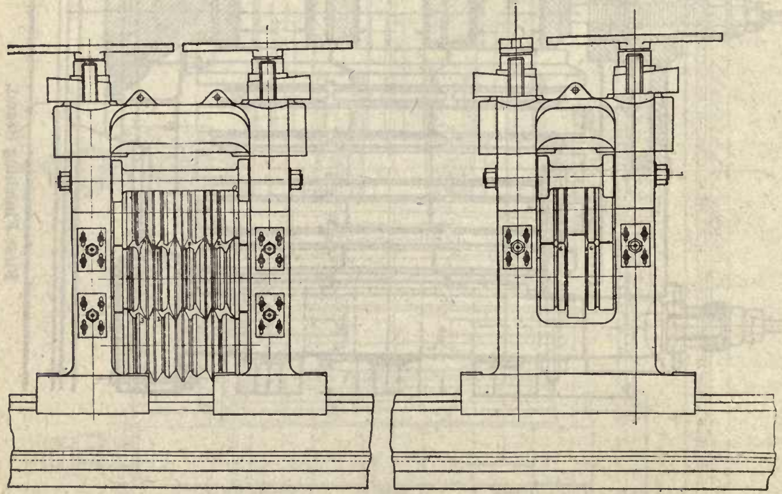
First Finishing Stand.

Rolling Heavy Rails by the Slab-and-Edging Method.

are used by the roll turner in cutting the grooves, which must be of the exact size and shape of the templets. At Edgar Thomson the roughing rolls are adamite or sand rolls, more often the latter; the second rougher, or former, are sand rolls; and the finishing are chilled rolls.



1st Roughing Stand. 1st Finishing Stand.



2nd Roughing Stand. 2nd Finishing Stand.

Fig. 79. Plan Showing Arrangement of Rolls for Diagonal Rolling of Rails from Billets

**The Diagonal Method** of rolling is represented on the accompanying cut of a light rail mill where this method is employed altogether. It differs from the slabbing method in that the shaping of the rail is begun with the first pass in the roughers and, instead of first compressing the bloom to a smaller size and then forming the section partly through compression and partly by spreading, the process is one of compression from beginning to end, as must be evident from observing the position of the piece in passing through the rolls. From a quality standpoint the method is thought to possess some advantage over the slabbing method by virtue of the fact that a greater amount of work is done on the tops of the head and flange, where it is needed. From the operator's standpoint it would seem to have both advantages and disadvantages. As an instance of the former, it is pointed out that the angular grooves make it easier to redress the rolls and tend to give them a greater life, because the cuts to restore the section need not be so deep. To restore a section of the flat grooving, cuts as deep as one-half inch are usually required on smaller sections, while as much as three-fourths inch is needed on the larger ones. The chief disadvantage of using the method lies in the great side thrust of the rolls, which is very undesirable and difficult to provide for. It also requires more roll space than the flat method for the same number of passes.

**The Mills:** There are four rail mills at the Edgar Thomson plant, but one of these, the oldest, is used exclusively for rolling sheet bar, billets, etc. Of the mills used for rolling rails, No. 1 mill is the older. It consists of three stands in tandem, each separately driven. The first roughing stand is driven by a 40″ x 78″ x 60″ horizontal vertical compound condensing engine, and the rolls are twenty-eight inches in diameter. The second stand, driven by a 50″ x 78″ x 60″ tandem compound condensing engine, contains rolls twenty-seven and one-half inches in diameter. The finishing stand, which is two-high, is made up of rolls twenty-five and one-half inches in diameter, and is driven by a 32″ x 56″ x 48″ tandem compound condensing engine. This mill, originally built for a twenty-four inch mill, is evidence of the rapid increase in the size of roll sections and the extremities the mills are put to in order to meet the demands made upon them for heavier rails. The mill now rolls rails from twenty-five pounds to one hundred pounds per yard. The No. 2 mill was completed in the early part of 1916 and is designed to roll rails up to one hundred fifty pounds per yard, which weight, it is hoped, will meet all demands for some years to come. Up to 1918 the largest section rolled was a hundred thirty pound rail. In this mill all the rolls are thirty-two inches in diameter, when new. The pitch of the pinions is twenty-nine inches, which adapts the mill to rolls as small as twenty-eight inches in diameter. Like the No. 1 mill, the No. 2 is made up of three trains in tandem, but the first roughing train contains two stands in order to provide ample roll space for rolling large sections by either the flat or diagonal methods. The bodies of the rolls in the first three stands are sixty-four inches in length, while in the finishing this dimension is reduced to forty inches. The first and second trains are driven by 50″ x 78″ x 60″ tandem compound engines. The fly wheels on these engines weigh 100 tons each, and the speed of the engine is about 60 r. p. m. The third train is driven by a 44″ x 74″ x 54″ horizontal vertical compound engine, which has a speed of 65 r. p. m. The first or roughing stands on each of these two mills are served by lifting tables, and the intermediate stands by tilting tables. The No. 3, an eighteen inch mill, employs 19″ x 42″, 19″ x 38″ and 19″ x 20″ rolls, and rolls rails from twelve pounds to forty pounds per yard. It consists of two trains in tandem, each of two stands; number one and number three stands, both three-high, make up the first train, while number two, a three-high stand, and the two-high finishing stand are in the second train. Each train is independently driven by a 1500 h. p. electric motor. Rails rolled on these mills have distinguishing marks. Thus, heavy rails rolled on the No. 2 mill have the sign, ⊖ , rolled on the web, and light rails rolled on the No. 1 mill are distinguished by the sign, ═, similarly located.

**Rolling Heavy Rails:** After the rolls have been properly turned they are placed in the housing in their proper positions and carefully lined up. A trial rolling on a short bloom will then be made, and during this rolling the boss roller will watch the piece closely to see that it goes through the mill all right. If the section is a new one, the roll turner and designer will also be present to watch the trials. If the trial piece goes through the mill without causing trouble, a section is sawed, cooled, and examined by the roller and roll designer. In doing this, the piece thus rolled is gauged by means of the male and female templet which the designer has furnished the roller. If this section is found to be correct, the mill is then ready to begin the rolling, which is really the simplest part of the process. The roller watches the mill closely to see that everything is running right, and at frequent intervals will gauge and examine samples of the rails. In addition, he walks down to the cooling bed about every fifteen minutes to examine the rails for any defects that may be caused in the rolling, such as collar marks, underfills, roll marks, overfills, guide marks, cracks or seams. If he finds a defect in rolling, he hastens to make the necessary adjustments to correct the trouble.

**Unavoidable Variations:** One of the things that cannot be avoided in the rolling is the wear of the rolls. While it occurs over the entire surface of the groove the parts of the groove subject to fastest wear are those which do the greatest work. Referring to the photograph of the drawing for the pass templets, it may be seen where the greatest wear will take place. This results in a decrease in the fishing of the rail as shown in the following sketch. It is also a difficult matter to keep the base perfectly flat, because the high collar in the finishing passes supporting this part of the rail tends to wear away the edges faster than at the bottom of the groove.

The slight overfill that results produces the defect known as the **rocking base.** This wearing is very rapid, and with the mill running steadily, one dressing of the rolls lasts but from twenty-four to thirty-six hours.

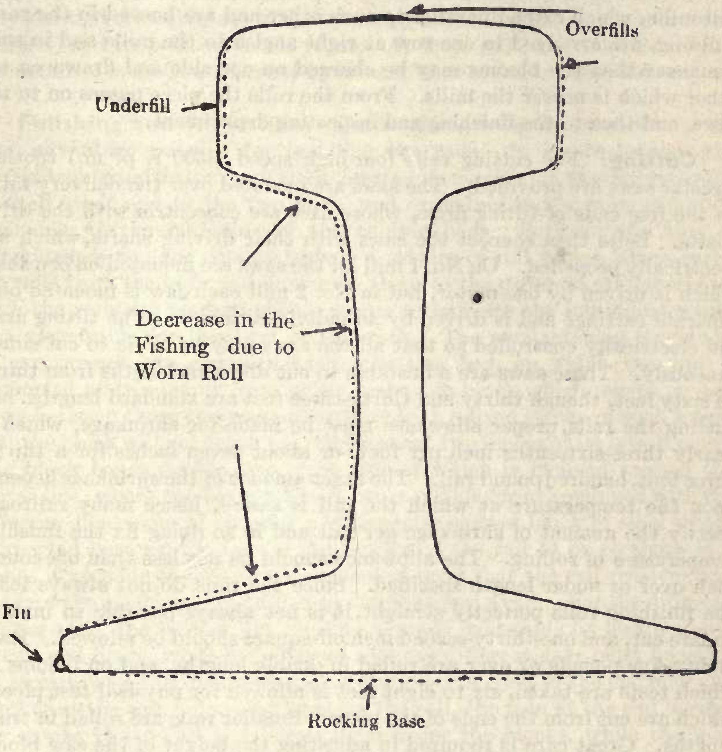


FIG. 80. Showing Defects in Rails Due to Wearing of the Rolls.

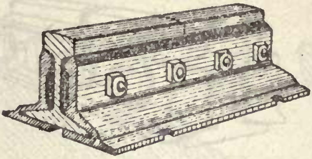
**The Various Steps in Shaping of Rails:** To trace the material from the ingot, the work begins at the forty-eight inch mill previously mentioned, where the very slow speed and relatively great reduction gives more of the pressing and less of the stretching effect of rolling, and is intended to avoid much of the danger of tearing or cracking the ingot. The large fillets used in the grooves keep the corners of the ingot well rounded. This mill, reducing the ingot from 23½″ x 23½″ to 15½″ x 18½″ leaves less work than usual to be done on the three-high bloomer which produces a 9½″ x 9½″ bloom. From the bloomer the long bloom passes to the shears where the proper discard, which is varied in different specifications, is made, and blooms of different lengths are cut to suit the conditions. Large rails are rolled two lengths to the bloom, while lighter ones may run into three lengths to the bloom. Leaving the shears, the blooms travel on roll tables to a distributing point, where they are sent to No. 1 and No. 2 rail mill furnaces or to No. 4 billet and sheet bar mill. The furnaces serving the two large rail mills, which extend parallel to each other and are housed in the same building, are arranged in one row at right angles to the mills and in such a manner that the blooms may be charged on one side and drawn on the other which is nearer the mills. From the rolls the piece passes on to the saws, and then to the finishing and inspecting department.

**Cutting:** For cutting rails four high speed (1500 r. p. m.) toothed circular saws are provided. The saws are mounted over the delivery table on the free ends of tilting arms, whose axes are concentric with the drive shafts. Belts then connect the saws with their driving shafts, which are electrically propelled. On No. 1 mill all the saws are mounted on one shaft which is driven by one motor, but in No. 2 mill each saw is mounted on a separate carriage and is driven by an individual motor. The tilting arms are electrically controlled so that all the saws may be made to cut simultaneously. These saws are adjustable to cut different lengths from thirty to sixty feet, though thirty and thirty-three feet are standard lengths. In cutting the rails, proper allowance must be made for shrinkage, which is nearly three-sixteenths inch per foot, or about seven inches for a thirty-three foot, hundred pound rail. The exact amount of the shrinkage depends upon the temperature at which the rail is sawed, hence many railroads specify the amount of shrinkage per rail, and in so doing fix the finishing temperature of rolling. The allowance should be not less than one-fourth inch over or under length specified. Since the rails do not always leave the finishing rolls perfectly straight, it is not always possible to make a square cut, and one-thirty-second inch off-square should be allowed. Rails eighty-five pounds or over are rolled in double lengths, and on blooms on which tests are taken, six to eight feet is allowed for physical test pieces, which are cut from the ends of the piece. Smaller rails are rolled in triple lengths. Great care is required in adjusting the height of the saw blocks in order to avoid kinking or scratching the rail, and to secure a square cut. From the saws, the rails pass under a stamping machine, which marks the heat number and the position of the rail in the ingot, the latter being designated by letters beginning with A at the top of the ingot. At Edgar Thomson the A cut is discarded on all heavy rails. About sixty feet from the stamper is located the cambering machine which consists of a set of horizontal rolls with a vertical roll on each side, all in one housing, and set to bend the rail slightly so as to make the top surface of the rail convex from end to end. A scale located near the end of the delivery table is used for checking the weight of the rails as often as desired, before they are sent to the cooling beds. The No. 1 and No. 2 mills, being arranged parallel to each other, deliver their product to what may be considered a single large cooling bed, where the rails from both mills are slowly moved in one direction, which is toward the finishing room.

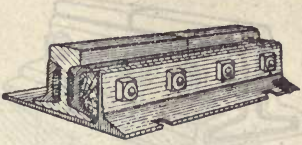
**Recording:** A complete record is kept of all the steel rolled in the mills from the time it is made in the open hearth or Bessemer converter until it is shipped. This work is done by the recorder, who traces the material through the mills, and is so complete that it is easy to show, not only the kind of steel from which each rail is rolled, but the heat, the number of ingot, and its position in the ingot. At these mills the work of tracing the material is much facilitated by the use of an electric signalling system.

**Finishing and Inspection:** The finishing room is arranged to the best advantage possible for handling the rails. In it are located the straightening and drilling machines (fourteen in number) in two rows parallel to each other and to the two mills, and extending in the same direction beginning at the mill side of the cooling beds. Between the row of straighteners and the cooling beds is a system of roll tables, which carry the rails from the beds and distribute them to the different straighteners. Here the rails are marked with a stamp to indicate the individual workmen responsible for this part of. the work. The straightening machines, or gag presses, are provided with a bottom bed, on which the rail is supported at two points from below, and a top block which moves up and down between these two supporting lines with a fixed stroke of such length that the block will not touch the rail by about two inches at its lowest point. The block has a double face, each side of which is inclined toward the center line, where the faces cut each other. This form, combined with the different dimensions of the gag, a rectangular shaped block of steel which is inserted between the face of the block and the rail to be straightened, makes it possible to control the amount of bend that the rail receives and to adapt the machine to the different dimensions of a rail. For the different sizes of rails, the faces of the blocks are made adjustable by means of set-screws and liners, while for different sections different gags must be used. To straighten a rail, one workman is stationed in front of the machine and another at the end. By sighting along the rail, the man at the end locates the crooks in the rail and brings them under the blocks, while the man before the machine, acting under directions from the workman at the end, inserts the gag in such a way that the stroke of the machine will bend the rail enough to straighten it, which requires that the rail be bent beyond its elastic limit in order to give a permanent set. Next, the burrs made by the saws on the ends of the rails are cut off with chisels, and smoothed with a file. The rails are then given a preliminary inspection by an employee of the Company, in order to avoid unnecessary work being done on rails that may be rejected. As the inspection is completed, the rails are moved to the drilling machines, which are arranged in pairs and so spaced that, when one machine has completed the drilling on one end of the rail, it is moved under the other machine which drills the holes in the opposite end. These machines are each provided with three drilling spindles, the middle of which is fixed, and may be made to drill from one to three holes at one time. The rails are then moved sidewise through openings in the building to the inspection beds where they are walked, or inspected, both by a company's inspector and by the customer's, if so specified. The outside inspection covers mainly surface defects, such as seams, slivers, guide marks, and pits that may have been overlooked by the inside inspector, and the bolt holes. The rails, having been measured and gauged by the inside inspectors and rollers, the dimensions are checked only at intervals by the outside inspector. The location of the defects are marked with chalk. If these are located near the end, that portion of the rail may be sawed off and the rail still applied on the order as a short of first grade. Rails that fall below the allowance as to length are also disposed of in the same way. If the defects are many or near the center, the rail is either classed as a number two or sent back to the mills to be rolled into a light rail. In both the inside and outside inspection, the rails are walked twice, once with the base up, again with the heads up. As the rails are accepted by the inspectors, they are counted, the number being checked up with the original order. Then they are picked up by immense magnets attached to over head electric cranes and placed in the cars where, after weighing, they are ready for shipment.

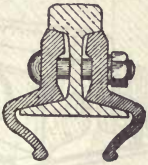
**Light Rails:** The rolling, finishing and inspection of light rails, as well as the material used, are somewhat different from the same operations for heavy rails. To begin with, the number three mill in which most of these rails are rolled, is operated as a separate unit, practically independent of the rest of the works, and with the exception of re-rollings from rejected heavy rails, all its product is rolled from billets which are obtained from other works. For this reason neither check analyses nor physical tests are made on light rails, because, even if such tests were made, there would be no way of indentifying the rail as having been made from the same steel from which the tests were taken nor of knowing that the tests represented the material in an order. The billets are heated in one of two continuous gas fired furnaces and are rolled by the angular method on six passes in the mill. Rerolled rails receive two additional passes in the first roughing stand, which is provided with tilting tables for the purpose. Leaving the rolls, the rails are sawed into lengths of thirty feet or under and are passed to the cooling beds. When sufficiently cold they receive a preliminary inspection, in which they are measured for length, and then passed through a roll straightener to punching machines where both bolt holes and bond holes are punched. Since the roll straighteners straighten the rail in one direction only and usually fail to produce a perfectly straight rail, even in one direction, gag presses are employed to complete the straightening. As for heavy rails, light rails are subject to a second, though less rigid, inspection after all work is completed. The mill is also equipped with cold saws, but cold sawing is undesirable, for it works a great hardship upon the mill, increasing the cost greatly, due to extra labor and scrap loss. For handling the rails a large gantry crane of an improved form which travels on tracks laid on the ground is provided. Light rails are weighed in cars before shipment.



Continuous Rail Joint.

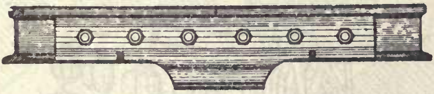


Weber Rail Joint.

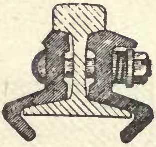


Duquesne Rail Joint.

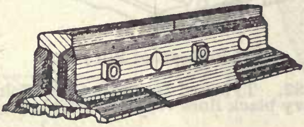
100 Per Cent Rail Joint.



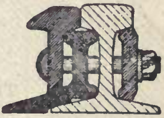
Duquesne and 100 Per Cent Joint.



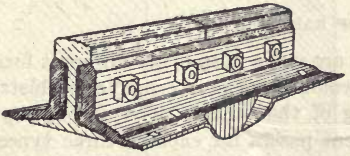
Hatfield Rail Joint.



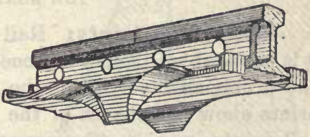
Wolhaupter Rail Joint.



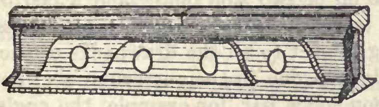
Barschall Rail Joint.



Q & C Bonzano Rail Joint.



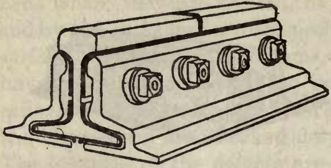
Abbott Rail Joint.



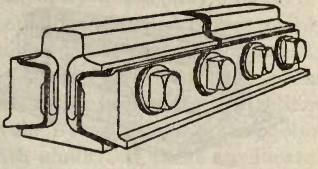
Williams Reinforced Rail Joint.

Atlas Rail Joint.

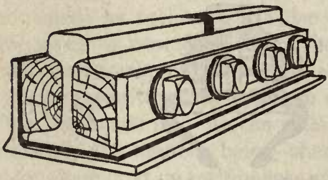
Fig. 81. Sketches Showing Different Kinds and Types of Rail Joints.



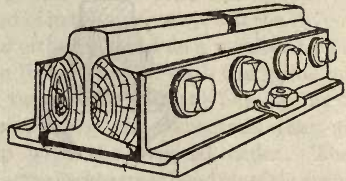
Continuous Insulated Rail Joints



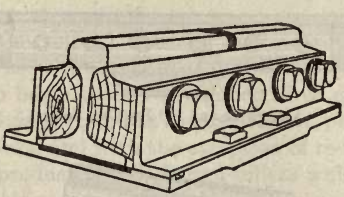
Keystone Insulated Rail Joint



Weber Insulated Rail Joint



Braddock Insulated Rail Joint



O'Brien Insulated Rail Joint

Fig. 82. Types of Insulating Rail Joints.
The heavy black lines represent insulating fiber.

## SECTION II.

### THE SHAPING OF RAIL JOINTS.

**Rolling Rail Joints:** Rail joints are made in so many different forms, it is impossible to select any one that would serve as an example to illustrate the problems involved in the rolling of the others. The accompanying prints show the shapes of the different passes for each of three types of rail joints, namely, the common splice bar, the Duquesne joint of the depending flange type, and the continuous joint of the bed plate type. The Braddock insulated joint is made up of two side plates and a bed plate, both being comparatively simple to roll. In a general way, rail joints are more or less difficult to roll, being subject to all the drawbacks of the rail section and to many others in addition, due to their irregular section and lack of symmetry. In the common splice bar, for example, the angles at which the section is rolled are limited by danger of undercuts, and the shape of the passes in which the piece is necessarily reduced are favorable to the formation of laps and seams. In the Duquesne joint, these dangers

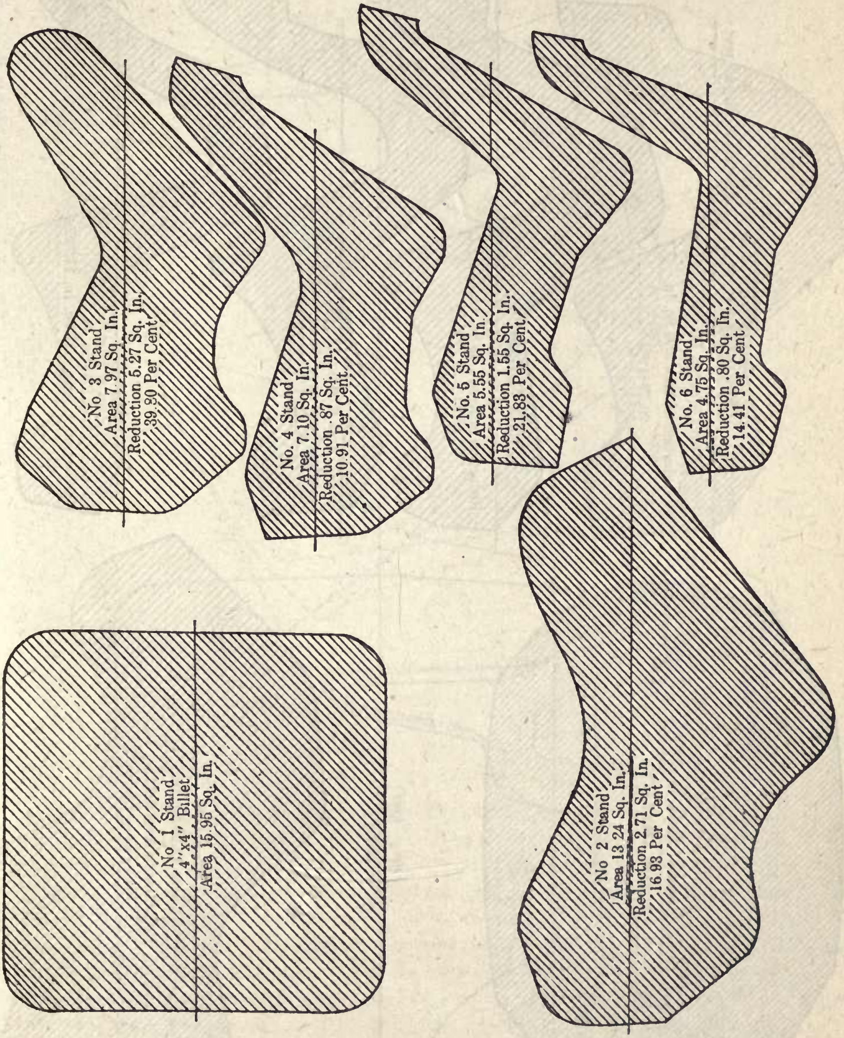


**Fig. 83.** Passes for Rolling Common Splice Bar.

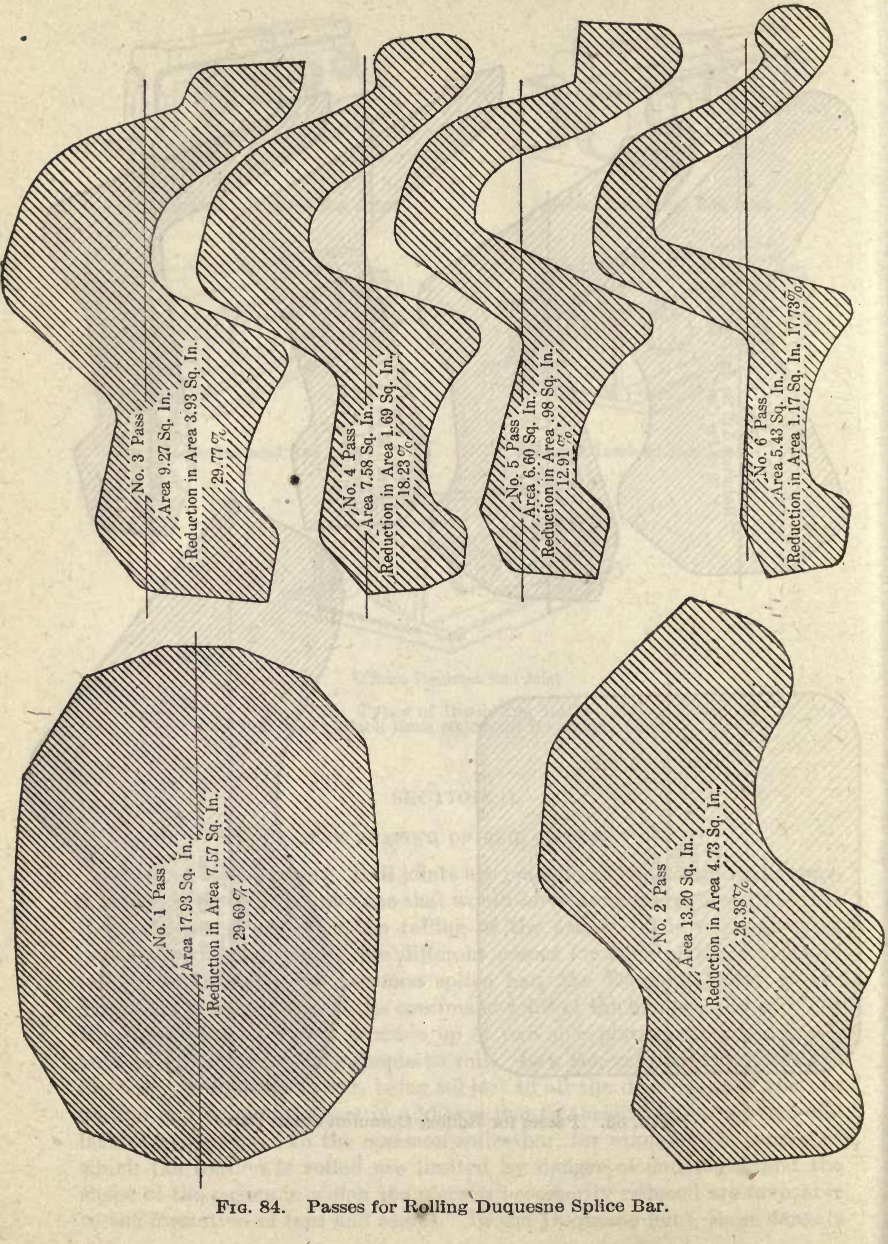


Fig. 84. Passes for Rolling Duquesne Splice Bar.

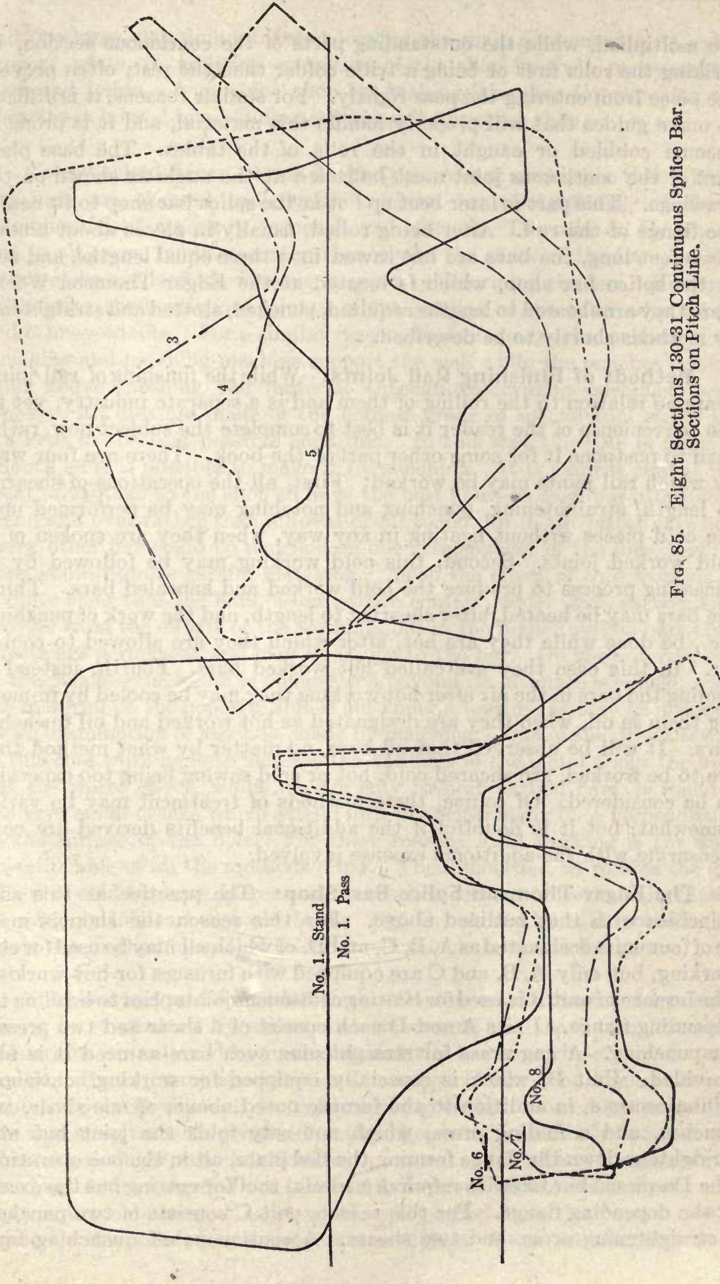


FIG. 85. Eight Sections 130-31 Continuous Splice Bar. Sections on Pitch Line.

are multiplied, while the outstanding parts of the continuous section, by striking the rolls first or being a trifle colder than the rest, often prevent the piece from entering the pass rightly. For similar reasons, it is difficult to make guides that will properly handle this material, and it is prone to become cobbled or caught in the rolls of the tables. The base plate part of the continuous joint must be rolled at the angle as shown on the drawings. This part is later bent up hot at the splice bar shop to fit neatly the flange of the rail. After being rolled, usually in pieces about ninety-three feet long, the bars are hot sawed into three equal lengths, and sent to the splice bar shop, which is located at the Edgar Thomson Works. Here they are sheared to lengths required, punched, slotted and straightened by methods shortly to be described.

**Methods of Finishing Rail Joints:** While the finishing of rail joints bears no relation to the rolling of them and is a separate industry, yet for the convenience of the reader it is best to complete the subject now, rather than to postpone it for some other part of the book. There are four ways by which rail joints may be worked: First, all the operations of shearing to length, straightening, punching and notching may be performed upon the cold pieces without heating in any way, when they are spoken of as cold worked joints. Second, this cold working may be followed by an annealing process to produce the cold worked and annealed bars. Third, the bars may be heated, after shearing to length, and the work of punching, etc., be done while they are hot, after which they are allowed to cool in air. In this case they are called hot worked bars. Fourth, instead of cooling the bars in the air after hot working they may be cooled by immersing them in oil, when they are designated as hot worked and oil quenched bars. It will be observed that all bars, no matter by what method they are to be worked, are sheared cold, hot or cold sawing being too expensive to be considered. Of course, these methods of treatment may be varied somewhat, but it is doubtful if the additional benefits derived are commensurate with the additional expense involved.

**The Edgar Thomson Splice Bar Shop:** The practice at this shop coincides with that outlined above. For this reason the shop is made up of four units designated as A, B, C, and D, of which all may be used for cold working, but only A, B, and C are equipped with furnaces for hot working. The furnace of unit B is used for heating continuous joints prior to bending the depending flange. Units A and D each consist of a shear and two presses for punching. A gag press for straightening such bars as need it is also provided. Unit B, which is especially equipped for working continuous joints, consists, in addition to the furnace noted above, of one shear, two punches, and a folding press, which not only folds the joint but also straightens down the flange forming the bed plate, all in the one operation. The Duquesne bar likewise requires a special tool for cutting out the excess in the depending flange. For this reason, unit C consists of two punches, a straightening press, and two shears. A continuous oil quenching tank and two large annealing furnaces complete the main equipment of the shop proper, while, in addition, a section of the shop is given to assembling insulated joints. A machine shop for making the dies for punching and shearing is housed in a building adjoining the working shop.

**Cold Worked Bars:** In this method the order of working is this: First, the bars are sheared to length, inspected for straightness and flaws, straightened, if necessary, punched and slotted. The dies on the shears are, in all cases, made to conform exactly to the shape of the bars, so that a nice clean cut is made without in any way deforming the bar. However, in shearing the continuous joint, a slight bending of the outer edge at one end is unavoidable. For a similar reason, the bottom blocks, or dies, of the punching and notching machine support the web while the punches descend from above, pushing the material through conforming openings in the blocks. All dies are made of the highest grade of special tool steels and are kept in the best possible condition. In this way the hole is made as smooth as it is possible to make it by punching. It is evident that it is a great advantage to the shop to have the bolt holes on each bar alternately round and oval rather than all oval or all round, for in the latter case only every other bar could be punched on one arrangement of the dies, and the bars would require careful matching. As to the effect of cold working, it is quite clear that the bars of low carbon content, under .28% carbon, soon recover from the effects of the working, but in the higher carbon bars these effects are permanent and may do injury to the bar. On the entering side of the punches the metal is compressed beyond its ultimate strength, while the material on the opposite side is put under a tension, as may be observed by an examination of any hole made by punching. One of the direct results of this cold working is to increase the hardness of the metal about the hole, but the worse effect, which applies only to high carbon bars, is found in the very small cracks which extend into the metal along lines perpendicular to the surface of the hole. For these reasons, cold working is the most objectionable of all the methods cited. The difficulties, as well as the evil effects of cold working, increase as the carbon content of the steel increases. Hence, only low carbon bars (below .28% C.) should be cold worked. As a rule the method is applied to the smaller angle bars and fish plates.

**Cold Worked and Annealed Bars:** The fine cracks due to cold working cannot be eradicated by subsequent treatment, but the internal stresses and strains are relieved by annealing and the bar as a whole is made more ductile. Hence, some specifications, more particularly on angle bars and insulated joints, will call for cold working to be followed by annealing. The annealing furnaces provided at this shop are divided into two sections, a heating chamber, which is fired with natural gas, and a cooling chamber. The bars to be annealed are piled, crib fashion, upon steel supports that rest on brick bottomed cars, which are pushed into the furnace. The furnace is then heated to a temperature slightly above the critical point of the steel. The proper temperature once reached, it is maintained until all the steel is thoroughly heated, which generally takes about two and one-half hours. The heat is then turned off and all doors in the furnace are closed. The steel is now pushed into the cooling chamber, where it is allowed to cool slowly. During this time the doors are closed tightly to prevent, as much as possible, scale forming on the steel. The cooling requires about two and one-half hours. After the steel is cold, the cars are pushed out of the furnace, and the bars are loaded on cars for shipment.

**Hot Worked Bars:** In hot working common angle bars, the order of procedure is as follows: shearing to length, heating, punching, notching, straightening, if necessary, and cooling. Patented bars may require additional operations. Thus, in working the Duquesne bar, the excess flange is sheared off after the heating and just before the notching. In hot punching any bar, in order to avoid spreading of the metal and consequent distortion of the bar, it is necessary to employ a confining die, that is, the cutting die must be enclosed in a die block or frame, the upper surface of which, together with the die itself, conforms in shape to the inside surface of the bar. Hot worked bars must, therefore, be punched from the outside, or inward. Most cold worked bars may be punched from the inside, or outward, as there is no danger of spreading the metal and enclosed dies are not necessary. The straightening machines are presses provided with a set of dies for each size of each section. One die conforms to the size and shape of one side of the section and the second die to the other side, and both are set in the press so that at the end of the stroke the space between the dies is of the same shape as the bar and just equal to it in thickness. As a rule the higher carbon angle bars, Duquesne and continuous joints are hot worked. In case the continuous joints are cold worked, they must be heated before the flange is bent down. The furnaces employed for hot working are of the continuous type. They are rectangular in shape and wide enough to admit two rows of bars laid end to end. Natural gas is the fuel used. In order to obtain an even distribution of the heat, the furnace is provided with four ports, and in addition four large burners of the Bunsen type are located at the bottom along each side of the furnace to supply heat under the bars. Recording pyrometers are employed, so the exact temperature of the furnace may be ascertained at any time. After being sheared to length, the cold bars are laid upon water cooled skid pipes and pushed into the furnace from the rear by means of electrically operated dogs. The length of the furnace and rate of charging is such that about two hours are consumed in pushing each bar through the furnace, this time being sufficient to bring the bar to the working temperature of about 800° to 830° C., which is a little higher than necessary for working, as the temperature drops by the time the bar reaches the machine to 790° or 815°. The skids end near the front of the furnace, and the bars descend to a hearth, whence they are removed with tongs through doors. Needless to say, the bad effects of cold working are entirely avoided by hot working.

**Hot Worked and Oil Quenched:** In this method, not only are the evils of cold working avoided, but the strength and ductility, or toughness, of the bar are much improved, also. The method, which is especially applicable to high carbon angle bars and Duquesne joints, consists in hot working the bars in the usual way and quenching them in oil before they have cooled to a temperature below that of the critical range. The necessity of completing the work before the temperature drops below this point may require the bar to be heated to 30° or 40° C. higher than for ordinary hot working, and permits no delay in the operation. For quenching the bars, a continuous oil tank in close proximity to the presses is provided. The tank is rectangular in shape and provided with a chain conveyor, which slowly carries the bars through the oil, the speed of the chain and its direction of travel being so regulated that the bars, upon entering at one end of the tank, are carried down into the oil, across the tank, and up to the opposite end and are cooled to 70° C. or less. The oil used is a special grade of petroleum product that will not get viscous and has the most favorable cooling properties. In order to keep it cooled to the proper temperature, the oil from the quenching tank is pumped through a set of water cooled pipes and into a large storage tank. The fresh oil for the quenching tank is pumped from the bottom of this tank. By means of this circulating system the temperature of the oil is kept, usually, at about 60° C. The temperature of the oil is taken at intervals of an hour or so to make sure its temperature does not rise too high.

## SECTION III.

### STRUCTURAL AND OTHER SHAPES.

**Plan of Study:** It is needless to remark that a detailed description of the rolling of each of the many sections included under this heading would result in a very lengthy discussion, and it is doubtful if such a discussion would prove to be of much value in accomplishing the ends at which this book aims. Besides, while the rolling of each shape or section presents difficulties peculiar to itself alone, there are certain problems common to all sections, and of these general features an example has already been given in the description of the rolling of rails. Unlike rail mills, structural shape mills vary much, both in type and equipment, and often the methods for rolling a given section must be adapted to the mill conditions. In general, the size of the section, for economic reasons, will determine the size of the mill, and the different sizes of the same section will be rolled on different mills. No one mill, therefore, can be selected as an example of the rolling of even one of these shapes. For these reasons a brief and more or less general discussion of the different roll designs for some of the more common sections is all that will be attempted here, and it is hoped the study will be found both interesting and profitable.

**Angles:** Among the first shapes to be rolled was the angle. Three methods of rolling this shape have been developed. In two of these methods the forming of the angle is begun from a rectangular bloom, or if the bloom is square, from a rectangular roughing pass in the mill. In what may be termed the first method, the grooves are so designed that each successive pass from the slab approaches the right angle of the finished bar, the piece being gradually bent and reduced at the same time. In the second method, called the butterfly method, the legs are kept flat until the leader and finishing passes, when they are bent to form a right angle. In the third method, the forming of the angle is begun from a rectangular bloom by first working off one corner and then recessing it till the desired thickness of the legs is obtained.

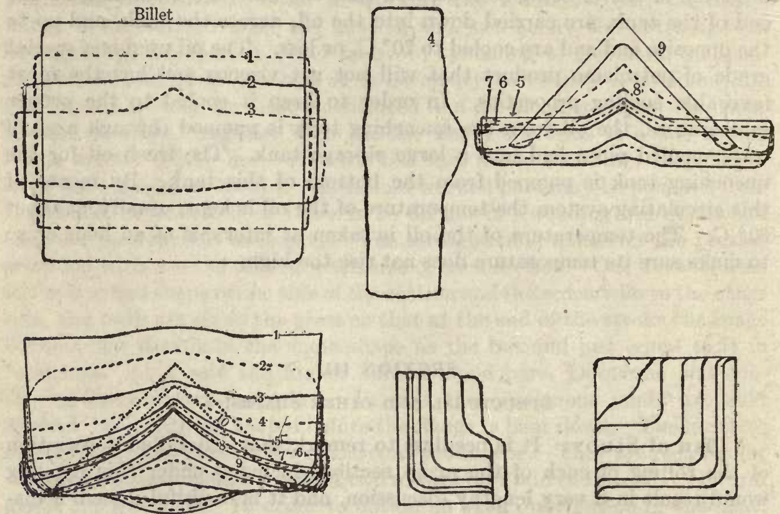
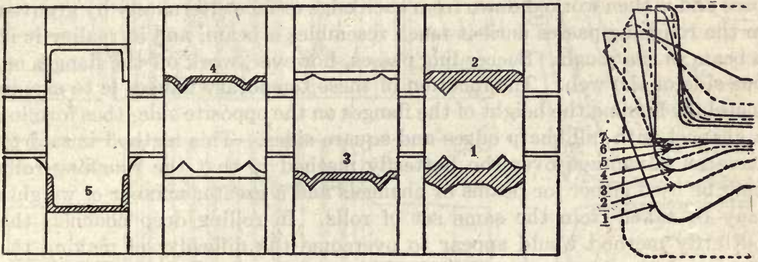
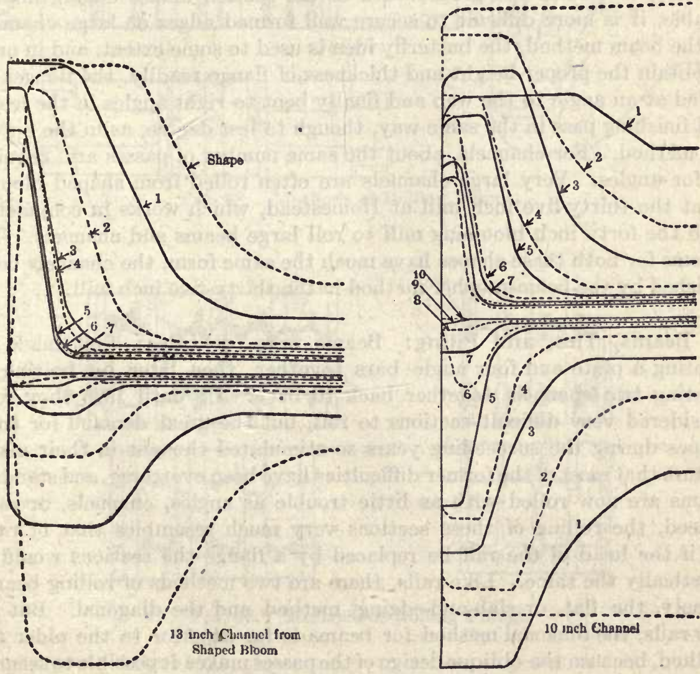


Fig. 86. Methods of Rolling Angles.

**The Three Methods Compared:** The part of the angle that gives the most trouble in rolling is the back and the apex, which must be square and sharp. As shown in the accompanying sketches, this difficulty is overcome in the first and second methods by reserving metal in the first passes on both sides of the bar where the apex is to be formed. In the last passes this excess metal is available to fill out what would be lacking on account of the bending, which tends to draw the metal down from the apex. In the third method the apex and back are perfect from the beginning. As to the relative merits of the three methods, there is, of course, much difference of opinion. However, there are two features about the butterfly method that appears to a decided advantage when compared with either of the other two. The ability to employ an edging pass so near the finishing to control the width makes it possible to reduce the piece rapidly in the roughing passes and so cut down the total number of passes required to form the section. Then, too, since nearly all the work on the section is done in the flat passes, the difficulties encountered when deep grooves are used in the rolls are entirely avoided. Usually angles are formed in from nine to eleven passes.



Butterfly Method for Channels as first designed



13 inch Channel from Shaped Bloom

10 inch Channel

Fig. 87. Methods of Rolling Channels.

**The Channel:** Channels are rolled by two distinct methods known as the butterfly and beam roughing methods. The butterfly method is said to have originated in the year 1873 at the Upper Union Mills of Carnegie, Klowman & Co., and is sometimes called the slabbing method. In being formed by this method, the section resembles two angles being rolled side by side in one set of grooves, and by the same butterfly method. In the second method the bloom, in the rectangular form, is edged for the first pass and is then worked down from each edge or face alternately by grooves in the roughing passes until it much resembles a beam, and in reality it is a beam in the rough. Succeeding passes, however, work off the flanges on one side of the web. The function of these temporary flanges is to supply metal for holding the height of the flanges on the opposite side, thus forming a channel with full sharp edges and square sides. This method is said to have an advantage over the butterfly method in that the roughing rolls may be used either for beams or channels and a greater number of weights may be taken from the same set of rolls. In rolling deep channels the butterfly method would appear to overcome the difficulty of making the flanges nicely, but more roll space is required than in the beam roughing method, and since the great width of the section makes edging impracticable, it is more difficult to secure well formed edges on large channels. In the beam method, the butterfly idea is used to some extent, and in order to obtain the proper height and thickness of flange readily, the flanges are rolled at an angle to the web and finally bent to right angles in the leader and finishing pass in the same way, though to less degree, as in the butterfly method. For channels, about the same number of passes are required as for angles. Very large channels are often rolled from shaped blooms, as at the thirty-five inch mill at Homestead, which works in conjunction with the forty inch blooming mill to roll large beams and channels. The blooms for both these shapes have much the same form, the channels being finished by the beam-rougher method in the thirty-five inch mill.

**Beams, Ties, and Piling:** Beams were, doubtless, first made by riveting a plate and four angle bars together, then later by bolting or riveting two channels together back to back. Up until 1895 they were considered very difficult sections to roll, but the great demand for these shapes during the succeeding years so stimulated thought in their manufacture that most of the former difficulties have been overcome, and standard beams are now rolled with as little trouble as angles, channels, or rails. Indeed, the rolling of these sections very much resembles that of rails, for if the head of the rail be replaced by a flange the sections would be practically the same. Like rails, there are two methods of rolling beams, namely, the flat, or slab-and-edging, method and the diagonal. But unlike rails, the diagonal method for beams is far superior to the older flat method, because the oblique design of the passes makes it possible to secure a much greater length of flange than was ever produced by the first method. This advantage is forcibly illustrated in the steel tie section, the rolling of which was first successfully accomplished at Homestead. This section with its very thin flange, which has almost no taper, would have been looked upon, fifteen years ago as an impossibility from a rolling standpoint, and is considered one of the greatest achievements in roll design. U. S. steel piling

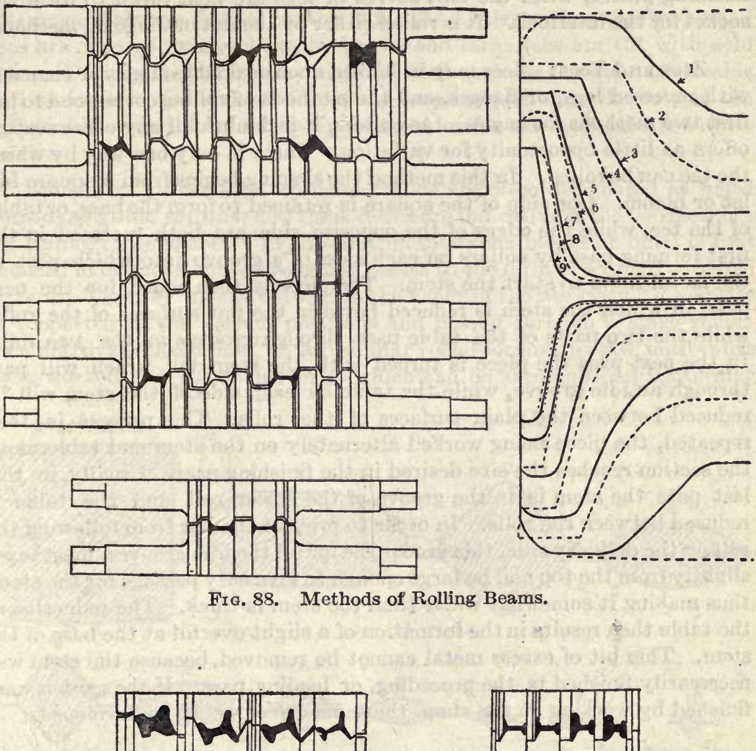


Fig. 88. Methods of Rolling Beams.

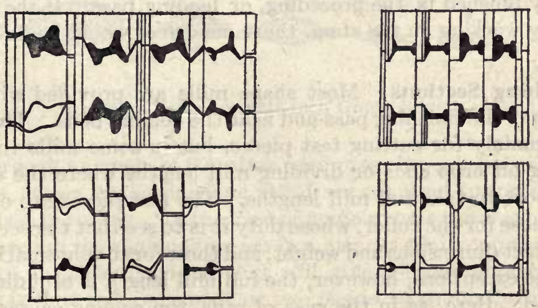


Fig. 89. Methods of Rolling Piling.

is another section which much resembles the rail in rolling. Here, the ball and web of the piling, as finished, is almost a duplicate of the head and web of the rail, and the remainder is rolled as a flange up to the leading and finishing passes, when the two halves or legs are bent down to form the socket for the interlock. It is rolled either by the flat or diagonal methods.

**Zees and Tees:** Zees may be looked upon as double angles or channels with reversed legs, or flanges, and the methods of rolling correspond to the first two methods for angles. As to tees, it is doubtful if any other section offers as little opportunity for variation. There is only one way by which the tee can be rolled. In this method the shaping begins from a square billet or bloom. One side of the square is retained to form the base, or table, of the tee, while the edges of the opposite side are both recessed in the first forming pass by collars on each side of a groove into which part of the metal flows to start the stem. The piece is then edged for the next pass, in which the stem is reduced between the flat surfaces of the rolls, while the two parts of the table pass through grooves in the two rolls. In the next pass the piece is turned with the stem up, which will pass through an idle groove, while the table on each side of the stem will be reduced between the plain surfaces of the rolls. This process is then repeated, the piece being worked alternately on the stem and table, until the section reaches the size desired in the finishing pass. Usually, in this last pass the stem is in the groove of the lower roll and the table is reduced between the rolls. In order to prevent the bar from following the roll on the delivery side, this groove, as for all the idle grooves, must taper slightly from the top and be large enough to give easy passage for the stem, thus making it somewhat wider than the stem is thick. The reduction of the table then results in the formation of a slight overfill at the base of the stem. This bit of excess metal cannot be removed, because the stem was necessarily finished in the preceding, or leading, pass. If the section were finished by working on the stem, the same defect would be developed.

**Finishing Sections:** Most shape mills are provided with hot saws located after the finishing pass and near the cooling beds. These saws are intended mainly for cutting test pieces, but in some mills they are used for cutting off crop ends or dividing mill lengths where the cooling beds are too short to take full mill lengths. The test pieces are of two kinds, namely, those for the roller, whose duty it is to see that the section is rolled to the correct dimensions and weight, and those for the physical laboratories. With these exceptions, however, the full mill length is sent directly to the cooling bed. Here, as in the case of rails, the cooling causes the shapes to bend considerably, and cold straightening is necessary. For this purpose, the piece is next passed through a cold roll straightening machine, and if necessary through a gag press. The roll straightener is capable of straightening in one direction only, so that if, through handling or other cause, the piece has been twisted or bent laterally, it can be made straight, in all directions, only by using a gag press after the roll straightener. From the straighteners the material passes the cutting machines, which, in order to keep up with the mill, must be either shears or cold saws. For this reason, exact cutting to length is out of the question, and a liberal cutting tolerance is always desired by the mill. As a rule, angles, zees and small tees are sheared, while channels, beams and large tees are cut with cold saws. During the cutting, any material that contains the more noticeable defects is discarded and cut into scrap lengths, and after the cutting the material is subjected to a very rigid inspection for the most minute surface defects.

**Rounds:** In the steel business, rounds are often designated as **hand rounds** or **guide rounds,** and these terms are indicative of the two methods for rolling these shapes. In the first method, the bloom or billet is first reduced in diamond shaped roughing passes to the form of a round cornered square. Then, by means of tongs in the hands of the workmen, this square is supported in the correct positions and passed through a single round-forming, oval-shaped pass, or two similar round-forming passes, until it has been worked into the round form, which can be accomplished by turning the piece through an angle of 90° after each pass through the rolls. From three to five passes in the finishing stand are required to form the round by this method of rolling. In the case of guide rounds the size of the billet may be reduced in the roughing passes in a manner similar to that for hand rounds, or by any other method that will give a round cornered square. This square is then reduced in one or two passes to an oval, which is then edged, and while supported in this position by a guide, it is put through a round finishing pass. The compression in this pass shortens the long axis, while the spreading of the metal lengthens the short axis of the oval to equal the radii of the round. In a general way, large rounds, that is, those over two inches in diameter, are rolled by hand, while small rounds,

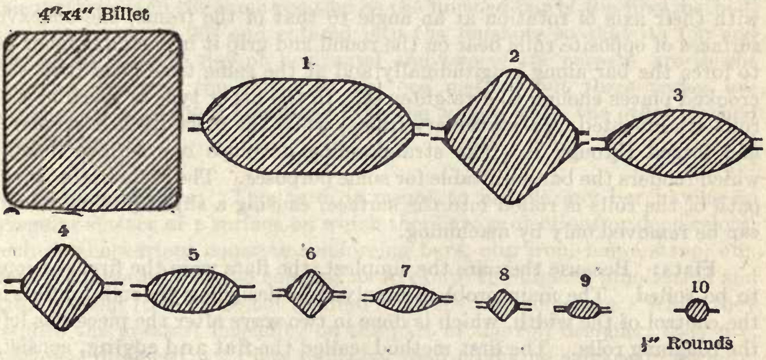


Fig. 90. Rolling a Half Inch Guide Round.

less than two inches in diameter, are rolled with guides, but there is a narrow range from about one and three-fourths inches to two and one-half inches where either method may be employed. Regarding the relative merits of these two methods, hand rounds are by many preferred to guide rounds where great accuracy and uniformity in diameter are required. However, guide rounds are now rolled with a high degree of accuracy, and since the uniformity and accuracy of the hand rounds depends on the skill of the workmen, it is doubtful whether equal care and attention applied to both methods would leave, on the average, much wherewith to choose between them.

**Cutting and Straightening Rounds:** In order to keep up with the mills, rounds are either hot sawed or cold sheared to convenient lengths, and neither method is at all exact. Hence, in these lengths, either single or multiples of those desired, proper allowance must be made for the exact cutting, which is performed by special cutting machines after the round is straightened. The straightening may be done either on the gag press or on special straightening machines, called from the inventors the Brightman and Abramsen straighteners. The Brightman consists of two rows, or sets, of concave rolls mounted upon opposite sides of a revolving frame, so that, with their axis of rotation at an angle to that of the frame, the concave surfaces of opposite rolls bear on the round and grip it in such a manner as to force the bar along longitudinally and at the same time bend it at the crooked places enough to straighten it. In the other type of machine the rolls are mounted on a stationary frame, while the piece itself is revolved and forced through it. The straightening develops one serious defect, which renders the bar unsuitable for some purposes. The scale in the spiral path of the rolls is rolled into the surface, causing a slight pitting, which can be removed only by machining.

**Flats:** Because they are the simplest, the flats were the first sections to be rolled. The main problem involved in designing the rolls for flats is the control of the width, which is done in two ways after the piece has left the roughing rolls. The first method, called the **flat and edging,** consists merely of rolling the piece on edge at intervals in deep grooves cut in the rolls. The other method of controlling the width lies in the use of the tongue and groove passes as described under the rolling of sheet bars, and is best suited to the rolling of thin material. In this method the last two passes will be between plain rolls, while in the flat and edging method the planisher will be an edging pass. It is in this pass that the three different edges on flats are formed. Thus, if the bottom of the groove is flat, a common swell or oval edge will be formed by the spreading of the material in the center, which is hotter than the outside; but if the base of this groove is made sufficiently concave, the edge of the bar will be round; if convex, a square edge will be formed. In the eighteen inch mill at Clairton and also in the fifteen inch mill at Lower Union City Mills there is used, next to the finishing pass, a set of vertical rolls, which eliminates the difficulty of rolling a wide thin flat in an ordinary groove.

**Hexagons:** There are two methods used for rolling hexagons. By one method all six corners are formed in the rolls, three in the top and three in the bottom. The clearance between the rolls in this case comes on opposite flat surfaces of the bar. In this manner of rolling, the corners of the hexagon cannot pinch out. Hexagons rolled thus are best suited for cold drawing purposes as they will be free from pinches which draw out into laps. In this method, the first pass in the strand, or first former, is a square which has been broken down from the billet in the roughing and pony roughing stands. The square is then put into the second strand, or former, and comes out in the form of a six sided flat, the two widest sides of which are convex. The bar is then edged into the leading or planishing pass where a reduction of about 25% takes place, in the case of small hexagons. The bar coming out of this pass has six sides as before but has two of its corners formed by the clearance of the rolls. The top and bottom sides are slightly concave to allow for the spread as the bar is edged into the finishing. Here the bar is given a light draft, in order to square it up, the reduction being only 8 to 10%.In the other method two of the corners of the finished bar are formed at the clearance of the rolls, and hence care must be taken to keep these corners from pinching out. The bar coming out of the planishing in this method, is in the same position as the finished bar of the first method. The bar is turned 90° and entered into the finishing so that its top and bottom surface are flat or horizontal and two of its corners are in the clearance between the rolls. In the one method but three passes are required to form the finished bar from the square while the other method requires four.

**Deformed Bars:** This term is meant to include any bar having an irregular surface or a surface on which there are projections or depressions, such as the various concrete reinforcing bars, clip iron, hame strap, etc. Some of these bars are so complex as to excite the highest admiration and astonishment from those not familiar with their manufacture. While they require the greatest ingenuity on the part of the roll designer, they are, however, produced with less difficulty than might be supposed. Briefly, the secret of their formation consists in first working the metal down through the ordinary passes to one of the common forms, such as a flat, square, round, or oval, whichever is best for forming the bar desired, and then putting it through one or two deforming grooves containing the necessary recesses or elevations. It is here the chief trouble occurs. As the deformations must be made in the finishing pass, or the leader and finishing combined, a heavy draught in these passes is necessary, and the metal is usually, even with the fastest working, at a very low temperature for working. These conditions put a heavy strain on the mill, and, owing to the lack of plasticity in the metal, the projections will not fill out easily. In order to avoid vibrations which cause the bar to slip in passing through the rolls, thus causing the deformations to be made at irregular intervals, mills rolling these sections are provided with separately driven finishing stands

# CHAPTER IX.

# THE ROLLING OF STRIP AND MERCHANT MILL PRODUCTS

## SECTION I.

### STRIP, OR HOOP, MILLS AND THEIR PRODUCTS.

**Meaning of the Word Hoop:** As originally applied, the word hoop meant that light narrow material which, cut into short lengths, was used to bind casks, barrels, buckets, and the like, but as now employed the word is a class name that stands for a large number of products. The Carnegie Steel Company, for instance, uses the term to cover all materials from 13 gauge to the thinnest material rolled on their mills, and from three-eighths inch to eight and five-eighths inches in width. This range covers material used for a great variety of purposes in addition to hoop, such as skelp for tubes, blades for knives, and blanks for stamping hundreds of hardware specialties, a class of material that should represent a little better grade than ordinary hoop. In a way, this use of the word hoop is unfortunate, especially as a more suitable class name is supplied by the term strip. With strip for a class name, hoop would have retained its original meaning, for which there is no substitute, and all danger of ambiguity would have been avoided.

**Hoop as a Rolling Specialty:** Being, perhaps, the largest producer of strip in the country, the Carnegie Steel Company's mills furnish the best example of the equipment and organization required to roll this class of material. A specialty mill is not a mill that rolls a specialty nor a variety of specialties, but one that has specialized in the rolling of a single product. According to this definition, and using the term hoop in its broad sense as outlined in the preceding paragraph, the hoop mills of this company are best described as specialized specialty mills, because they are laid down, not for the general purpose of rolling hoop or strip, but in such a manner that each mill is designed and equipped to roll a certain kind or grade of hoop. The advantage of such a system is at once evident, making it possible for the mills to meet the many demands of the trade most readily. Thus, they are able to give accuracy, where accuracy is required; finish, where finish is desired; quantity, where quantity is the main consideration; and all with a better quality to the customer and at a greater saving to the producer than would be possible in any other way.

**The Carnegie Hoop Mills:** From what has just been said, it will readily be surmised that the hoop mills of this company are many in number and of various types, and no detailed description of all of them can be expected. This excuse will be better appreciated when it is known that their hoop mills number no less than twenty-five, and among these at least six types, or designs, of mill are represented. However, these mills present certain features of a general nature, for the omission of which no valid excuse can be found. In size their hoop mills range from seven to twelve inches, the most common size being eight and ten inches. In some of the mills the different stands of rolls will vary in size. Thus in the McCutcheon No. 6 Mill, eleven inch rolls are employed in the roughing stands, nine inch in the intermediates, and eight inch in the planisher and finisher. The rolls may be of different sizes in the same stand, also, as will be explained later. As to the materials of which the rolls are made, the roughing rolls may be of steel and the intermediates of sand or adamite, but the finishing rolls are always of the hardest chilled iron. The number of stands in these mills vary from eight to twelve per mill, and their arrangement is such as to produce the kind of hoop desired to best advantage, as will be more clearly explained later.

**Methods of Rolling Hoop:** While hoop of the heavier and medium gauges and narrower widths is successfully rolled by the flat and edging method, it is readily understood that this method is not applicable to all sizes of hoop. After the material leaves the roughing rolls there is but one way remaining, then, by which it can be reduced, and that is by the tongue and groove method already described. These tongue and groove passes will be found to be three or four in number, though only two are used in some of the mills, and to be followed by two or three stands of plain rolls. As to the manner of breaking down in the roughing stands, there are two methods of rolling—one in which the billet is reduced by flat and edging passes and another in which the roughing passes are ovals and squares. The latter method gives a more rapid reduction, and will be employed usually where only two roughing stands precede the tongue and groove rolls.

**Precautions Required in Rolling Hoop:** The chief difficulty encountered in rolling this light strip lies in getting the hoop through the rolls before it becomes too cold to roll, or in keeping the temperature uniform at the finishing roll, which is necessary to produce a strip uniform in gauge. Considering the rapidity with which the metal is cooled on account of the thin section and the chilling effect of the cold rolls, the accuracy as to gauge and width maintained by the hoop mills is little short of astonishing. In this case the ingenuity of the engineer who builds the mill and that of the roll turner who designs the rolls are both required, in addition to the skill of the rollers, to produce the desired result. By reducing the number of passes to a minimum in the ways already described, the roll designer has done his bit, but even then the last end of a long strip will be cooled to a temperature so much lower than the first that it will finish several thousandths of an inch thicker, unless the mill is adapted to rolling it. These drawbacks are overcome by a combination of ingenious schemes. First, the mill is run at as high a speed as practicable. Second, it is arranged and operated so that as little time as possible intervenes between passes. Thus, in the more modern hoop mills, roughing rolls on the continuous plan are used, and these are placed very close to the furnace, whence the billet, being at once reduced in the two or three roughing passes, passes over roll tables to the tongue and groove rolls, which are arranged on the continuous plan or in train. If the latter plan is followed, mechanical repeaters are employed for short lengths, or the piece is looped from pass to pass by hand, by which means it may be rolling in two or more stands at one time. In order to avoid having the loop, which increases with the length of the piece, run far out on the floor, and thus become chilled, each pass following the tongue and groove passes is made to run as much faster as its predecessor as is necessary to take up the slack due to the elongation. Other schemes to equalize the finishing temperature are also employed. It is said that at some hoop mills the end of the billet which represents the last end of the hoop to pass through the rolls is heated to a higher temperature than the first end. In the cotton tie mill at Youngstown, where the strips are about 1800 feet in length, one end of the billet will be in the furnace, while the other will be coiling some 200 feet away at the other end of the mill as finished strip. Other factors affecting the uniformity of gauge, or thickness, are the wear of the rolls and the bearings. To overcome the wear of the former, which also affects the finish, the path of the piece through the leading and finishing passes is moved over to a new surface about every twenty minutes, or whenever these surfaces become too rough. The vibration of the mill pinions produces waves or slip marks on the surface, if the last stands are in train with the tongue and groove rolls, hence the planishing and finishing rolls are generally separately driven in mills rolling the best grades of hoop, and only one of the rolls is driven, the other revolving by friction due to contact with the driven roll. The planisher may be in train with the tongue and groove rolls, but the finishing stand is almost always separately driven. At some of the mills where the finisher or planisher, or both, is in train with the rest of the stands, the bottom roll is much larger in diameter than the top roll or the rest of the mill, and is driven, while the top roll revolves by friction. The larger diameter of the bottom roll increases the speed of delivery of the stand. The finish on some hoop is of great importance. To provide for this requirement scrapers are employed in front of the chill, or finishing, rolls. These scrapers consist of two horizontal bars spaced about eight inches apart and fixed parallel to and just in front of the rolls, and of two other bars similarly arranged but fastened to the two prongs of a fork that can be moved up and down by means of a lever. In this way the movable bars can be lowered as desired into the spaces between the fixed bars and the rolls. As soon as the rolls grip the piece the scraper is brought into action, and the piece is bent sharply up and down over its edges, thus cracking the scale and removing it at once. As the piece, after coming out of the finishing pass, is near or below the critical temperature, no more scale is formed, and a smooth bluish surface results. About five or six feet of hoop on the front end is not thus scraped, because the great speed of the piece carries it through this distance before the scraper can be brought into play. In order to eliminate this unfinished end with as little waste as possible the shears are located, preferably, at the mill end of the cooling bed, so that this end of the strip is the last to be cut. The adjustment of the rolls is also an important matter in rolling hoop. To illustrate this point, if one of the finishing rolls is enough out of level to make a difference of only one-ten-thousandth of an inch in the thickness of the hoop on its edges, it will bend toward the heavy side in leaving the pass an amount equal to one foot in thirty feet of length. As the stiffness of an ordinary hoop is only sufficient to push it, even on a very smooth run out, a distance of about thirty feet, some means of cheaply delivering the strip away from the last stand of rolls must be used. In Carnegie mills, this delivery is accomplished in three ways, namely, by hot coilers, by conveyor belts in the runouts, or by pneumatic runouts. In the last named type of conveyor, air blown at high pressure through holes in the bottom of the runout and at angles directed away from the mill, lifts the strip, decreases the friction and helps to carry it along.

**Finishing Hoop:** Hoop may be finished in many ways. As to the cutting of hoop, it is always cold sheared, and this may be done so as to give either both ends square or one end square and one end round. For this kind of cutting, a special die with a double edge, one round, the other square, is used, and the shapes on the ends of the hoop are formed by punching out a small part of the hoop. Ordinary hoop, not coiled, is cut on alligator or small guillotine shears, but the cotton tie mill is equipped with two shears of a special type, which consists of two revolving wheels on each of which a shear knife is mounted. By regulating the relative speeds of the wheels, these shear-blades are brought together in every so many revolutions, so that as the strip is fed into the shear at a definite speed, it is cut into approximately equal lengths. Anything near exact cutting is impossible on this machine, due to slipping of the belts and the play in the parts of the machine. Flaring and punching machines are provided at some of the mills, and in this connection it is to be remembered that the flare on a hoop is measured correctly by one-half the difference between the largest and smallest diameters. All three methods of bundling, in strips, in scrolls and in coils, are practiced. As to coils, some of the mills can coil in multiple or single strips, while others can coil only in singles. Hot coiling can be done only at certain mills, also. It is a matter of pride with the men at the mills to turn out the finest product, and any order that calls for extra quality and finish is sure to receive the attention it deserves. On such material special tests, such as the acid test for scale pits and bending-over tests for seams, are often made in addition to the ordinary inspection for surface defects and gauging for thickness and width.

## SECTION II.

### MERCHANT MILLS.

**What the Merchant Mill Is:** The first mills were what we of to-day would call merchant mills, though the term was perhaps not then applied to them. In the beginning of the industry, all mills doubtless rolled a variety of simple sections such as rounds, squares, flats, etc., but as the business grew and the demand for heavier material and for certain shapes increased, mills designed to meet a given demand or to roll a certain kind of product began to appear. Then it was that the smaller or older mills, which continued to roll a variety of sections and often stocked material that was retailed out later, were designated as merchant mills, in order to distinguish them from the specialty mills and those whose product was handled in large lots. Later on, especially in this country, the mill manner of handling materials and doing business underwent a change, and the mills were more or less divorced from the store house, so that these mills, while they continue to roll a variety of sections, always roll to orders. Thus, though they have lost all the characteristics, they still retain the name of merchant mills. Therefore, in this country a merchant mill is any small mill, say twenty-two inches and under, which regularly produces more than one shape.

**Kinds of Merchant Mills:** In touring the various works, the visitor is surprised and often not a little confused by the great number of and seemingly meaningless terms applied to these mills. Thus, there is heard the term "bar mill" applied to two mills of altogether different types. The term "guide mill" is apparently used in the same way. Added to these are such names as "Morgan mill," loop mill, shape mill, continuous mill, and semi-continuous mill, hoop mill, Belgian mill, combination mill, etc., and such local terms as the "iron mill," and the "steel mill," the "electric mill," or just "merchant mill," as at one of our own plants where there is but one merchant mill. While one not familiar with the mills is inclined to think most of these names are accidental localisms, many of them are really descriptive of the mills and also form links in a systematic classification based mainly on construction and design. These terms and the classification of the mills is best explained from a historical viewpoint. For this reason it is desirable to trace very briefly the evolution of the small mill.

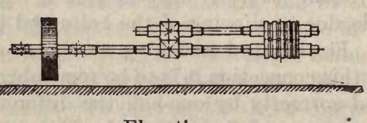


FIG. 91. First Merchant Rolling Mill.

**Development of Merchant Mills:** The first mill, which also stands for the simplest kind of mill, consisted of a single stand of rolls driven in one direction only, and for many years all bars or sections were rolled on this simple mill. No guides were used at first, and the roller guided and supported the bar between the rolls by means of tongs. In order to avoid the labor of pulling the bar around the mill, the catcher returned it by laying one end on the top roll, which carried the piece forward with little effort on the catcher's part. To avoid this idle pass, the idea of placing a third roll above the second, so as to work the bar as it passed in both directions, was conceived and resulted in a great economy in labor. Up to this point the bars were comparatively short, sixteen to twenty feet being the usual lengths. It was next discovered that a great saving in both labor and material could be effected by making the bars longer, but to accomplish this increase, a larger billet had to be used. The increase in the size of the billet was secured by increasing its length, which required wide heating furnaces, and by increasing the size of its cross section, which called for a greater number of passes for reducing than could be placed in one stand. To supply these extra passes, additional roll stands were needed. These stands were coupled together to form the roll train of Figure 92.

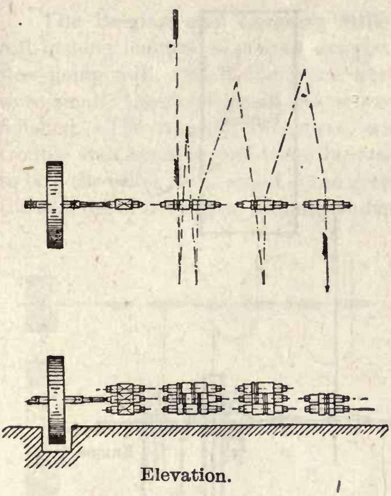


FIG. 92. Diagram of a Simple Type of Three-High Merchant Mill.

**The Guide Mill:** The rolling of rounds, which have always been an important product, led to the first use of guides. The method first used was like the method for hand rounds previously referred to, but a greater number of passes were used to finish the piece. Since the tonnage, especially on small rounds, was held down by the time consumed in passing the piece back and forth through the finishing groove, it was natural that the mill man should seek some way of reducing the number of these passes. This endeavor led to a really great discovery, namely, that a round could be rolled in one pass from an oval, provided the oval was of the right dimensions and was supported by metal guides. This success of the guide led to its use for other shapes, also, and to its adoption in modified forms to nearly all mills. Thus, another word, guide, came to be rather loosely used. In general, a guide is any device used to support the piece in the correct position during its passage through the groove. In order to perform this function, the guide must fit neatly against the roll or rolls, so one end must be shaped to conform to the shape of the space in front of the rolls. Entering guides are usually of the closed type. They are made in two parts.

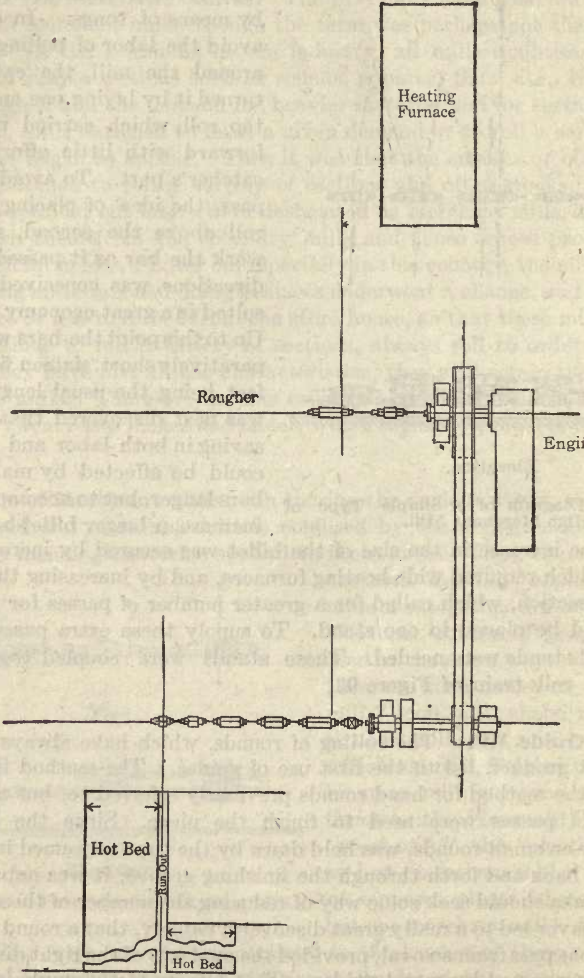


Fig. 93. General Layout for an Eight Inch Guide Mill—Belgian Type.

In each of these two parts a groove is cut parallel to its long axis, so that when the two parts are fitted together the opening formed by the grooves will be of the required shape of section to support the piece properly. The guide proved to be of immense advantage in another way, in as much as it permitted the rolling of very long lengths. Today, any mill designed to roll sections that require the use of guides may be called a guide mill.

**The Belgian and Looping Mills:** Though it was now possible to roll in long lengths, a serious drawback was encountered in the old and slow-going mill, for, if the piece were long and, especially, if the section were small, the steel would get too cold to roll before the piece could be finished. The remedy, of course, was found in greater speed, but here trouble was again encountered because of the roughing rolls which refuse to bite the billet if the speed is too great. Then there originated in Belgium the scheme of setting up an independent roughing stand that could be driven from the main drive shaft of the engine at a lower speed than the finishing train, which was driven by power transmitted by belt from a large pulley on the drive shaft to a much smaller one mounted on a short shaft connected with the train pinion. Up to this time the piece was rolled throughout its length in a given pass before it was started into the next. Who the man was, or what his degree, that was responsible for the next advance in rolling, history does not say, but doubtless it was some bold Belgian catcher who first conceived the idea of catching the first end as it came through the rolls and returning it immediately through the next pass, thus rolling the section in two passes at once. Since the speed of the piece on the delivery side is greater than that of the rolls, due to the elongation, the material overfed and formed a loop. By this looping scheme, the capacity of the finishing train was increased beyond that of the roughing stand.

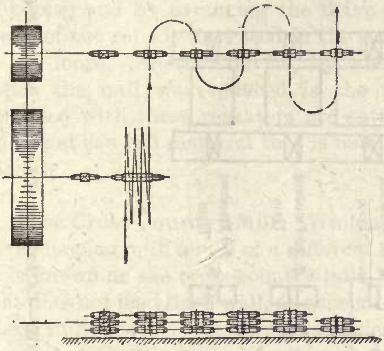


FIG. 94. Early Type of Looping Mill.

**The Semi-continuous or Combination Mill:** Such was the extent of the development until a few years prior to 1900, when two things combined to force another advance in the merchant mill; one was the previous development and success of the continuous mill as a semi-finishing mill; the other was the necessity for economy due to labor troubles and a severe depression in the steel business. So, in order to decrease labor costs and speed up the mill to the limit of the finishing train, the continuous rougher was installed to replace the single three-high roughing stand of the Belgian mill. By this inovation the mill force was decreased by about nine men, while the output was increased 50%. The mill proper was then in a position

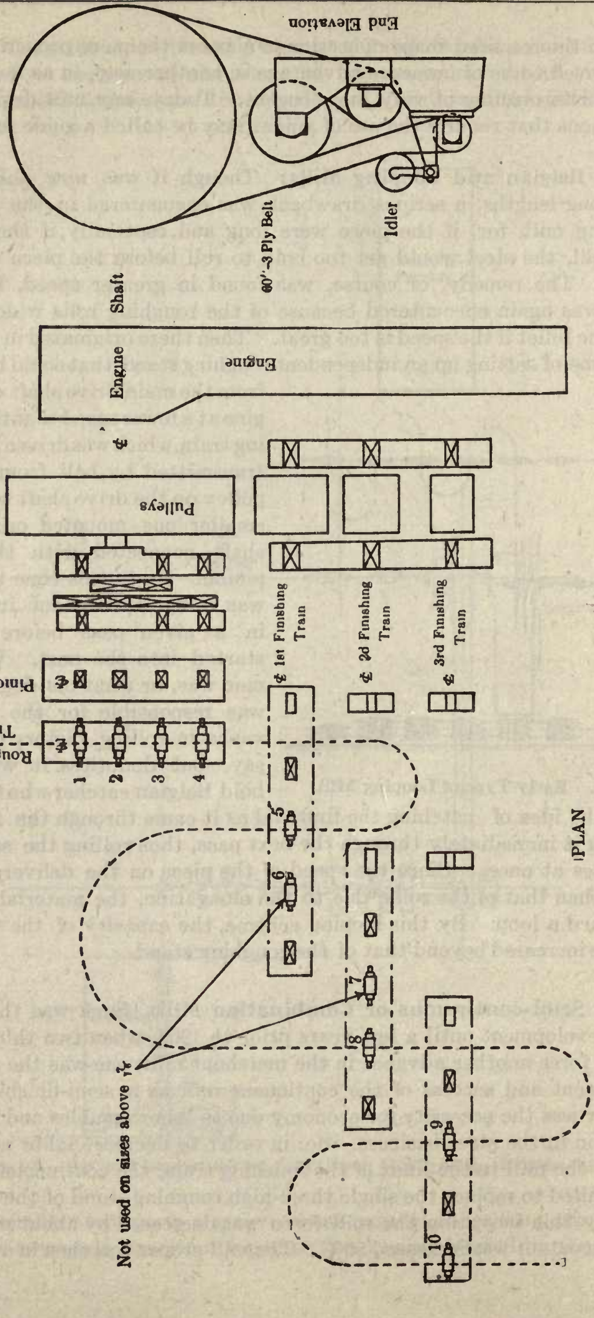


FIG. 95. General Layout for a Ten Inch Mill—Later Type of Looping Mill with Continuous Roughing Stands.

to roll in unlimited lengths and thus effect another saving; but two things combined to limit the length of the piece rolled, namely, the difficulty of handling long pieces on the old style cooling bed and the problem of keeping the bar uniformly hot for finishing. The first problem was solved by the invention of the mechanical cooling bed. These beds consist of a runout, in which are live rolls, for delivering the piece; a device for stopping and transferring the material, which is delivered at speeds as high as twenty-five feet per second, and at intervals of only one or two seconds between pieces; a system of notched or fingered racks, by means of which the hot bars are moved away from the runout; and a receiving table, also containing live rolls, by means of which the bars are delivered to the shears. Examples of these tables will be found at all modern mills. The problem of uniform heat was then solved by speeding up the mill; by locating the roughing rolls near a continuous furnace, as was pointed out in discussing the rolling of hoops; and by arranging the drive of the mill so that the peripheral speed of the rolls is increased in the successive passes to take up the slack in the loops. Another device, by which the number of hands employed about the mill was reduced, is the mechanical repeater. Many mills equipped with these repeaters are entirely automatic in operation of the rolls, and can roll material that is much too stiff to be turned or looped by hand.

**The Cross Country Mill:** While these improvements were being made in the looping mill, a mill of a different type altogether has been developed. It is known as the cross-country mill, and is intended for rolling material that does not lend itself well, on account of size or shape, to loop mill rolling. These mills involve the continuous idea, but the stands are placed so far apart that the piece must leave one set of rolls before entering the next. For carrying the piece from stand to stand stationary roll tables are employed. To save space and avoid complicating the drive the stands may be arranged on two or more parallel lines, and the direction of travel of the piece will be reversed during the rolling. Three-high stands are placed at the reversing points, so that, by means of mechanical repeaters and diagonally placed tables, the feeding of the mill is made automatic throughout. In the latest types of these mills, as for example the No. 7 mill at Duquesne, which made its first trial rolling in July, 1917, the three-high stands have been eliminated and two-high substituted, the piece being moved over from the first roll line to the second then to the third by transfer and skid tables. In general, the tendency is to return to the two-high stand, because it is the simplest as well as the strongest and most rigid in construction.

**Future Development:** From the preceding sketch, it would appear that the merchant mill, so far as the mill is concerned, has been developed almost to the highest stage of perfection. At present, the trend of improvement is in two directions, one looking toward economy in power and the

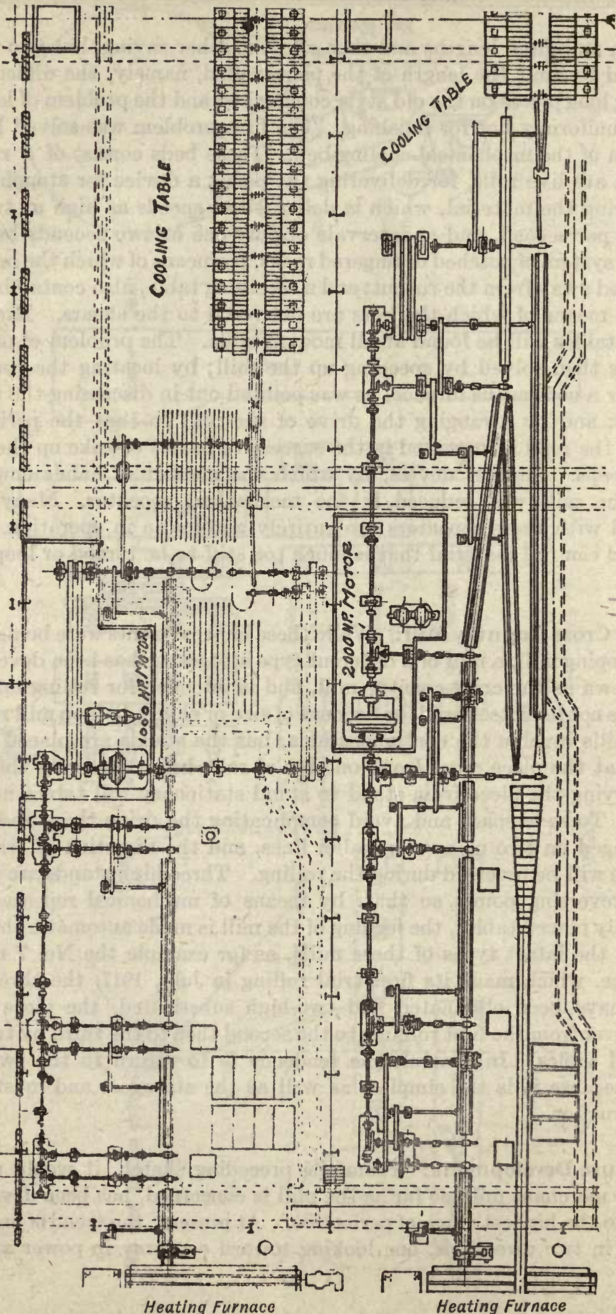


FIG. 96. General Layout for Eight Inch (top) and Ten Inch (bottom) Electrically Driven Merchant Mills. Examples of the most Recent Types showing part only of each Cooling Bed and Heating Furnace.

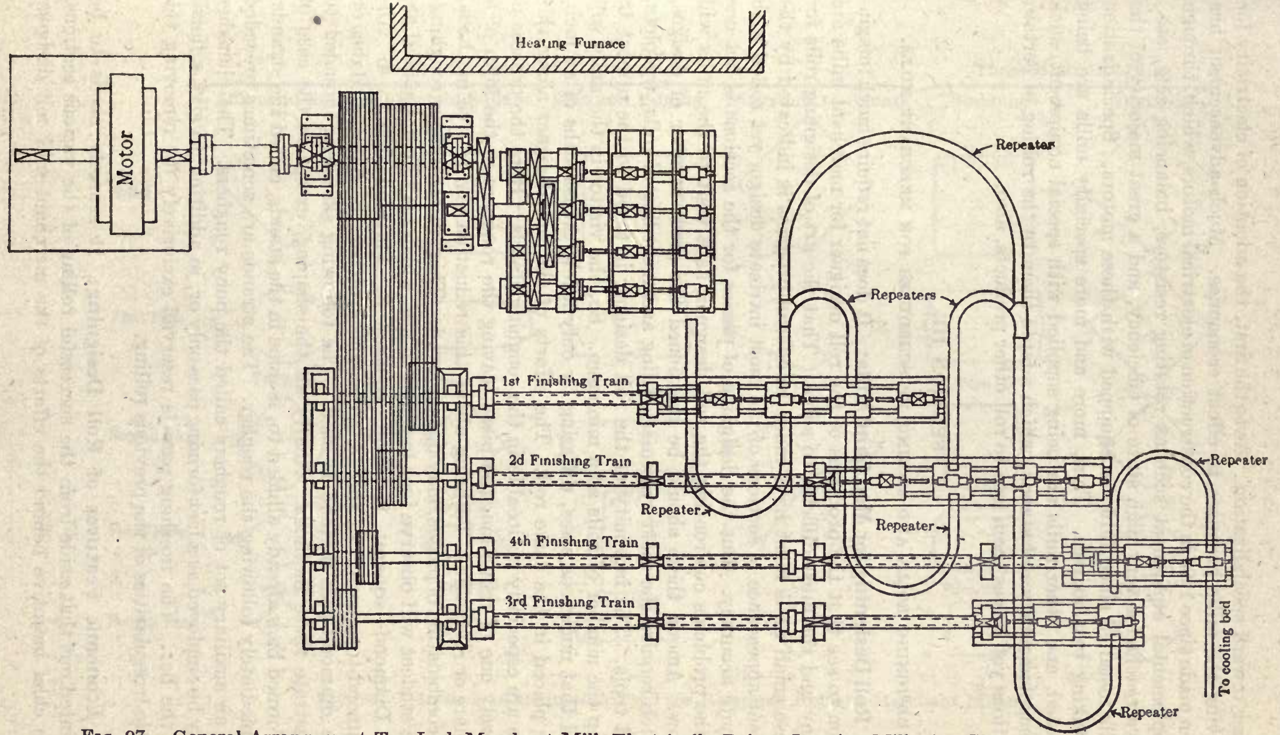


Fig. 97. General Arrangement Ten-Inch Merchant Mill, Electrically Driven Looping Mill with Continuous Rougher and Mechanical Repeaters.

other toward specialization. As to the first, the adoption of electricity for driving the mills promises to effect economies. Much advancement has been made since 1900 in the construction of electrical motors, which, through supplemental equipment such as rotating resistors, balancing sets, etc., have reached a very high state of efficiency, and a great majority of the mills installed since 1916 are equipped with these motors. Specialization is taking two courses. Thus, more and more specialty mills are being erected, and other mills are being supplied with special equipment, such as supplementary roll stands, which adapts them to the rolling of certain sections yet leaves them free to roll other products, also.

## SECTION III.

### DESIGNING ROLLS AND MAKING UP SCHEDULES FOR MERCHANT MILLS.

**Roll Designing for Merchant Mills:** It does not require much imagination to see that the problems of the roll designer for merchant mills are many and the most difficult to solve. That the art of designing rolls for these small mills must have made wonderful progress is indicated by the recent appearance of sections of the most intricate design, yet rolled with minute accuracy. But the designing of passes for the sections is but one of the problems confronting the roll designer, as a visit to the mills will show. Among these should be mentioned the great number of designs, which require the most systematic filing and recording of rolls, templets, and tools. The ingenuity of the roll designer is taxed to the utmost to keep the number of rolls at a minimum. So, the visitor in the mills will find that numerous sizes, differing by only a few thousandths of an inch, are placed in the same roll. The efforts of the roll designer along this line are especially noticeable in the roughing stands. Here the process is merely one of reduction, the piece leaving the roughers in the form of a square or rectangle. To bring about this reduction one of five methods, or combination of passes, may be employed. Thus, in continuous roughing, the student will observe four methods in use, which may be designated as: 1. Diamond—square; 2. Oval—square; 3. Flat-and-edging; 4. All-diamond-to-square. In three-high roughers, either the flat-and-edging or the diamond-pass method is used. The following sketch is intended to illustrate these methods. Nearly all the shaping, except in the case of deformed bars already alluded to, is done in the stands, called the strands, immediately following the rougher. The strands are sometimes preceded by an auxiliary set of roughers called the pony roughers. The planisher may be employed as a last forming pass only or, in addition, to give a finish to the bar. The finishing pass is reserved exclusively for removing the little irregularities of the previous rolling.

**Economic Features of Roll Designing:** It scarcely needs to be pointed out that aside from the successful rolling of the various sections, the chief incentive behind the efforts of the merchant mill roll designer

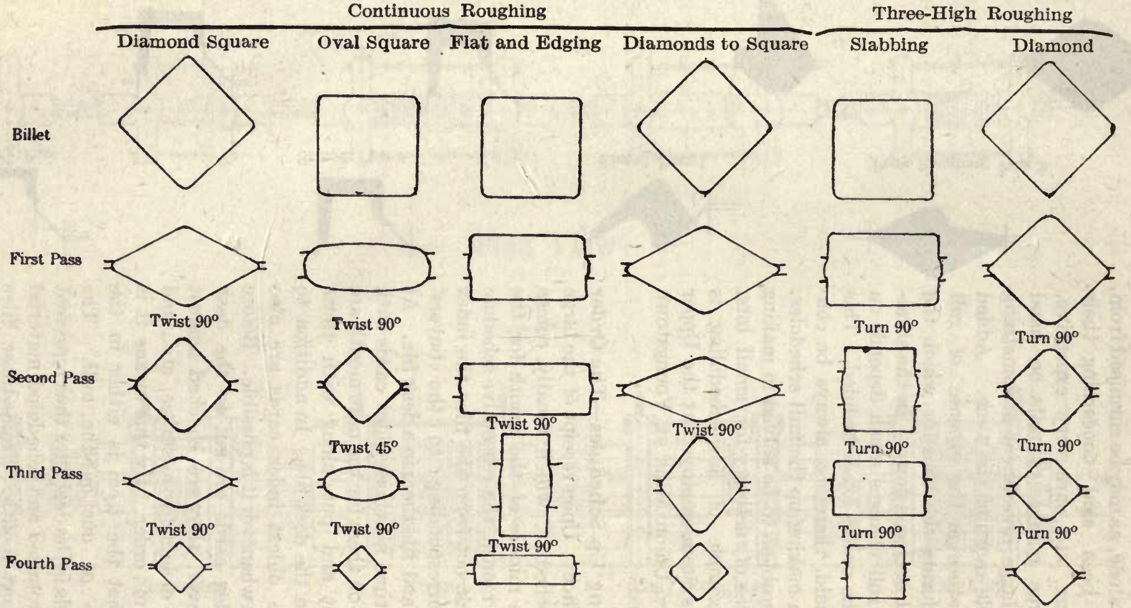


Fig. 98. Methods of Reduction Used for Roughing Rolls in Merchant Mills.

is found in the necessity for economy. The rolls, alone, as may be surmised from what has been said concerning their manufacture, etc., are very expensive, and a large number of rolls on hand means a large investment in something that is idle most of the time. Added to this feature is the expense of roll changes, during the time for which the entire mill is closed down. In the elimination of roll changes much depends on the way the orders are scheduled. This point should, therefore, always be considered in making up the mill schedules, and is a problem to be solved in making up promises of delivery for small lots. As an example of how scheduling is done, the system employed at the Upper and Lower Union Mills at Youngstown is explained.

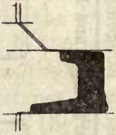
**Making Up Schedules—The Order in the Office:** Upon receipt of the large buyers' schedule, which usually comes about the middle of the month for the following month, the respective schedule clerks pick out from the files the index cards corresponding to the buyers' schedule and file them in a desk file. At the same time all those index cards with promises on them for the next month are taken out and put along with those already in the desk file. In addition to these the oldest index cards are also worked in whenever it is possible. Before these index cards are put in the desk file, however, they are checked against the book orders for mistakes, etc., and the date of order. By this means it is known that the item is either in the desk file or out on the mill. The index cards in the desk files thus represent all the promised and scheduled material for the next month. From these files the schedule clerks make up rollings for their respective mills. For this


Pony Roughing Pass 1


Pony Roughing Pass 2


Pony Roughing Pass 3


Strand Pass 1


Strand Pass 2


Strand Pass 3


Planishing Pass


Finishing Pass

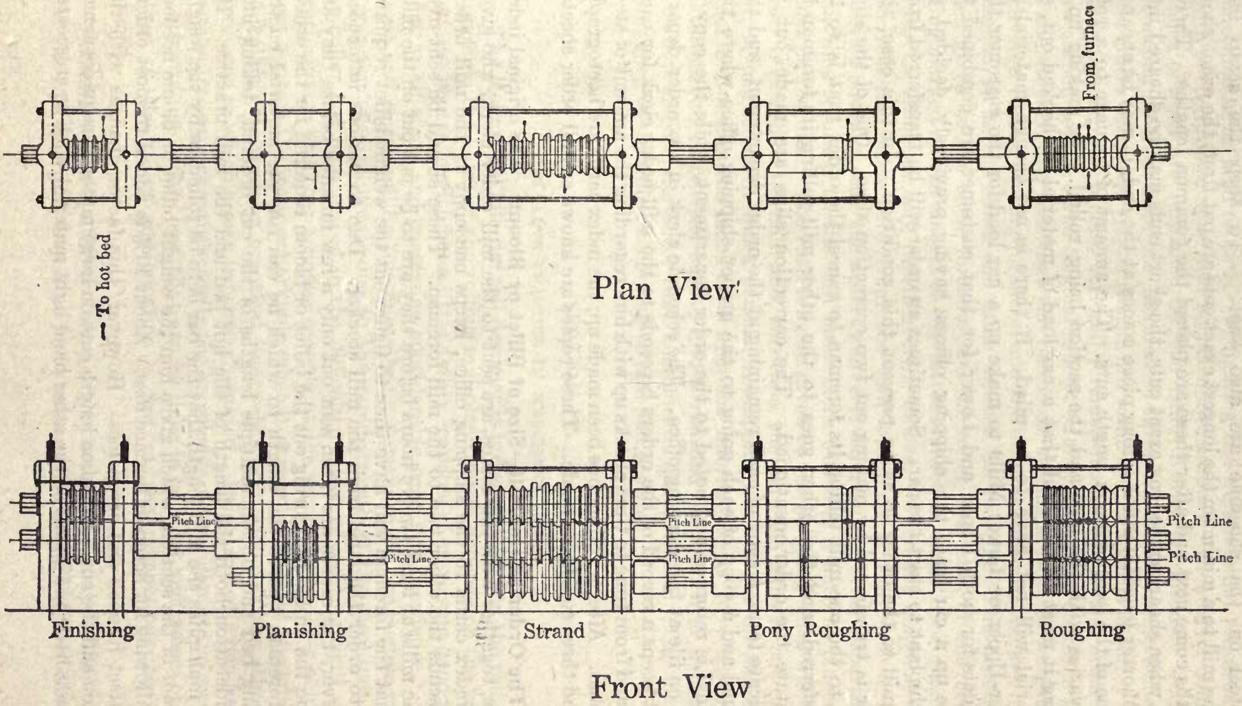


Fig. 99. Sketch Showing Passes and Location of Same in Rolls for Window Sash Section.

purpose index cards showing the different sizes of sections and grades of steel on the schedule are also kept. To keep the scrap loss on the mill to a minimum the longest exact cuts are put first, the exact short lengths come next and after these are placed the common lengths. Therefore, when shearing the long exact cuts, the short ends may be sheared into the shorter lengths; and if a long piece comes at the end, it may be sheared to one of the long common length cuts. The amount of tonnage to a rolling varies with the mill and the section being rolled. In making up a rolling it must be watched that a car load of material is checked out, so material will not have to be piled. If there is not enough material at either Upper or Lower Mills to make up a car load for the customer the products for both Upper and Lower for that customer are combined to make up a car load, the shipping offices having previously decided at which plant to start the car. Sometimes an order will be transferred from one mill to the other so as to prevent this condition. In this case, the order is transferred by making out two correction slips. One of the slips goes to the one mill telling its foreman to cancel the order that is to be transferred, and the other goes to the other mill telling its foreman to reinstate the order mentioned. The correction slips are made out in triplicate form, a copy of each remaining at the order department, and the original and a copy of each going to the proper shipping office where the original is returned and noted to the order department, while the copy is kept on file at the shipping office. The schedule clerk in the order department keeps a record of the orders he sends to the mill order clerk for each mill and from time to time checks up with him regarding the amount of steel on hand. After a rolling has been made up, the index cards are hectographed and three copies are made. These copies are known as mill order sheets.

**The Order at the Mill—Size of Billet or Bloom:** The original index cards, together with the copies, are sent to the mill order clerk, who gives the index cards to the shipping office, keeps one copy of the mill order, and sends the other two to the mill foreman. These should be sent over to the mills at least twelve hours before they are to be put out on the mill, so that the foreman will have time to figure out the weight billet required and to order the steel from the mill stocker. Due to various influences, however, the orders are often sent out only a few minutes before they are put on the mill. In figuring out the billet or bloom required for the order, the foreman figures the length to which he can run the material on the cooling bed and obtain multiple lengths of the cut ordered, taking into consideration both the length of the hot bed and the mill practice. He then multiplies the mill length that the bar is to be rolled on by the weight per foot of the section, which gives him the weight billet or bloom needed, not allowing for scrap or furnace loss. About 10% is added to most orders to offset furnace and scrap loss. However, this factor changes with the section and the cut. Common length cuts on large material requires sometimes as little as 5%, but on the other hand light material, such as crescents, on which the cut is exact and the inspection rigid, the amount added will sometimes be as high as 25%. In figuring the weight billet required, the width of the furnace must also be taken into account. Blooms for common grades of steel are furnished by the Ohio Works in different weights, increasing by fives from one hundred to three hundred pounds, while billets, unless otherwise requisitioned, are furnished in lengths of thirty feet. After figuring the orders, the mill foreman makes out a steel order with two carbon copies. The original is kept on file; one of the copies is given to the stocker, who sees that the billets or blooms are cut to weight and delivered to the heating furnaces; and the other is given to the steel yard foreman, so he can check the same against his records. The orders are then given to the shear foreman and the roller, the size of the section being marked on the margin of the latter's sheet in large clear figures in order to eliminate any possible error in size. When the shipping office receives the index card from the mill order clerk, the card is blue-penciled showing date the order was received from the order department. It is then returned to the mill order clerk who files it until he places the order on the mill. The card is again given to the shipping office when the order is placed on the mill, and, this time, the date the order is put on the mill is marked with black pencil. A shipping clerk looks up the book order and marks the index card with the information as to whether the material is to be piled or loaded into a railroad car, which is dependent upon how much material for that customer is being rolled. The marked index card is then filed according to size and section.

## SECTION IV.

### ROLLING PRACTICE IN MERCHANT MILLS.

**The Roller:** While the roll designer is indispensible, and the roll shop represents the heart of the rolling mill plant, much depends on the roller. He must be a man with not a little ability, capable of exercising good judgment at all times and possessing considerable practical knowledge. With closer and closer rolling tolerances being demanded by the customer and larger tonnages required, due to the rapid growth of the steel industry, the roller has been placed in the difficult position of meeting rigid specifications and breaking tonnage records at the same time. This achievement appears the more remarkable when it is recalled that all the training the roller gets is along practical lines. His only school is the school of experience in which a man is never graduated. It is manifestly impossible, therefore, to explain satisfactorily the knowledge of the roller or the method of his working. The best that can be done is to point out some of the duties of the roller and mention a few of the precautions he must observe.

**Precautions in Rolling:** In a word, it is the duty of the roller to see that the rolling is properly done and the material meets the specification as to size, shape and freedom from rolling defects. In building up rolls in the housings care should be taken by the roller that they are plumb, square and level. If the rolls are not plumb, i. e., if the line joining their centers is not straight and perpendicular to a horizontal, the bar will not deliver properly, and trouble with the guides will undoubtedly occur. This condition is often caused by bearings wearing out or poor babbitting originally and can only be remedied by changing bearings or, in some instances, by the use of side liners or wedges. Should the rolls be out of square, that is, if the center of the pass in the top roll is not directly above the center of the pass in the lower roll, the bar will be out of square and will twist as it issues from the rolls. In order to square up the rolls, set screws which work against the bearings are provided on the sides of the housings, and thus the rolls can be thrown either one way or the other as the case may demand. The directions for correcting this fault are, in the language of the mill, "Follow the twist," and the top roll is always thrown over in the direction that the bar is twisting. In the event that the rolls are not level, that is, perfectly parallel, more work will be done on one side than on the other, with the result that the bar will not deliver straight but will tend to curve around toward the side on which there is the lightest draft, due to the other side being elongated the more. This condition may be remedied either by the use of liners or by operating the screw down at the proper side. Guides and guards play a most important part in rolling mill practice, and the proper setting of these is one of the roller's most important duties. His assistants may set the guides for the strand and planishing rolls, but those for the finishing pass are always set by the roller. Entering guides on the finishing passes are usually closed, the inner end being so shaped that it will provide sufficient bearing to hold the piece up in correct position while entering the pass. If the guides are not set properly, the bar will not be formed rightly. Especially when rolling rounds, the entering guides should be tight in order to hold the oval in a vertical position, for a leaning to either one side or the other will produce a high and a low shoulder on the finished round. The position of the guides on the delivery side is also most important, for since the bar has a tendency to follow the smaller roll diameter, the guide against which the bar is thrown must be watched most carefully. If the bottom roll is the smaller, then the bottom guide should not be placed too low, for the bar coming out would have a tendency to follow the roll down for a short space before striking the guide. This would cause an up and down kink, or a buckle. A short guide has the same effect.

**Rolling Defects:** In addition to working for the proper size and finish on the bar, the roller must watch for such surface defects as overfills or pinches, underfills, buckles, slivers, seams, laps, firecracks, roll marks, etc. Overfills or pinches must be watched especially in changing from Bessemer to open hearth steel, as the latter has more of a tendency to spread than does the former. When overfills occur, the amount of stock entering the pass that is producing the overfill must be reduced by adjusting the rolls in preceding passes. Underfills are corrected by reversing these operations. Buckles are sometimes caused by worn out pinions. Slivers can be produced from many causes at the blooming mill or by the bar shearing against a guide or collar of a roll at the finishing mills. The former condition cannot be corrected by the merchant mill roller, but the latter can be eliminated by a proper adjustment of the proper guide or by reducing the stock in the bar which is shearing against the collar. Seams are defects in the steel that cannot always be corrected by the finishing mill, as they are usually formed in the bloom or the billet. A lap is caused by an overfill or fin being formed and then being doubled over and rolled down in the subsequent passes. This defect can be controlled by the roller by going back to the stand at which the overfill was formed and reducing the stock. Firecracks are caused by the rolls becoming overheated and cracking on the surface. These cracks cause corresponding small elevations on the surface of the bar, which in some instances condemn the material. When this defect appears, the roller "moves over" and uses a "clean" pass. The same procedure is followed when any other roll mark appears on the finished bar. Roll marks occur at equal intervals along the bar and signify that there is a piece out of the roll or that the roll is marking the bar with each revolution in some other manner.

**Two Different Finishes** on bars are furnished at the Youngstown plant, namely, common and special. The special finish has a smooth, highly polished appearance and is produced by cleaning all scale from the bar at the planishing stand and finishing at such a low temperature that no more scale will form on the surface.

**The Special Finish** is produced on rounds by holding the square back before entering the planishing, until a dark scale has formed and then bending the bar with a pair of special tongs as it enters the rolls. A stream of water plays directly upon the bar as it enters both the planishing and finishing passes, and scouring blocks covered with emery powder are used on the finishing stand in order to keep the pass clean. Material requiring the special finish is always rolled ahead of the common orders of like sizes, so that a clean pass will be available. Flats are not scraped in order to furnish the special finish, but are simply held back until their temperature reaches the critical range before entering the planishing pass. On large flats, water is used on the bar as it issues from the planishing, so that the scale thus broken up will be removed and not be rolled into the steel. Another reason for using water on large sections is that they will be delivered to the hot beds below the scale forming temperatures. Cooling is unnecessary, however, on small sections, such as crescents, half ovals and ovals, as these lose their heat so rapidly that even water is not used directly on the bar. A scraper, located at the entering side of the finishing stand, is the only means used for producing the special finish upon these sections. Due to the fact that scale adheres more tenaciously to open hearth than it does to Bessemer steel, the latter takes a much better finish than the former. Open hearth steel will become smooth but does not have the highly polished appearance of Bessemer steel. It is the roller's experience that Bessemer screw steel takes the best finish of any grade turned out at the converting mills. This grade not only takes a smooth finish but some times gives a mirror-like surface. It should be observed that the holding back of the bar to produce this finish may so retard the rolling as to decrease seriously the total output of the mill.

## SECTION V.

### SHEARING AND BUNDLING MERCHANT MILL PRODUCTS.

**The Methods of Shearing and Bundling** vary at the different plants according to equipment, product, location, etc., and no description of value yet general enough to be descriptive of all plants can be given. As the greatest variety of sections are produced at the Youngstown Upper and Lower Union Works, a brief outline of the methods and practices at this plant may be found of value.

**Duties of the Shear Foreman:** The man who is responsible for completing orders, i. e., for the shearing and the bundling on each mill, is the shear foreman. His force is usually composed of a shearman, a gauger, a push-up, a pull-up, and two or more bundlers. The first duty of the shear foreman is to keep the different orders, heats and turns separate on the cooling beds and to tag each item on the truck properly. The different lots are kept separate on the trucks by means of bands. A load sheet is made out for each truck, showing the material loaded on it. When the truck is full, it is the duty of the shear foreman to notify the yard master or dinkey engineer to pull the load to the warehouse, or shipping room. It is also the duty of the shear foreman to set the gauge for shearing the material, allowing a certain amount for contraction during the cooling process. The amount allowed on the smaller mills is one-fourth inch over or under for every five feet, but this amount varies with the size of the bar. When material is to be bundled, the weight of the bundles is nearly always specified, but when instructions are not given, it is the mill practice to bundle material to weigh 100 to 150 pounds per bundle. By multiplying the weight per foot of the section by the cut and dividing the product into the weight of a bundle, the shear foreman determines how many bars to put in a bundle; but in order to check himself up he weighs the first bundle of each new cut. It is the object of the shear foreman to put the same number of bars in each bundle, as this not only makes all the bundles of uniform weight but facilitates the recounting of a bar order by the men in the warehouse. On some mills the head bundler counts the bars, while on other mills tally boys are employed. In bundling material up to twelve feet on domestic orders only two "Carnegie" bands are used. Up to twenty feet three "Carnegie" bands are used, while four are used on all cuts twenty feet and over.

**Bundling Export Material:** On export orders, the weight of a bundle is always specified, the weight usually being 112 pounds, so that twenty bundles make one gross ton. On lengths up to fourteen feet three bands, marked "Carnegie, Made in U. S. A.," are used. From fourteen feet to twenty-two feet four bands are used, and one additional is put on for every six feet above twenty-two feet. On all export orders, special "export" tongs are used, as with these tongs the material can be tied very securely. The following rules apply to the handling of export orders: All orders must be complete. All bundles, excepting the last, must contain the same number of bars. All bundles are to be tightly tied with "export" tongs whenever possible, and bands used are to be in accordance with instructions on orders. These instructions may call for export bands, plain bands, or wire. All export material must be loaded on separate trucks, except in very small orders, or when the material is needed by the warehouse to complete an order hurriedly. All trucks containing any export material must bear a red export tag, and all excesses are to be loaded on trucks but kept distinctly separate, tagged plainly as "Excess," and showing order number, customer, size, etc. The name of the man who is responsible for tallying and bundling is placed on the tag, and all orders are very plainly tagged, the tags being so placed that there is little liability of their being torn, pulled off or made illegible. On all trucks are placed load sheets which are put in oiled envelopes so that weather conditions can not destroy, or blur, the writing.

**Special Bundling:** Some material, such as ovals, tees, etc., often specify "Tie with wire," while other orders, especially for large material, specify the material to be shipped loose. A good many orders, such as hoops, flats, rounds, squares, and small nut steel, are often ordered coiled. This is accomplished by means of coilers with adjustable pins so that coils of different diameters can be furnished. The usual diameter, however, is twenty-four inches. These coilers are located at one end of the hot bed or at some other convenient point according to available space. All coilers are electrically driven.

**Handling the Material in the Warehouse:** When the truck load of material arrives at the warehouse, the pile-boy takes the load sheet into the office and gets the corresponding index cards, because the load sheet shows only the order number, size, cut, grade of steel and remarks. The index cards show customers name and loading and shipping instructions.

As each item is weighed off from the truck, it is entered on a weight sheet by a weigh-man and checked off on both the index card and load sheet. If the index card is marked "Car" a car is started for that customer, if this has not already been done, and material is so loaded. If index card is marked "Pile" the item is piled and so noted on the weight sheet. One weight sheet is made out for each truck load, and when this car has been weighed off, the sheet is checked off on the car card, of which there is one for each car, and returned to the office. Here the weight sheets are checked against the order books. Memorandums are made out for the items that have been piled so that these can be given out to the weighmen when a car load has been started for the customer. When an item of an order is under weight or short in number of pieces, the shortage is discovered by a weekly survey of the order books by a clerk in the shipping office, who makes out a reindex card for the shortage and notes the date made out with blue pencil on both the reindex card and the book order. If, however, there is a chance to get the item on the mill immediately, the book order and the index card are black penciled. A rolling order is made out from the reindex card and hectographed, after which the index card and three mill order sheets are given to the mill order clerk. He returns the reindex card to the shipping offices, and if he does not have the grade of steel in stock, he has to make out a requisition for it, the procedure then being the same as for ordinary orders.

**Straightening:** At the lower mill, straightening is done by the Labor Department, machines for this purpose being located at three different places. These machines are of the seven roll type, the rolls being built up in a casting similar to roll housings. Four rolls are below and three above, the bar passing between in grooves which are designed to fit each separate section. On account of the vast amount of tire and window sash sections rolled at the Upper Mills, the straightening is under the jurisdiction of a special department for that purpose. Angles and sash sections, molding tees, and mud guard sections are straightened at the mill, there being a straightening machine located at each mill where such material is rolled. Round edge tire, however, is straightened in the tire house, where two straightening machines of a new type are located. These are more flexible than the old type and are more easily adjusted to the various sizes.

**Invoicing:** After the cars have been loaded, the car cards are taken into the shipping office, and from these, invoices are made out. The original office copy of the invoice, which is made out in the shipping office, is sent to the order department where it is carefully checked against the book order, the number of bars or bundles and tonnage being entered on same. The invoices are next given to a clerk who enters all detailed information on a "recap" sheet. The credits for the various sections and sizes are also entered under the proper headings on a "credit recap sheet."

## SECTION VI.

### INSPECTION DEPARTMENT OF A MERCHANT MILL PLANT.

**The Inspection Department** makes all physical tests and keeps records and samples of the various sections. One of the duties of this department is to inspect and accept or reject all special steel before being rolled into finished product. Check analysis is made of all steel requiring the same, and a close inspection of all material when being rolled is provided for. All special steel ordered from the semi-finishing mills must pass inspection by this department. Approval or disapproval of material is based upon chemical analysis and surface conditions. Only very low limits for the various impurities are allowed on special steels, and the inspection is very rigid. Consequently, any heats not falling within the requirements must receive special attention. Much in the way of good judgment is required to dispose of such heats satisfactorily. Usually, the department will endeavor to consult the customer before permitting an off grade heat to be rolled as originally planned. Certain orders require the ladle analysis to be checked before being rolled into the finished bar. Orders requesting check analysis are held in the yard until drillings from the billets are analyzed. If this analysis shows that the composition of the steel is as ordered, the steel is rolled on the order for which it was originally intended. If the check analysis does not practically agree with the ladle analysis, the steel is applied on a less particular order. Check analysis may also be made on finished material. Some orders require that the steel be inspected for surface defects before rolling. In such cases each billet is carefully examined to detect any slivers, seams, checks, or faulty shearing that may occur. Billets found to be defective are chipped and put into condition for rolling if at all possible. When orders specify physical requirements, it is then the duty of this department to supply such chemical specifications as will fulfill the physical requirements.

**Another Function of this Department** is that of mill inspection, which is one of most importance. In this capacity the department acts as a check upon the rolling. Mill inspection requires one man on each mill, devoting his entire time to gauging and watching for faulty steel. Sections not fulfilling the prescribed measurements are either held for further inspection or thrown out as scrap. The rollers as well as the inspectors, have the given dimensions and tolerances. The inspectors check the rollers and inform them of any faults that the rollers themselves have not already detected. In case an inspector does not accept steel as rolled, and the roller continues to make the section, the inspector signals for the department superintendent and lays the case before him. If the fault cannot be remedied, and it is known the customer will not accept the steel as rolled, the mill must go off the order. The defects watched for most closely depend upon the section being rolled. Accurate size applies to all sections.

For the more complicated sections templets are furnished. Usually one exact and one full templet is made. For gauging rounds, squares, flats, etc., only a gauge and micrometer is used. Readings on the micrometer are accurate to .001 inch, while on the gauge one-sixty-fourth inch is about the most exact reading that can be determined. Other tools used for special purposes are squares and steel tapes. The square is used to detect diamonding in certain instances where each surface must be at right angles to the adjacent one. The tape is used when inspecting clip sections, to determine the regularity of the impressions that are rolled on the bar.

**Surface Defects:** The inspector is responsible for the detection of surface defects. These may appear as buckles, kinks, overfills, underfills, slivers, laps, seams, or burned steel. While the nature and causes of these defects have already been more or less fully explained, the following resumé of defects most likely to occur in merchant mill rolling is appended for ready reference:

**Buckles and Kinks:** A bar, when delivered from the finishing rolls, may be wavy, either up and down or sideways. The former is known as a buckle, while the latter is a kink. These defects are more injurious to some sections than others. However, all sections should be rolled as free from buckles and kinks as possible. Crescents have a tendency to buckle, consequently they must be watched closely.

**Fins:** If a bar has a fin or extra amount of metal at the sides where the finishing rolls come together, the bar is said to be over-filled. Bars rolled for cold drawing must be free from over-fills, for these draw into laps. On the other hand, in order to get perfect corners on half ovals, a well known file manufacturer requests a small overfill at the edges.

**Underfills:** When a bar is scant in certain dimensions or when it is not completely filled out, the bar is said to be underfilled. This defect sometimes appears on rounds and channels.

**Slivers** are loose pieces of steel rolled flat on a bar. They may be present on the billet or be caused by faulty shearing, or incorrect entering of the bar in a closed pass. Slivered steel is thrown out as scrap and seldom held for further inspection.

**Laps:** If a bar is given a pass in the rolls after an overfill has been produced, a lap usually results. This defect is especially liable to occur with skelp, hoop and cotton-tie. Faulty ingots and poor rolling at the semi-finishing mills also cause laps.

**Seams:** Steel must be inspected carefully for seams, a surface defect always difficult to detect. A seam is a crevice in steel that is closed up but not welded. Seams are caused by blow holes and cracks in the ingot, as well as faulty methods of rolling. They render steel unfit for hardening.

**Burned Steel** shows up in the finished bar in the form of rough, checked edges. Burned steel is ruined, and the only alternative is to scrap it.

**Roll Marks:** Sometimes a roll is nicked, or a piece breaks off the roll, resulting in periodic impressions along the bar. The defect is corrected only by a new pass. Fire cracked rolls make similar impressions.

**Finish:** The finishing pass, if worn, does not give a smooth surface, consequently when the surface of a bar is not up to the standard in finish the pass must be changed. This defect is especially objectionable when rolling cotton tie, hoop, skelp and sections requiring the special finish.

**Pipe:** The inspector must watch the sheared ends of bars for piping. This defect, however, is usually detected at the billet shears before the steel is charged.

**Testing for Defects:** Tests for detecting some of these defects are employed by the inspectors. The tests most commonly employed for this purpose are the upset, forging and pickle tests. The upset test consists of heating a short sample piece in a forge or furnace and upsetting under a hammer. This is a severe test and readily shows up seams and laps. For forging tests, a bar about ten inches long is heated and forged along the longitudinal axis of the bar, which is then nicked and broken. Piped steel is readily detected by this treatment, as the forging opens up the pipe. The upset test is more often used than the forging test, especially when rolling forging steel. The pickle test consists of immersing for a few moments short pieces of the material in dilute sulphuric acid. The acid removes the scale from the bar, exposing to view and exaggating any surface defects that may be covered by the scale. Tests pieces of hoop and file steel are pickled. At the Youngstown Upper and Lower Union Mills all forging tests must be turned in for the personal inspection of the department superintendent, while the pickle tests are saved at the test house for six months before being discarded. With hoop, the pickled samples are held in a vise and the edges turned over with a hammer. This distortion of the metal opens up any laps that may be present. On special section the inspectors are required to save samples every half hour. These are bundled together, properly tagged, and sent to the test house, where they are saved for three months.

**Other Duties of Inspectors:** Besides inspecting material for surface defects, the mill inspector must check the bundling requirements as well as the length of cut. This practice reduces bundling and shearing errors to a minimum. An hourly report with carbon copy is made by each mill inspector. This report shows the variations in size of the bar for each hour of the day. Notations are made of any steel held up and the cause of the same. These reports must be delivered to the inspection office at the end of each turn. Since the different sections are gauged differently, the make-up of the reports will differ accordingly.

**Manner of Gauging Different Sections:** Rounds are gauged on four diameters, distinguished at the mill as top-and-bottom, sides, and high and low shoulder. By top-and-bottom of a round is meant those two surfaces subject to compression in the finishing pass, and by sides is meant the points opposite the clearance between the rolls in this pass. The shoulders lie between these two diameters. The longer of the shoulder diameters is called the high shoulder, the shorter the low shoulder. Three samples are taken from each bar gauged, namely, front end, middle and last end. These samples are taken at the shears as the original bar is being cut into the lengths ordered. The top and bottom of a round may be distinguished from the sides by the way the scale is broken along the sides. If an overfill occurs, it shows also on the sides of the round. Usually, the ends of a mill length of a round are slightly overfilled. Flats, squares and nut steel are gauged for width, thickness and diamonding, but only the variations in width and thickness are reported. Cotton-tie, hoop, and skelp are reported for width and gauge thickness. Special sections are usually gauged by means of templets, but certain overall dimensions are generally given on the report. A sketch is sometimes made and the important dimensions lettered. The hourly variations for these dimensions are then inserted under the proper heading. Clip-iron, box-strap and bit-mouth are peculiar sections requiring special attention for gauging, and the various dimensions must be watched to get the section uniform. Inspectors at the cotton-tie mill have special duties to perform. They must get from each buckle machine every half hour a sample, which must be properly tagged and taken to the department superintendent for personal inspection. They are required to weigh ten bundles of cotton-tie every half hour and to post the weight on a blackboard in plain view of the roller. Concrete bar is rolled to weight, and inspectors must check the weights of the shear foreman. If for any reason an inspector is not willing to take the responsibility of passing slightly defective bars, the trucks loaded with such steel are marked with green tags, signifying, "hold for further inspection." This steel is examined by the assistant chief inspector, who either scraps the entire lot or details a specially instructed inspector to sort the good from the bad. Uses for which steel is rolled, as well as customers' claims, offer guides as to what defects a customer can accept.

# CHAPTER X.

## CIRCULAR SHAPES.

### SECTION I.

### SOME GENERAL FEATURES PERTAINING TO THE ROLLING OF CIRCULAR SHAPES.

**The Rolling of Circular Shapes** presents one of the most interesting studies of the rolling mill industry, because it is the latest development in rolling, and, though the idea of rolling wheels originated in Europe, it is in America that the art has been most highly developed. The beginning of this branch of the industry dates from the year 1903, when solid rolled steel car wheels were first used under freight cars. The use of such wheels resulted from the introduction in 1896 of all steel freight cars, which on account of their increased weight and great carrying capacity required a stronger and tougher wheel than any that had been made up to that time. It was to meet this requirement that Mr. Charles T. Schoen, who was the pioneer in the manufacture of all steel cars, perfected the mill, which now bears his name, for rolling these wheels. Later on, Mr. Schoen's method of preparing the steel, which will be explained later, was much improved by the Carnegie Steel Company, who purchased this mill in 1908. Considered from the standpoint of circular shapes in general, the Schoen mill has the one drawback of a very limited product. Being designed for one particular purpose, it can roll only car wheels, or wheels of that class, and of these it is limited to wheels between thirty and forty-two inches in diameter. While wheels as small as twenty-eight inches in diameter have been made on this mill, these smaller sizes are rolled with much difficulty, due both to the form of the rolls and the manner of rolling. For forming wheels less than thirty inches in diameter the Carnegie Steel Company has found that the forging press gives the most satisfactory results.

**Preparing the Blanks:** The circular shapes all require a round blank to start with. Mr. Schoen originally sheared his blanks from slabs with a specially constructed punch-like shear, the further work being then completed in much the same manner as it is done today. But this method had the serious fault of producing a wheel in which the line of segregation, or pipe, if any were present in the slab, was located diametrically across the wheel and terminated at both ends in the tread. From what has already been said about pipes and segregated steel, it is easy to see how this location of the segregated area might develop defects at these two opposite points. As has already been intimated, the Carnegie Steel Company was responsible for bringing about the correction of this fault, which is removed by locating the segregated line at the center and at right angles to the radii of the wheel, where the faulty material may be punched out for the bore. It is evident that the line of segregation may be so located in any one of three ways, namely, by casting the blanks individually, by cutting the blanks from round or hexagonal ingots, and by rolling the ingots into a round bloom from which the blanks may be sheared or sawed. All these methods are in use by the various manufacturers of wheels, but it would appear that the second and the third method should produce the best wheel, because more work is put on the steel. The third method is the one used by the Carnegie Steel Company. The round blooms for the Schoen mills are rolled at present on a twenty-eight inch bloomer at Homestead. Here a 22″ x 22″ ingot is slowly and carefully reduced in from twenty-one to thirty-one passes to a round bloom, eleven or fifteen inches in diameter for forged products, or fifteen inches in diameter for all wheels that are to be rolled at Schoen. From the blooming mill, the bloom, is delivered to a patented shear, known as the Slick shear, which is so located, in conjunction with the delivery table and the manner of rolling, that first cuts are made from that part of the bloom corresponding to the bottom or butt of the ingot. This first cut, usually about 5% of the ingot, is just sufficient to square up the butt end of the bloom and is always discarded. The remainder of the bloom, excepting the discard for pipe, is then cut into lengths to give the proper weight of metal required in the wheel, with an allowance of ten pounds over or under weight, and, if requested, each cut is hand stamped with a letter to indicate its position in the ingot, starting with A for the first cut next to the discard at the top of the ingot. Cut A, and often cut B, also, is used in making wheels for the use of the Steel Corporation only. In any case the total discard, which may include both A and B cuts, on wheels to the customer is never less than 25%, which amount is sufficient to insure sound steel in the wheels. For marking the heat number and weight of cut, the shear is provided with a stamp mounted on the revolving clamp for the shear knife, so that each disc, or blank, is plainly stamped with its heat number and weight. From the shears the blanks are taken to a shipping yard, where they are carefully inspected for surface defects, which are cut out by means of pneumatic chipping tools. Such of the blanks as pass this inspection are then sent to the mills to be worked into wheels.

## SECTION II.

### THE CARNEGIE SCHOEN METHOD FOR MANUFACTURING STEEL WHEELS.

**The Carnegie Schoen Method:** At the Schoen plant, which consists of three separate units, the finished wheel is produced in several stages, the number of which depend upon the kind of wheel, the unit in which it is made, and the working conditions of the heating furnaces. Upon receipt of the blanks at the plant, they are check weighed, and the heat number of each blank as well as the letter indicating its position in the ingot are all recorded in the form of a serial number. The blanks are then charged in order into a reheating furnace, where they remain for about two and one-half hours. In the older units, mills number one and two, the reheating furnaces are all of the regenerative type and use producer gas; but in the most recent mill, or number three, the first furnace is of the continuous type, the bottom of which is inclined sufficiently to cause the blanks to roll down from the feeding end as rapidly as they are removed at the drawing end. This type of furnace heats the discs very slowly and gradually, because it is intended merely to give the discs a preliminary heating, and its temperature is therefore low. At the drawing end, the temperature is maintained at about 800° C. After being subjected to this preliminary heating, the discs are transferred to a regenerative furnace for the final heating previous to forging. When the discs have reached the proper temperature, they are withdrawn from the furnace and taken to the forging presses where each is forged to a shape resembling that of the finished wheel before dishing or coning. As to dimensions, this forged blank is from four to five inches under size in diameter, some three-fourths inch over size in that part of the web near the rim, somewhat oversize, also, in depth of rim, a little oversize in width of rim, but of correct or slightly full size in the hub and a small part of the web next to the hub.

**Forging the Blanks—First Method:** The forging may be done in one heat or two heats and on one press or on two different presses. When two heats are used, two presses are usually employed for the forging. In this method, the disc is cleaned of scale on its two ends and then placed vertically in the first press, where it is first perfectly centered by two arms which engage it from opposite sides of the press and so support it till the top die has descended upon it. In this press the bottom die corresponds to the outside face of the wheel while the top die is plain, but may be slightly convex to cause a radial flow of the metal in taking the shape. The pressure, applied in successive steps by means of accumulators and intensifier, starts with about 700 pounds per square inch, then increases to 2500 pounds and, finally, to as much as 4500 pounds per square inch, if needed. At the beginning, the scale is cracked from the disc and falls into the bottom die, from which it is blown by means of a steam jet, in order to avoid pitting the surface of the blank. This pressing is, in itself, a severe test upon the metal, and any flaws, such as seams or cracks, are sure to be exposed, although they seldom occur. When such flaws do develop, the blank is scrapped at this press. The perfect blanks are now placed in a second reheating furnace, where their temperature is equalized and brought again to the forging point. When these conditions have been attained, the blank is cleaned of scale and placed in a second press, in which the top die conforms to the shape of the inside face of the wheel. Before applying the pressure, a little fine coal is thrown on the bottom die and upon the blank to prevent the dies sticking and to keep their surfaces smooth. After this forging, the blank is placed in a third press, where the bore is punched.

During the punching, the hub of the wheel is supported in neatly fitting dies in order to avoid forcing this part of the wheel out of shape.

**In the Second Method of Forging,** the press is provided with the two top dies mentioned in connection with the two presses used in the first method. These dies are mounted upon a sliding frame in such a manner that either may be brought at will beneath the piston of the press, thereby dispensing with the first forging press and permitting the forging to be accomplished in one operation when the conditions are favorable. Thus, if the blank is at a temperature sufficiently high and is evenly heated throughout, the second top die, conforming to the inside of the wheel, is brought over the blank, and the forging is completed in a single stage. If the conditions are such as are likely to cause an uneven flow of the metal, which results if the blanks are unevenly heated, the plain die is used first, then the inside die is moved into position and the pressure applied, thus forming the blank in two stages, but on a single heating. The bore is then immediately punched as in the first method. After the forging, by whichever method that may have been used, and the punching of the bore, the blank is placed in a reheating furnace where it remains until it has reached the proper temperature for rolling.

**The Rolling Mill:** The two older mills are very similar in every detail of their construction, but in the number three mill, which made its first trial rolling June 5th, 1917, a few changes looking toward an improvement in construction over the older mills have been made. For this reason this mill, rather than either of the older ones, will be described. This description is, however, made rather brief, for the mill, itself, is a somewhat complicated piece of machinery, as the reader will surmise when he is told that seven rolls play upon the wheel at one time during the rolling. These rolls consist of one tread roll, two web rolls, and four (2 sets) rim rolls, and are supported, together with all their bearings, pinions, or gears, adjusting screws, levers, etc., in one pair of horizontal housings, which are large steel castings and placed one above the other. The bottom housing lies directly upon the mill foundation and forms the support for the rolls and for the top housing some four feet above it. The housings are held apart by suitable pillars or posts and are bound firmly together by means of immense bolts. Between these housings the rolls are located; they may be described as follows: The largest roll is the tread and flange roll. In form it resembles a wheel, some thirty-three inches in diameter, and is so located back near the central point of the housings that, during the rolling, it revolves in the same vertical plane as the wheel and bears upon its tread from the rear. Its face is somewhat wider than the rim of the wheel and is grooved to correspond to the tread and flange. It is friction driven and is carried on a slide bearing, so that, by means of a screw, connecting the sliding box to a fixture at the rear of the housings and operated through a worm shaft and gear by means of a 15 h. p. electric motor located on

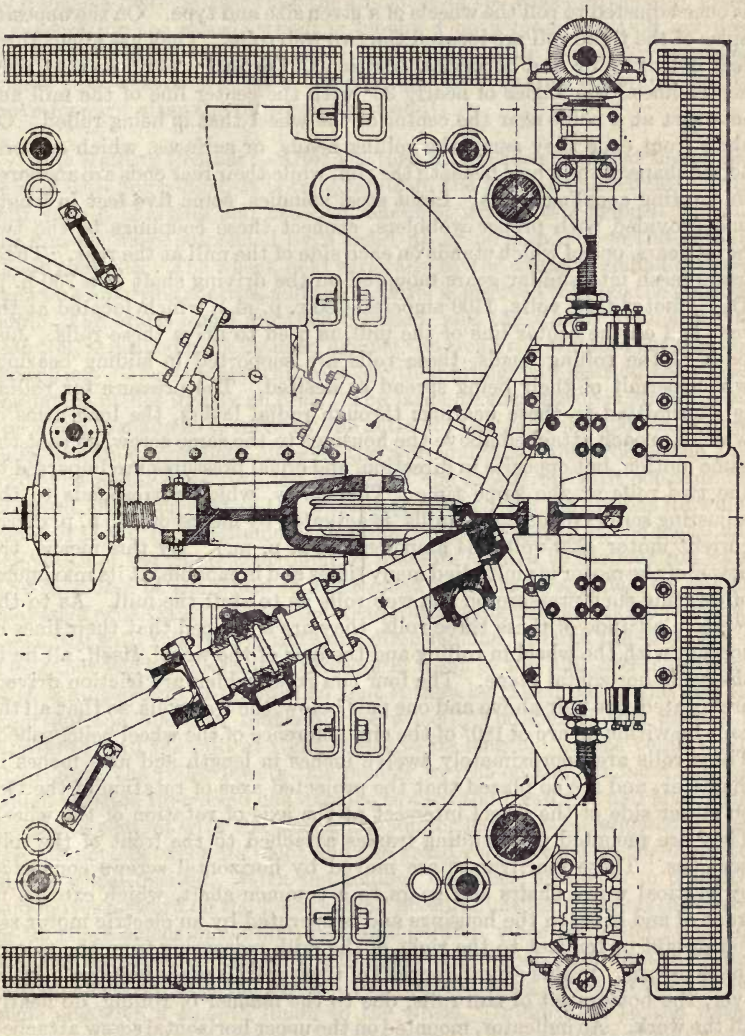


**Fig. 100.** Drawing of Schoen Mill Showing Wheel with Web, Tread, and One Set Rim Rolls in Position at End of the Rolling Operation.

top of the upper housing, this roll may be moved backward or forward at the will of the operator. Few operators, however, move this roll after the mill is once adjusted to roll the wheels of a given size and type. On the opposite sides of the tread roll are located the two web rolls. They are about three feet in length, lie in a horizontal position and extend inward, so that their center lines form angles of nearly 30° with the center line of the mill and intersect at a point near the center of the wheel that is being rolled. On their front ends they carry the rolling heads, or surfaces, which conform to the shape of the wheel beneath the rim, while their rear ends are anchored in rotating coupling boxes. Light steel spindles, some five feet in length and provided with proper wobblers, connect these couplings to the two bevel gears, one of which stands on each side of the mill at the rear. These gears mesh into similar gears mounted on the driving shaft of a 750 h. p. D. C. motor (500 volts, 1100 amperes, 130 r. p. m.), which, located at the rear and on the center line of the mill, is used to drive these rolls. Just back of the rolling heads, these rolls are supported in sliding bearings which permit of their being spread as desired. The pressure for rolling is transmitted to these bearings through radial levers, the long arms of which are each attached above the housings to the same screw, so that the same motion, but opposite in direction, and equal pressures are imparted to the two rolls at the same time. This screw, which corresponds to the adjusting screws on ordinary mills, is actuated by means of a 15 h. p. direct current motor (220 volts, 64 amperes, 550 r. p. m.). By this means, the power of the motor is multiplied many times and is capable, at its maximum, of exerting such pressure on the web rolls as to stall the mill. As to the relative altitude of these three rolls, they are so placed that their lines of contact with the wheel in rolling and the axis of the wheel, itself, all lie in the same horizontal plane. The four rim rolls, which are friction driven, are located, one pair above and one pair below, the web rolls, so that all the rolls lie within an arc of 180° of the circumference of the wheel being rolled. These rolls are approximately twelve inches in length and nine inches in diameter, and are so placed that the projected axes of rotation of the two on either side of the wheel intersect at the axis of rotation of the wheel. They are mounted upon sliding frames attached to the front of the mill housings. These four frames are moved by horizontal screws connected by vertical worm shafts and gears to a common shaft, which extends in front of and beneath the housings and is operated by an electric motor set some eight or ten feet to the right of the mill, measuring from the side of the housings. In this way the spread of these rolls is made uniform. However, the bottom set of rim rolls, due to the manner of rolling, do nearly all the work. An indicator, mounted on the upper horizontal screw attached to the sliding frame on the right side of the mill, is in plain view of the operator, who is able, by this means, to read the spread of the rolls and thus control the width of the rim. These rolls may be so formed that they will roll the sides of the rim at a slight angle to the vertical, so that these surfaces will lie in parallel planes after the dishing, or coning, process. Two shelves attached to the housings in front of the tread and web rolls and separated by a space a little greater than the thickness of the wheel at the hub, gives a support for the wheel, which is mounted on a loosely fitting mandrel during the rolling. This mandrel is provided with removable bearings, which rest, unattached, upon the shelves, thus leaving the wheel free to move forward after the rolls have gripped it.

**The Rolling Process:** After the forged blank has attained the proper temperature for rolling, it is removed from the furnace and carried to the mill with a charging and drawing machine, where it is gripped beneath the rim by tongs suspended by a small jib crane standing on the housing above the rolls. The wheel, held vertically by the crane, is guided between the two supporting shelves, and the mandrel is inserted through the punched bore. The crane tongs are then released, and the wheel, resting on the mandrel, is pushed back by hand against the tread roll and into the position for rolling. The web and rim rolls are then brought to bear on the wheel, the latter rather lightly at first. The large driving motor is started, and the wheel is made to revolve by the action of the web rolls upon it. These rolls, working upon both sides of the web and the under side of the rim, force the metal back into the groove of the tread roll with considerable pressure, until this part of the wheel has reached the dimensions for which the mill is set, or the diameter desired, while the spread of the metal and the width of the rim is controlled by pressure applied to the four rim rolls. The diameter of the wheel is ascertained by means of a gauge, or caliper, one end of which is attached to the tread roll housing, so that it is moved simultaneously with this roll, in the same direction and through the same space. The other end of the caliper projects in front of the mill, and is provided with a hinged arm or pointer, so that it may be raised out of the way for inserting the blank or removing the wheel. The end of this pointer is curved toward the mill at right angles to its length. At the beginning of the rolling, the roller lowers this pointer to rest on the left hand shelf, in which position its curved end extends toward the tread roll and is opposite its line of contact with the wheel, the pointer having been adjusted so that the distance between its point and the tread roll is equal to the diameter of the wheel desired. With the rolling, the wheel increases in diameter and moves forward on the loose sliding mandrel until a circle on the center of its tread comes in contact with this pointer, when the roller stops the mill and spreads the rolls for the release of the wheel. During the rolling, jets of water are directed against the surfaces being rolled to remove the scale and give a smooth finish to the wheel. In addition to the water, a salt jet is also directed against the tread. The actual rolling process requires about one minute, so that the maximum capacity of the mill is more than 500 wheels per day of twenty-four hours. However, on account of the care exercised to assure a high quality of product, these mills are operated at only 50 to 60% of their capacity.

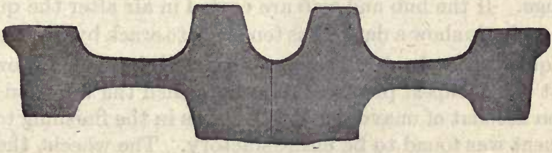
**Effect of the Rolling:** It will be observed that all the work of the rolling is concentrated upon the outer part of the web and the rim, where the additional refinement due to rolling is most needed. This refinement is very marked, as is shown by Brinell tests on sections of the wheel and by the visible difference in the structure of the metal between the hub and rim. This effect is most marked on the tread, where the hardness of the metal and closeness of grain can, no doubt, be considerably increased by rolling at low temperature or by chilling the metal by using an increased amount of water during the rolling. However, as such practice is likely to cause spalling, it is not employed by the operators. As machining the tread removes much of this super-refined metal, it would appear that the wheel rolled to a finish should be far superior in wearing properties to the machined wheel, on first run, at least. Evidence of this fact is seen in the increasing demand for rolled to finish wheels for passenger cars, even where formerly only machined treads were used. The mill practice on rolled to finish wheels is high, but a greater or less number of the wheels require machining in order to eliminate slight surface defects or true up the dimensions.

**Punching Web Holes and Coning:** After the rolling, the wheel is taken on a buggy to a small press, where the web holes are punched, when these are required. This press is fitted to punch either two or four holes, one and three-fourths inches in diameter, and equally spaced on radii of 8½, 9¼, 10, 11, or 12 inches, which are standard radii for all the different sizes of wheels. From the punching press, or from the rolling mill, if web holes are not required, the wheel is taken to the coning press, being hot stamped in transit with the word Carnegie on the inner surface of the web. This press is provided with dies which conform to the exact contour of the finished wheel, the top die corresponding to the inside of the wheel. For preserving the rotundity of the wheel, the bottom die is surrounded with a series of tread blocks in the form of segments of a circle, while the top die is similarly provided with a tapered ring to fit over these segments. Thus, when the dies are brought together for coning, this ring slips over the outside of the segments and forces them firmly against the tread while the coning or dishing is being effected. As these blocks leave slight impressions on the tread where adjoining blocks meet, the wheel is turned through an arc of a few degrees and again subjected to the pressure, which removes all but traces of these marks, except in occasional cases where they are unusually deep. Upon removal from this press, the wheel is hot stamped with a mill serial number, the heat number and the date, then it is passed to the cooling bed.

**Inspection of Carnegie Schoen Wheels** is very rigid. When cold, the wheel is rolled to the inspection platform for its initial inspection. This inspection covers surface defects, location of the hub, rotundity of tread, and the size, which is measured in Carnegie Standard tape sizes. These

A. The Blank.

B. Blank after First Forging.



C. Blank after Second Forging.

D. Wheel, after Punching, Rolling and Coning.

**Fig. 101.** Sketches Illustrating the Manufacture of Car Wheels by the Carnegie-Schoen Method.

tapes are graduated in eighth's of an inch, beginning with seven feet for a zero mark. The surface defects consist principally of over-fills, under-fills, slivers, scale pits, and block marks, and as they are seldom deep, they may be removed by machining. The tape size and all defects are plainly marked on each wheel, the former with a stencil, the latter in chalk. After this preliminary inspection, the wheels are machined as required to meet the specifications or remove the defects. On rolled to finish wheels, the machining consists of rough boring and facing of the hub and cutting in the limit of wear circle on the outside of the rim. The wheels are then rolled back to the platforms for final inspection, which is even more rigid than the first. In this inspection the wheels are tested for size, eccentricity and size of bore, position and size of hub, thickness and height of flange, radius of throat, thickness of rim, coning, rotundity, and soundness. After being re-stenciled with tape size and marks requested by the customer, such wheels as come within the allowable tolerances are mated and sent to the shipping platform.

**Heat Treating Car Wheels:** Heat treating is a recent innovation in the manufacture of car wheels, and may be said to be still in the experimental stage. Owing to the irregular section of the wheel, quenching is a difficult process, because, if the entire wheel is quenched, the uneven cooling of the heavy and light parts set up stresses in the shape that result in the destruction of the wheel. In order to overcome this tendency, the Carnegie Steel Company's research department has developed a method whereby the rim only is quenched, after which the wheel, before the hub and web have cooled, is given a drawback at a suitable temperature under the lower critical range. If the hub and web are cooled in air after the quenching of the rim, the wheels show a dangerous tendency to crack by this method, also, hence the quick draw back. From an economical point of view, it would appear that the cheapest plan would be to quench the wheel on the rolling heat, but on account of unavoidable variations in the finishing temperature this treatment was found to be unsatisfactory. The wheels, therefore, are allowed to become cold after rolling and coning, when they are reheated above their critical range before quenching. This process is accomplished in a rectangular tank provided with rollers grooved to conform to the tread and flange and so placed in the tank that they support the wheel in a vertical position transverse to the tank, which contains enough of the quenching fluid to cover the rim only. With the rollers, which are mounted on a shaft connected to a motor, revolving, the wheel, at the proper temperature, is placed in position on the rollers, which immediately start the wheel revolving, or spinning, also. The spinning is continued until the rim becomes sufficiently cooled when it is withdrawn and immediately given a draw back, as stated above. The process adds considerable to the cost of the wheel, and though there are many wheels in service thus treated, and apparently with promising results, sufficient time has not yet elapsed to determine just to what extent the wheels are improved by the treatment.

**The Forging of Circular Shapes:** As previously indicated, only those circular shapes which are more than thirty inches in diameter can be finished by rolling on the Schoen mill. However, this plant, which represents the circular shape department of the Homestead works, produces a great number of smaller circular shapes by forging only. These smaller shapes include such articles as wheels for low type street cars; double flanged crane track wheels; automobile fly wheels; turbine discs; shaft couplings; pipe flanges; pistons for locomotives; gear rings; and gear blanks for automobiles, farm tractors, turbo generators, street cars, etc. In addition to these, a miscellaneous lot of circular shapes ranging in form from the most intricate sections to plain discs, and in sizes from twenty-five pounds to five hundred and even a thousand pounds are produced. For forming all these shapes the same powerful presses are employed as are used in preparing the rolled wheel blanks, and in general the methods of forging are similar, with the exception that additional precautions in the removal of scale before forging are observed. In this connection it should be noted that forging will not produce the smooth finish obtained by rolling on the Schoen mill, and all forged articles requiring a perfectly smooth surface must be machined to finish.

# CHAPTER XI.

# FORGING OF AXLES, SHAFTS AND OTHER ROUND SHAPES.

## SECTION I.

### HOWARD AXLE WORKS AS AN EXAMPLE OF A FORGING SHOP.

**The Plant and Its Equipment:** Aside from the forging of armor plate and other articles required by our government, small wheels and a miscellaneous lot of shapes for its own use, the Carnegie Steel Company has restricted its market activity in the forging line to the manufacture of axles, shafts and similar heavy products. For these products the company operates a plant especially designed for the work, known as the Howard Axle Works, which may be taken here as an example of a modern forging plant. The essential equipment of the plant includes three continuous coal fired furnaces for heating the blooms, a twenty-four inch roughing mill of two stands of rolls in tandem, ten 7000 pound and two 7500 pound double acting steam forging hammers, three gag press straighteners, thirty double cutting-off and centering machines, twenty-seven rough turning lathes, two finishing lathes, one boring lathe, two hollow drill machines, and a complete heat treating plant that will be described more in detail later. The forging limits of the plant as to size is as follows: Maximum weight, 2500 pounds; maximum length, ten feet; maximum diameter, twelve inches; minimum diameter, three inches. As to arrangement, the layout of the plant provides for the most economical handling of the materials. The blooms start in at one end of the plant and continue in one direction, progressing step by step through the various operations, until, upon arrival at the other end of the plant, they are in a form ready for shipment.

**Precautions to be Observed in the Manufacture of Axles:** As the failure of an axle in service usually results with serious consequences, great responsibility rests upon the manufacturer at all times to see that each and every axle is as nearly perfect as it is possible to make it. Before describing the processes of manufacture, it may be well to point out some of the things that may cause axles to fail, because the thing aimed at in developing a method of manufacture is the elimination of as many of the causes of failure as possible. There are many of these causes of failure, according to some writers upon the subject, but the majority may be traced to the following, which are to be looked upon as the chief sources of danger: 1. Pipe; 2. Segregation; 3. Unequal or improper heating; 4. Slag inclusions; 5. Forging strains; 6. Incipient cracks. From this list it is seen at a glance that some of these sources of danger are very difficult to eliminate and that the making of a good axle must begin with the making of the steel, itself. The other defects may be overcome by proper attention to details during the processes of rolling and forging the steel. Starting with the steel after it has been rolled into blooms, which must correspond in dimensions and weight to the size of the axles it is intended for, the various steps in the process of manufacture at these works are as follows:

**Inspection of the Blooms:** Located at Homestead, Pa., the Howard Works receives its steel from the Homestead Steel Works at Munhall. Here, before the steel is shipped to the axle works, the blooms are subjected to a rigid inspection. Those blooms that show any signs of pipe or insufficient discard at the blooming mill shears are rejected. Surface defects, such as seams, slivers and surface cracks, are carefully chipped out, and those blooms in which the defects extend beyond certain depths, or occur on the part that corresponds to the wheel seat are also discarded. Such blooms as pass the inspection are shipped to the axle works, where they are stored under cover until needed.

**Heating the Blooms:** The proper heating of the blooms for forging requires that they be uniformly heated throughout and be brought gradually to the forging temperature, which should be kept as low as possible and yet permit the work to be done. The advantages of a low finishing temperature in securing maximum grain refinement is readily understood. The importance of heating slowly is also realized, when it is pointed out that rapid heating may cause the outside of the bloom, which is first to rise in temperature, to expand away from the more slowly heating core and thus cause ruptures that may not be welded up by the action of the hammers. Slow heating gives the heat a chance to "soak" into the bloom, thus giving that uniformity in temperature from center to surface so necessary to secure a finished forging of the best quality. As to the proper temperature, the manufacturer has always had to depend upon the eye and judgment of the trained heater in the past, and must continue to do so to a great extent in the future. The use of pyrometers does not replace this human element, because the pyrometer records the temperature of the furnace and not of the steel, particularly in the case of the continuous furnace. The rate of heating is fixed by the type of furnace. At these works, therefore, the continuous furnace is used because this type heats up the steel very gradually. The bloom is placed in the furnace at the cold end and is slowly pushed toward the hot end, so that it reaches a full forging temperature only a short time before it is drawn from the furnace.

**The Rolling and Forging Operation:** Having been brought to the proper temperature for forging, the blooms, within a certain range of sizes, are pushed out of the hot end of the heating furnaces upon a conveyor, which serves all three furnaces, and are carried by it to the rolling mill.

This mill consists of two stands of rolls in tandem, as previously stated. Each stand is provided with four passes cut to take four different sizes of square blooms. These sizes are 6½, 7½, 8 and 8½ inches. The passes are shaped to round off the corners of the bloom, to secure which result is the main object in the use of the mill. The reduction in cross sectional area due to the rolling varies from 3½% to 5%. From the mill, a roll table distributes the blooms to the hammers, which are arranged in two rows, one on each side of the table. Adjustable deflecting rails built in the side guards of the table serve to divert the blooms to small receiving tables, of which there is one for each hammer, and leave them in positions to be most conveniently grasped by the hammer tongs, which are suspended from cranes. The tongs having been quickly clamped on, the bloom is swung around between the forming dies of the hammer. These dies are provided, when desired, with two or more grooves; one, the plain groove used to do the greater part of the forging, is located directly under the piston rod, while the other grooves, used to form special sections, such as the journals, are placed beside the plain groove. The forging is begun at the middle of the bloom, which is rapidly reduced by heavy blows of the hammer, the forging progressing toward the free end of the bloom. Here, by the special grooves in the die, the journal or other special section is formed by a few strokes, when the piece is again placed in the plain groove, and the forging is smoothed up and brought, by light strokes of the hammer, to correct diameter, which is determined by caliper. The tup is then brought to rest upon the axle, which is held between the dies while the tongs are released, and those on the opposite side of the hammer are made fast to the finished end. The other end of the axle is then forged down like the first, except that, in addition to diameter, the length is also fixed. The crane is then swung around, and the axle is placed on the cooling bed, where it is supported about three feet above the floor by two rails, which arrangement allows it to be cooled uniformly by the air. The average reduction in cross sectional area under the hammer is about 50%. Forgings requiring blooms larger than eight and one-half inches are reduced entirely by hammer. Two crews, each made up of a hammerman, who has charge of the forging, and three helpers, and one hammer driver, are assigned to each hammer. The crews work alternately, each crew completing one axle at a time.

**Advantages of the Method:** Aside from the increased tonnage made possible by the rapidity of the work, the method of forging employed at Howard presents many advantages which bear directly upon the quality of the product. The rolling mill, which accomplishes only a small fraction of the total work done upon the axle, is a great help to the hammers. By rounding off the corners of the bloom, it practically eliminates all danger of forming hammer laps, and permits the forging to be accomplished in the shortest time possible. Hence a low initial temperature can be used for forging, and the work can be completed at a more uniform temperature.

This uniformity of the finishing temperature is a very noticeable feature at Howard. Thus, in observing closely various axles at different stages of the forging operation the eye can detect little difference in temperature between those axles on which the forging has just begun and those that are being finished. That this rapid method of forging on one heat is far superior to the old method of forging on two heats is apparent, because it not only promotes greater uniformity in individual axles but eliminates, to a far greater degree, the variation in different axles.

## SECTION II.

### FINISHING PROCESSES FOR FORGINGS.

**Straightening:** Except in the case of heat treated axles, and driving and trailing axles, the next step after the forging is the straightening, which is accomplished by means of gag presses. From the cooling beds the forgings are carried forward by over-head cranes to similar beds in front of the presses. Here each axle is inspected for straightness, and those that require it are straightened. Heat treated axles are straightened after being treated, but driving and trailing axles are too large to be straightened by the gag press.

**Cutting-off and Centering:** After passing the inspection for straightness, the forgings are moved forward by overhead cranes and distributed to the cutting-off lathes. These lathes are double combination cutting-off and centering machines, and are designed to work on both ends of the forging at the same time. Upon being inserted in this machine, the forging is grasped at the wheel seats by adjustable revolving centering clamps, which hold it firmly to the central axis of rotation, while two cutting tools, placed one at each end and adjusted to the correct length, are brought to bear and cut off the excess metal at the ends. In this cutting, a tolerance of one-eighth inch over length and nothing under is permitted. When these tools have cut to within about one-half inch of the center, they are run back out of the way, the pieces of excess metal are detached with a sledge, and with the forging still held by the centering clamps, the revolving centering tools are brought to bear at each end. These tools are shaped to cut a 60 degree cone-shaped centering hole, five-eighths inch in depth, one and one-eighth inch in diameter at the top, and with a clearance hole

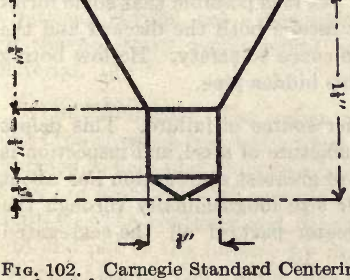


Fig. 102. Carnegie Standard Centering for Axles.

for points at the bottom one-half inch in depth and three-eighths inch in diameter. When axles are ordered to be smooth forged only, the operation of cutting off and centering completes the work done by the mill. On such axles some excess stock is necessarily left on those parts that are to be finished later. This allowance on car axles is generally one-half to three-fourths inch over the finished diameters of the end collars, journals, and dust guards, and one-fourth to three-eighths inch on wheelseats.

**Rough Turning:** On account of the saving that can be effected in handling and transportation of excess weight, it is a decided advantage to both the customer and the shop, especially to the latter, that all rough turning be done before shipment is made, as it is only by rough turning that certain flaws can be detected. Rough turned material falls into two classes, known as "rough turned on journals and wheelseats," and "rough turned all over." Axles of the first class are put into service with the center portions between the wheelseats smooth forged to size. In the case of axles rough turned all over, the center portions are forged slightly over size to provide for the metal removed in turning to size. In the case of car axles or other axles with a tapered body, this metal is removed at the same time (or after) the journals and wheelseats are rough turned, in a special lathe provided with two tools controlled by a former-bar whose contour is the same as the middle portion of the axle. In finishing rough turned axles, the wheelseats are finish-turned only, while the dust guards, journals and collars are finish-turned and burnished, and in order to provide the excess metal required for this work, these parts are rough turned one-eighth inch over size on their diameters.

**Hollow Boring:** Owing to the many apparent advantages arising therefrom, the practice of boring large axles and forgings longitudinally through the center is being advocated more and more strongly. These advantages are briefly discussed under the following headings:

1. **Piping,** it will be recalled, was given as one of the causes of failure. While the Carnegie Steel Company, by a generous discard and close inspection, aims to eliminate this defect, yet it is possible that some forms of piping, notably compound pipes, may escape both the discard and the inspection, and remain in the axle as a menace to safety. Hollow boring gives the inspectors a chance to detect this hidden pipe.

2. **Segregation** was given as another source of failure. This defect cannot be entirely overcome in the manufacture of steel, and inspection is no safeguard against it. But as the area of greatest segregation lies about the central axis, boring a hole of proper size longitudinally through the center should, and does, remove the greater part of all the segregated material from the axle.

3. **Strength and Weight:** The central portion of an axle removed by boring is really a non-essential part so far as strength is concerned.

The transverse strength of rounds is proportional to the cubes of their diameters. So, for example, if a three inch bore be made in a six inch axle, the maximum loss in strength is but 12.5%; in an eight inch axle, but 5.25%. These figures represent the loss in strength provided the center is as strong as the outer portion, which condition is never true in axles or similar forgings, so that the actual loss in strength in nearly every case would be much less than these figures indicate. Again, the axle with the bored center may actually be stronger than it would have been solid, provided it contained much segregated material or the remnant of a pipe—conditions that favor the formation of internal cracks. Another factor concerns the relation between the loss in strength and the loss in weight. In this connection it will be observed that, whereas the strength varies as the cube of the diameters, the weight varies as the squares. Referring to the example just cited, and applying this law, the reader will find that while in the case of the six and eight inch axles, the three inch boring gives a loss in strength of 12.5% and 5.25%, respectively, the loss in weight is 25% for the first and 14.3% for the second.

4. **Hollow Boring and Heat Treating:** As an aid in heat treating, especially in quenching and tempering, or toughening, hollow boring is of great importance. In heating, it permits the heat to be absorbed much more rapidly, and in quenching, the heat is more rapidly removed than in solid pieces, with the result that the structure is more uniform. Furthermore, contraction and expansion strains are largely overcome, and shrinkage cavities in the center are avoided. The American Society for Testing Materials specify that all forgings over seven inches in diameter that are to be quenched shall be bored. The diameter of the hole bored should equal or exceed 20% of the largest diameter of the forging exclusive of collars or flanges. Howard Axle Works are equipped to bore holes either two or three inches in diameter.

**The Heat Treating Plant** is housed in the same building with the hammers and lathes and consists of two furnaces for heating with the forgings in a horizontal position, one furnace for heating the material in a vertical position, one water quenching tank, one oil quenching tank, and all the necessary supplemental equipment for handling and testing the material.

**The Furnaces:** The inside working space of the two furnaces of the first type are each twenty-four feet in length and nine feet in width, and are designed to heat uniformly to a height of about four feet above the bottom. They are provided with removable bottoms of the car type, which much facilitates the charging and drawing operations. This bottom is moved into and out of the furnace by means of a toothed rack attached to the bottom of the car and a stationary pinion actuated by an electric motor, the car itself resting on rollers that move over a double track. The doors of the furnace are of the vertically lifting type, and are hydraulically operated.

These features, together with the close proximity of the quenching tanks, permit the drawing and quenching of a charge in the quickest possible time, less than a minute being required to transfer a charge from the closed furnace to either of the quenching tanks. The measures taken to secure uniform heating are particularly noticeable in this furnace. The furnace is of the reversing flame type, in which natural gas is employed as fuel, and is heated by means of burners placed at space intervals of less than two feet along each side, thus permitting the temperature at any point in the furnace to be controlled to a nicety. At the top, the furnace is closed with a roof, arched from side to side, while, inside, high bridge walls extend along in front of the gas burners to prevent the flames from impinging upon the charge. In order that the entire surface of the material may be exposed to heat of the same intensity, the charge is supported at a height of about eighteen inches above the floor of the car bottom by two steel rails that extend the entire length of the car. These rails are spaced about four feet apart and are supported by castings in the form of four-legged stools. The floor of the car bottom is constructed of brick laid upon a bottom of steel plates, and is of such thickness as to give ample insulation from the heat of the furnace. The bottom is made to fit the furnace neatly, and the escape of hot gases from the heating chamber is prevented by means of sand seals. The construction of the furnace for heating the charge in a vertical position is somewhat like that of a soaking pit. It has a capacity of about six axles and sufficient head room for maximum lengths of ten feet. In operating this type of furnace, the axles are loaded on a cast steel rack, which is specially designed to support them in a vertical position, and are lowered through the top into the furnace where they are maintained in a vertical position throughout the heating operation. This furnace is seldom used, as more satisfactory operating conditions are obtained by using the other type. For taking temperatures the Siemens Water pyrometer is used exclusively.

**The Quenching Tanks:** For use in connection with these heating furnaces, the plant is equipped with one water quenching and one oil quenching tank. These tanks are both placed as near as possible to the furnaces, the water tank being directly in front of one of the furnaces of the horizontal-heating type. This tank, approximately twenty-five feet long, twelve feet wide and fourteen feet deep, is of the sub level type and is constructed of concrete. When in use, the water level lies about two feet above the floor of the shop. So, an ample volume of water is supplied for any charge it is practicable to handle, and, in addition, provision is made whereby fresh water may be introduced during the quenching operation at one corner of the tank and the excess conducted away at the diagonally opposite corner, both inlet and outlet being located near the top of the tank. Two beams extending the full length of the tank and supported about two feet above the bottom, prevent the charge from resting on the bottom when lowered by the crane, thus securing more uniform cooling. The oil quenching tank is some sixteen feet in length, nine feet in width, and ten feet in depth, inside. It is made in two parts—an oil container and a cooling jacket. The container is made of steel plates and is set within the cooler, which is constructed of concrete and is about twenty inches longer and wider than the container, so that a space of about ten inches separates the walls of the two vessels. This space is kept filled with cold water, which serves to prevent the temperature of the oil rising too high during quenching, and to cool it down rapidly after each charge.

**The Testing Equipment** includes all the latest devices for testing materials. In the shop, two hollow drill machines for cutting out tests are provided, and as all heat treated axles are given individual shock tests, a drop testing machine for giving these proof tests is also located here. Two drop testing machines, adapted for testing axles in accordance with standard specifications are provided. Other physical tests are made in the physical laboratory, which is equipped with one planing, one turning, one pulling, one torsional, one bending and one Brinell machine, and all the supplemental appliances for accurate testing.

**Advantages of Heat Treating Axles:** While the proper heat treating of axles is accomplished with some difficulty on account of their size, and is attended with great danger if improperly done, yet with proper equipment, great care and good judgment, born of knowledge and experience on the part of the operator, the dangers may be eliminated, and decided advantages result therefrom. It is the only way in which the grain structure can be refined and made uniform, and in doing this all the evils due to variations in the grain, which result from the heating and working of the bloom, are overcome, as well as forging strains. But greatest of all these advantages is the improvement in mechanical properties effected through correct heat treatment. It offers the only positive means of markedly increasing the strength and wearing properties of axles without in any way increasing their weight—a thing that is much desired under modern conditions of traffic.

# PART III.

## THE CONSTITUTION HEAT TREATMENT AND COMPOSITION OF STEEL.

**Introductory:** It is the desire in this part of this little book to center the interest of the reader chiefly about the heat treatment of steel. So much progress in the study of this subject has been made in recent years that many are inclined to look upon it as something new. That remarkable changes in the physical properties of a given steel can be brought about through the agency of heat alone has been known for many years, but until 1890 the subject had received very little attention from scientists. Up to that time both the scientific knowledge about the subject and the technical application of the art of heat treatment were very limited, being confined for the most part to the making of tools and a few specialties. The invention of the automobile, the aeroplane, and other machines, the different parts of which are required to be light and at the same time suitable for the usages to which the parts are subjected, gave rise to demands for steel of great strength combined with various other specific properties. These demands directed the attention of investigators to heat treatment because it was found that this was the only means of meeting these requirements. Practically all alloy steels must be heat treated in some way, and few steels in their natural state will give their full value in service, so that the various combinations of static and dynamic strength and wearing qualities required can be obtained in their highest degree only by adjusting and correlating both the chemical composition and the heat treatment. Just as certain chemical components intensify one set of properties, and others another set, so the heat treatment may be changed to develop different qualities in a similar way. Thus, by combining the proper chemical composition with the proper heat treatment, there results a product possessing in the highest degree the properties most desired for the work the steel is to do. So it is evident that the intelligent application of heat treatment to secure the best results requires a thorough knowledge, on the part of those supervising the work, of the composition of the steel and the effect of the various elements that are to be found in all steels or that may be added as alloys to produce the special steels. Again: Heat treatment consists in heating and cooling steel under conditions that will produce the desired change or changes in physical properties, and embraces the three processes of annealing, hardening, and tempering, to which may be added the special processes known as "process annealing," "patenting," "case hardening," etc. The remarkable changes in properties that may be obtained, together with the phenomena observed during heating and cooling, all connote vital changes that are brought about by the heat treatment. As no change in composition of the metal takes place, the cause for the phenomena must be sought in changes of arrangement or condition of the constituents of the steel itself. Another pre-requisite, then, to the study of heat treatment is the study of the structure and constituents of steel, a thorough knowledge of which is essential to any understanding of the subject, whatever. For this reason, the study of heat treatment should be prefaced by a brief summary of the knowledge concerning the structure and constitution of steel.

Before beginning this study, however, the student should understand that part III of this book is intended merely as an introduction to the study of metallography, heat treatment and composition of steel. Those who desire a further knowledge of these valuable and fascinating subjects are referred to such authorities as Albert Sauveur[1], whose plan of developing the subject is closely followed in this study; H. M. Howe[2], whose iron carbon diagrams are used herein; and D. K. Bullens[3], whose practices in heat treatment are frequently referred to.

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[1] See the Metallography and Heat Treatment of Iron and Steel, Published by Sauveur and Boylston, Metallurgical Engineers, Cambridge, Mass.

[2] See Iron, Steel and Other Alloys, and The Metallography of Iron and Steel. Both published by McGraw-Hill Book Company, Inc., 239 West 39th Street, New York.

[3] See Steel and Its Heat Treatment, Published by John Wiley & Sons, Inc., New York City.

# CHAPTER I.

# THE CONSTITUTION AND STRUCTURE OF PLAIN STEEL.

## SECTION I.

### STEEL AS AN ALLOY OF IRON AND CARBON.

**The Constituents of Steel:** Steel is not a single element or compound, but a complex artificial product, composed of many elements held in the solid mass as a mechanical mixture of alloys and chemical compounds with the element iron. In ordinary steel, these elements are iron, carbon, manganese, phosphorus, sulphur, silicon and oxygen, with traces of nitrogen, hydrogen and other elements, such as aluminum, copper and arsenic. Of these, all are to be considered as impurities except carbon, which is an essential ingredient, and manganese, or other elements added for a definite purpose. For the sake of simplicity and brevity only pure steel, consisting of the two essential elements, iron and carbon, will be considered in this chapter. Even in this case steel is found to be an aggregate made up of mineral-like components, some of which are visible only with the aid of the microscope after the surface of the specimen has been highly polished and etched with dilute acids or other corrosive mixtures which affect the various constituents in different ways. To the structure thus revealed by the microscope the term micro-structure is given, to distinguish it from the macroscopic structures, or those visible to the naked eye; and to the different constituents mineralogical names have been applied. Thus, in pure steels which have cooled slowly from a high temperature, three distinct constituents are recognized. They are called ferrite, pearlite, and cementite, and in the different steels will vary in amount according to the carbon content.

**Ferrite** is the term applied to pure iron, i. e., carbonless iron, when it is considered as a microscopical constituent of steel. It is soft, ductile and relatively weak, having a tensile strength of about 40,000 pounds and an elongation of 40 per cent. in two inches. It has practically no hardening power, a high electric conductivity, and can be magnetized. It appears white in color after being etched with dilute alcoholic nitric or picric acids. It is best seen in steels containing .10% to .30% carbon, when it appears as a network surrounding bodies of pearlite, another constituent of steel to be described shortly.

**Cementite:** As already stated, iron and carbon are the essential elements in steel, and of these carbon may be termed the controlling element. When steels are cooled slowly from high temperatures, from the fusion

1. Photomicrograph showing a grain of pearlite surrounded with free ferrite as a net work. Specimen taken from annealed steel containing carbon .48 per cent. and manganese .54 per cent. Magnified 750 diameters

Etched first in 5% alcoholic picric acid for eight seconds, then in 5% alcoholic nitric acid for five seconds. White area represents ferrite. On account of a too rapid rate of cooling, the pearllite is not fully developed. Compare with Figs. 48 and 113.

2. Photomicrograph of a specimen of steel containing carbon to the extent of 1.50 per cent. The excess cementite is here seen in the form of spines, or needles.

Magnified 100 diameters. Etched for eight seconds in five per cent. alcoholic picric acid and for two seconds in five per cent. nitric acid, making the free cementite, which stands in relief, brilliant white in color.

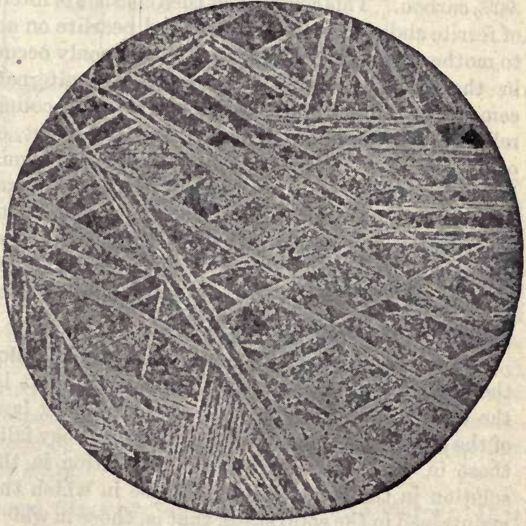


FIG. 103. Photomicrographs illustrating the micro structure of Steel. (Photographs prepared by O. M. Ash. Portland office, U. S. Steel Products Co.)

point, for example, all the carbon is found combined with a definite amount of iron in the form of a carbide of iron corresponding to the chemical formula $Fe_3C$. This compound consists of carbon, 6.67 per cent. and iron, 93.33 per cent., and it is known micrographically as cementite. Any excess iron is practically free of carbon at atmospheric temperatures and remains as ferrite in steels that have cooled slowly. Little is known about the properties of cementite except that it is very hard and brittle. Indeed, it is the hardest component of steel, and will scratch glass and feldspar but not quartz. It is about two-thirds as magnetic as pure iron under an exciting current. After polishing the surface of steel, it stands in relief, and is brilliant white after etching with dilute hydrochloric or picric acids. It occurs free in ordinary steels of more than .90% carbon, in which it appears as a network or as spines and needles. It takes its name from cement steel, made by the cementation process, which contains a great deal of this carbide, $Fe_3C$.

**Pearlite:** One of the most remarkable characteristics of cementite and ferrite is their power of forming the conglomerate known as pearlite. During the process of slowly cooling steel from higher temperatures, say above 1000° C., it has been found that the cementite and ferrite always form, at about 700° C., a mechanical mixture made up of definite amounts of each and in the proportion of about seven parts ferrite to one part cementite, so that the resultant conglomerate will contain approximately .90% carbon. This constituent then consists of interstratified layers or bands of ferrite and cementite, and is called pearlite on account of its resemblance to mother of pearl. While pearlite commonly occurs in slowly cooled steels in the lamellar formation, composed of alternate layers of ferrite and cementite, it may under different rates of cooling and dependent on the relative amounts of ferrite and cementite present, exist in other formations, or phases, of which some authorities have recognized at least four, making in all five modifications. Normal pearlite has a maximum tensile strength of about 105,000 pounds, and an elongation of about 10% in two inches. It is regarded as a separate and distinct constituent of steel because it forms distinct masses or "grains," always contains this definite percentage of carbon and is always formed at a definite temperature, or a range of temperatures, to be more exact.

**Manner of Freezing of Solutions and Alloys:** In order to clarify the explanation of the formation of pearlite, it is necessary to digress to the extent of explaining some of the freezing laws of solutions. A study of the freezing of solutions has shown that they fall into two classes, namely, those in which the ingredients in solution in the liquid state remain in solution in the solid state and those in which the state of solution is not maintained in the solid state, that is, those in which the ingredients separate on freezing.

**An Example of the First Class of Solutions:** One of the best examples of the first kind of solution is a mixture of gold and silver. If quantities of these two metals be placed in a vessel and heated until they melt, a homogeneous mixture, or a liquid solution, results; and if this mixture be allowed to cool to the solid state, it is still homogeneous, that is, it is a solid solution. A study of many mixtures in which the proportions of gold to silver are varied shows that freezing begins at a different temperature for each mixture. Pure gold freezes at 1062° C. and pure silver at 961° C., and the freezing points of the mixtures occur between these two points. Unlike the pure metals, however, these mixtures do not solidify completely at a constant temperature, but their freezing is prolonged through ranges of temperature. These facts, definitely determined by experiment, may be represented by a diagram, or curve, such as the following, in which the ordinates represent temperatures and the abscissae the percentage of gold or silver or both.

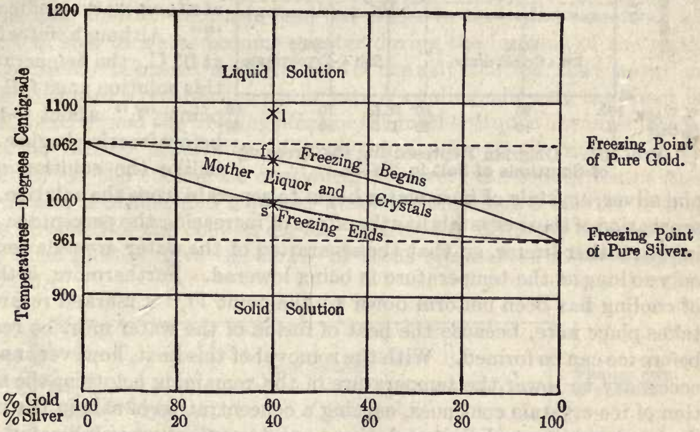


FIG. 104. **Diagram of the Freezing of Liquid Gold-Silver Alloys.**

To illustrate further, suppose sixty ounces of gold be mixed with forty of silver, and the whole heated to a temperature of 1090° C. The locus of this point would be at "l" in the region of the liquid state. If now this molten mass be allowed to cool, crystals, each of which contains 60% gold and 40% silver, begin to separate out at "f," about 1041° C., and continue to do so until the point "s," about 990° C., where the last of the liquid freezes, is reached. No further change takes place as the cooling proceeds, and the solid mass is found to be homogeneous and of the same composition as the liquid solution. Any other mixture of these two metals would give a like result, except with respect to the freezing points, and the solid crystals would be found to be made up of gold and silver in the same proportion as they were in the liquid state.

**Example of the Second Class of Solutions—Salt and Water:** It is a well known fact that a solution of common table salt freezes at a lower temperature than pure water. This lowering of the freezing point, or rather the temperature at which freezing begins, varies with the proportion of salt to water until this proportion has reached the definite limit of 23.5%, when any further addition of salt causes the point at which freezing begins to rise. This lowest temperature, at which the solution containing 23.5% of salt freezes, is —22° C. These facts are represented by the diagram of Fig. 105.

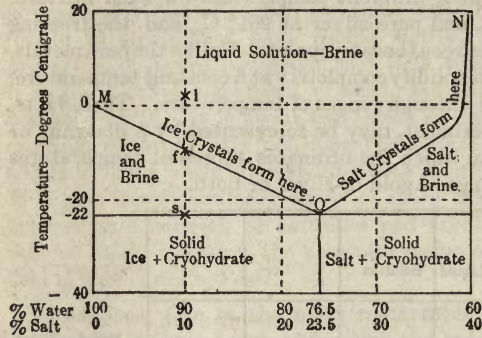


Fig. 105. Diagram Representing the Freezing of Solutions of Salt in Water.

Two or three examples will suffice to explain the freezing of solutions containing varying amounts of salt, and any other points about the diagram that may not be clear. Thus, suppose a solution containing 10% of salt is at a temperature indicated by "l". Although water freezes at 0° C., the temperature of this solution must fall to the point "f," about —10° C., before freezing begins. Here, unlike the solution of gold and silver, crystals of pure water begin to separate from the solution. The separation of these crystals has the effect of increasing the percentage of salt in the mother liquor, so that the separation of the water crystals continues only so long as the temperature is being lowered. Furthermore, if the rate of cooling has been uniform down to the point "f," a marked retardation takes place here, because the heat of fusion of the water must be removed before ice can be formed. With the removal of this heat, however, and that necessary to lower the temperature of the remaining solution, the separation of ice crystals continues, causing a concentration of salt in the mother liquor that bears a definite relation to the temperature as indicated by the line M O. Finally, when a temperature of —22° C. is reached, the mother liquor, which now contains 23.5% of salt, freezes as rapidly as the heat of fusion is abstracted. When all this liquor has solidified, the temperature of the solid mass will continue to fall uniformly in a manner similar to that before freezing began.

If instead of the weak solution, a strong brine containing more than 23.5% of salt is substituted in the experiment just described, it is found that, just as ice separated along the line M O., salt crystals separate out along the line N O until the temperature —22° C. is reached and the mother liquor contains 23.5% of salt. This liquor then freezes as described before. When these facts were first observed, it was thought that the mother liquor that is the last to freeze was a hydrate of sodium chloride of the formula $NaCl.10\,H_2O$. and was called, therefore, the **cryohydrate,** cold hydrate, meaning a hydrate that could exist in the solid state only at low temperatures. It has since been shown that these cryohydrates are not chemical compounds, though they have a definite composition, but are mechanical mixtures made up of crystallized salt and ice in intimate contact.

**Lead and Tin Solutions as Another Example of the Second Kind of Freezing:** Many of the fused alloys exhibit the same phenomena in freezing that saline solutions do, showing that their constituent metals form a solution when in the liquid state but that they are insoluble in one another in the solid state. As an example of such an alloy, that of lead and tin is most convenient for study. To cite a specific example, let a mixture composed of 30% tin and 70% lead be heated to a temperature of 350° C. As this temperature is above the fusion points of both lead and tin, which melt at 327° C. and 232° C., respectively, it is sufficiently high to insure that the mixture will be completely fused. Now, as this solution cools down, no crystallization takes place until a temperature of about 270° C. is reached, when crystals of lead begin to separate out, making the remaining solution poorer in lead but richer in tin in the same way as the ratio of salt to water became greater during the freezing of the weak saline solution. Likewise, as in the case of the salt solution, the separation of the lead causes a retardation of the rate of cooling, showing that heat is evolved thereby; and the freezing point of the mother liquor becomes lower, so that no further separation of lead takes place until more heat is abstracted. If the cooling be continued, however, the separation of the lead will also continue, and if proper measures be taken, a number of loci may be obtained of the cooling curves for alloys of different composition, which, when plotted, give the curve M O as represented in the diagram of Fig. 106.

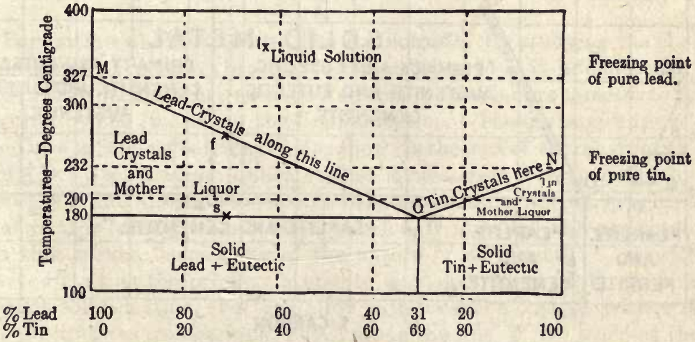


FIG. 106. Diagram Illustrating the Freezing of Lead-Tin Alloys.

When the cooling and the accompanying separation of lead has reached the point O., corresponding to a temperature of 180° C. and 31% of lead, or 69% tin, in the mother liquor, the whole mass becomes solid, forming a banded structure composed of minute crystals of lead and tin and corresponding to the cryohydrate of salt and water, but called, in the case of alloys, **eutectic alloy**, which signifies easily melted alloy. To the right of the point O, tin separates along N O like lead along M O. This manner of freezing, where one metal separates alone, is known as **selective freezing** to distinguish it from the kind of freezing illustrated by the gold-silver alloys, which, since both metals separate together, is known as **non-selective freezing.**

**The Iron-Carbon Eutectic:** Coming now to a consideration of the iron carbon alloys, the student finds that the freezing of alloys of these two elements presents phenomena that are like those of both the gold-silver and the lead-tin alloys. The freezing of these alloys is represented by the following diagram, from which it is seen that the carbon content

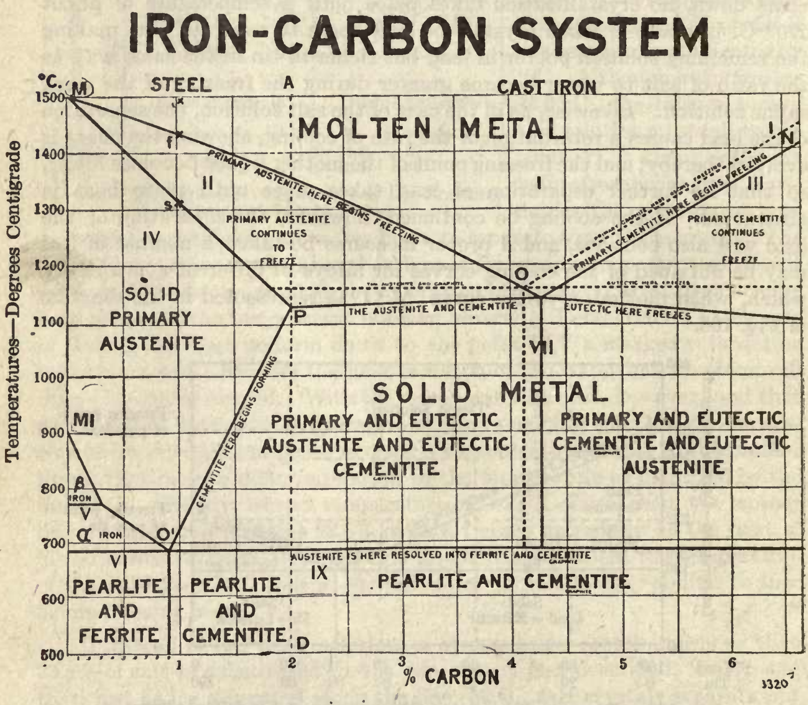


Fig. 107. Diagram Demonstrating the Freezing and Cooling of Iron Carbon Alloys. After H. M. Howe.

of the eutectic alloy is about 4.30%. Therefore, when alloys that contain more than this amount of carbon are cooled from temperatures above the line M O N, carbon in the form of graphite separates along N O until the point O is reached, when the eutectic solidifies. Naturally, the reader would expect a similar separation of iron along the line M O; but it is here that the freezing of the solution produces phenomena similar to the freezing of gold-silver alloys, for it is found that, instead of pure iron separating, a definite mixture, or alloy, containing approximately 2.0% carbon and called **primary austenite**, separates from all mixtures in which the carbon content is two per cent. or more. By drawing in the vertical line A D, corresponding to about 2.0% carbon, this diagram is divided into two parts. The part to the right of A D shows the freezing of the iron carbon alloys to be like that of the lead-tin alloys, that is, selective, while that part to the left of A D shows that the freezing of all iron-carbon alloys whose carbon content is less than 2.0% is non-selective and analogous to the freezing of the gold-silver alloy. For example, suppose an iron-carbon alloy containing 1.0% carbon to be at a temperature of 1500° C. It is in the liquid state and represents a homogeneous mixture of iron and carbon, or a solution of carbon in iron. If now this solution is allowed to cool, crystallization will begin when the temperature indicated by the corresponding point "f" on the line M O is reached, and will continue up to the point "s" on the line M P, when the solidification will have been completed. Each crystal that separates contains 1.0% C., and when the point "s" is passed, the mass represents a solid solution with a carbon content of 1.0%. This solid solution is also known as primary austenite. Because of this difference in the freezing of the iron carbon alloys between those containing more than 2.0% carbon and those containing less than 2.0% carbon, the carbon content of 2.0% may be considered as the dividing line between steel and pig iron; consequently, this study is concerned mainly in the changes that occur in alloys whose composition is represented by the region in the diagram that lies to the left of the line A D.

**Formation of Pearlite and the Eutectoid:** By studying the cooling of the primary austenite through the region below M P, it is found that this solid solution of carbon in iron undergoes changes similar in character to those presented by the freezing of the liquid solution. These changes are represented by a secondary set of curves as shown in the part of the diagram to the left of A D. This diagram indicates that a substance corresponding to the eutectic of liquid alloys is formed and that it contains about .90% carbon, but since it is formed from a solid solution, it is called the **eutectoid,** a term that means "something of the nature of an eutectic." It will be observed that as the primary austenite is cooled from M P, the line of complete solidification, that any alloy with a carbon content greater than .90% precipitates iron carbide, $Fe_3C$, along the line P O′, whereas those, in which the carbon content is less than .90%, throw out of solution pure iron or ferrite along M′ O′ until the eutectoid composition is reached. The unchanged alloy, to which the term mother metal may be applied, then undergoes a change wherein the precipitation of both the iron and the iron carbide, $Fe_3C$, is completed simultaneously, with the result that the eutectoid thus formed consists of interstratified layers of ferrite and cementite, commonly called pearlite, as previously explained. Hence, the term eutectoid is often applied to pearlite, when it is desired to indicate the manner of its formation and its structural characteristics. Since the metal is in the solid form during these changes, it having reached its freezing point 500° to 800° C. above the temperature of formation for pearlite, the cause for these changes cannot be ascribed to a change in state. While many theories have been advanced to explain this and other facts the most satisfactory explanation is that iron exists in at least two, possibly three, allotropic forms. Thus, below a temperature of 690° C. it exists in a form designated as the alpha form, in which it has no power of dissolving carbon or the carbide, cementite, whereas above this temperature it can hold this constituent in solid solution. At these higher temperatures it is designated as the gamma form, and the solid solution of carbon, or carbide, in iron, is, micrographically, called **austenite.** Furthermore, the change from austenite to pearlite is not instantaneous, and, as will be explained later, several transition products may intervene, the complete series being austenite, martensite, troostite, sorbite and pearlite. From what has been said, it is evident that a steel that contains .90% carbon will, if cooled slowly from any point above the critical temperature for its formation, consist entirely of pearlite. Such steels are designated as **eutectoid steels,** while those that contain less than .90% carbon are termed **hypo-eutectoid steels,** and those in which the carbon content exceeds .90% are called **hyper-eutectoid steels.** Other phenomena which accompany the cooling of the primary austenite will be described in the next section.

**Structural Composition of Slowly Cooled Steel:** All steels that have been cooled slowly from a temperature above that for the formation of pearlite will contain it as a constituent. Thus, in the case of hypo-eutectoid steels, all the carbon present will be found as pearlitic cementite, the amount of pearlite being controlled by the amount of carbon present. Any ferrite above that required by the cementite in the formation of pearlite will be rejected as free, or excess, ferrite. In such steels, this excess ferrite is in the form of a network surrounding small masses of the pearlite. In the case of hyper-eutectoid steels, the amount of pearlite is again controlled by the carbon, but in an indirect way. As all the carbon combines with iron to form cementite, only a limited portion of ferrite remains for the formation of pearlite. As this ferrite is not sufficient to interstratify with all of the cementite, an excess of the latter remains. Like the rejected ferrite, this excess cementite will also appear as a network about the masses of pearlite. Thus, from the carbon content of a slowly cooled steel it is possible to determine accurately the structural composition, or from the relative proportions of pearlite and ferrite or cementite as revealed by the microscope, the practiced metallographer can determine the approximate carbon content.

**Effect of These Constituents Upon the Physical Properties:** The data on the physical properties of these constituents enables the student to understand the remarkable effect of carbon upon the physical properties of ordinary steel. In brief, the facts in their relation to the static strength of slowly cooled steel are as follows: 1. Each constituent has the power to impart to the steel its own properties in proportion to the extent of its presence. 2. Ferrite has the minimum tensile strength but maximum ductility. 3. Pearlite has maximum tensile strength with low ductility. 4. Cementite has great hardness and brittleness with very little strength. The effect of these constituents upon the properties of steel are plainly shown in the accompanying diagram.

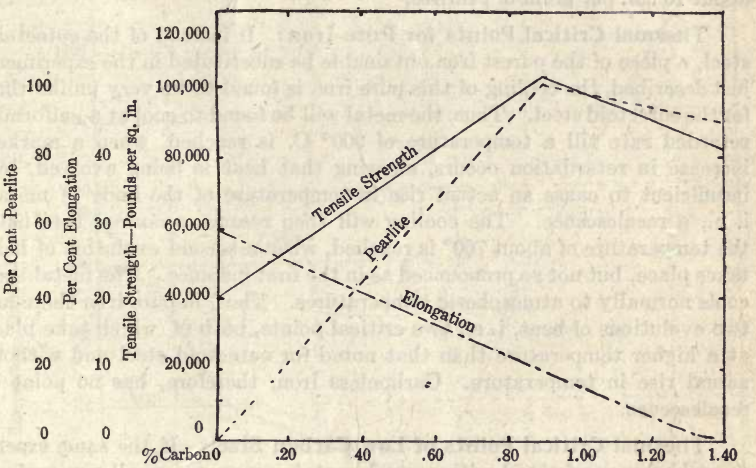


FIG. 108. Diagram Showing the Approximate Influence of Carbon Upon the Strength and Ductility of Steel and its Relation to the Pearlite Content.

## SECTION II.

### THERMAL CRITICAL POINTS OF STEEL.

**Nature of Critical Points or Ranges of Steel:** The structural and other changes in steel just described take place at temperatures known as the thermal critical points, or critical ranges, because they are points in the cooling or heating of the metal that are marked by the spontaneous evolution or absorption of heat. The most marked of these is the range commonly called the point of **recalescence** and point of **decalescence.**

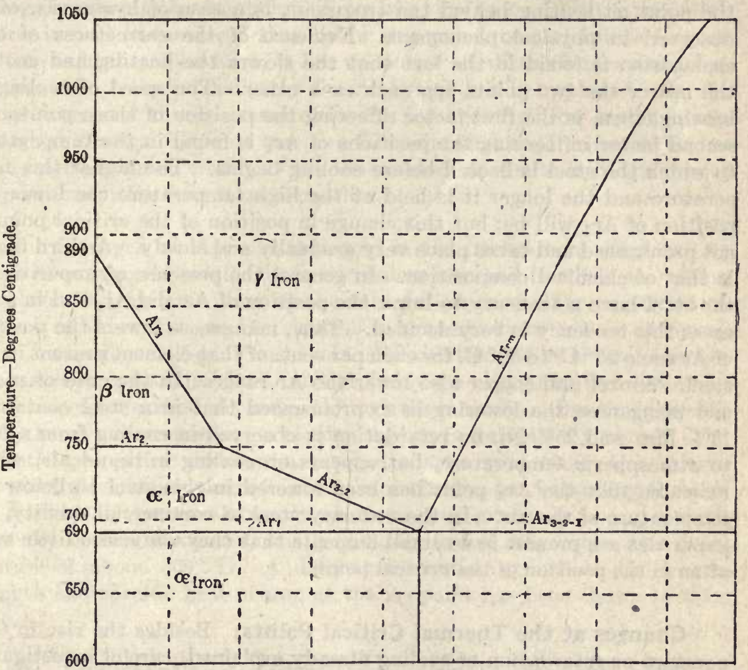
**Thermal Critical Point for Eutectoid Steel:** For example, suppose a piece of steel, containing .90% carbon and at a temperature of 1000° C., be allowed to cool slowly. If, now, the rate of cooling be carefully ascertained by means of a pyrometer, it will be found that the cooling proceeds at first at a uniformly retarded rate, thus following the law for all cooling bodies. But when a temperature of about 700° C. is reached, the uniformly retarded cooling is momentarily arrested. A pyrometer will not only fail to record any further decrease in temperature, but in most cases, when the conditions are favorable, will show that the temperature of the cooling mass actually rises. These facts show that heat is spontaneously generated within the metallic body in amount sufficient to balance, or more than balance, that lost through radiation and conduction. If the experiment is performed in the dark, the steel will be observed to glow at this point due to the heat evolved, and so the term recalescence has been applied to it. Investigation has shown that the amount of heat given off in this case is about 16 cal. per gram of pearlite.

**Thermal Critical Points for Pure Iron:** If instead of the eutectoid steel, a piece of the purest iron obtainable be substituted in the experiment just described, the cooling of this pure iron is found to be very unlike that for the eutectoid steel. Thus, the metal will be found to cool at a uniformly retarded rate till a temperature of 900° C. is reached, when a marked increase in retardation occurs, showing that heat is being evolved, but insufficient to cause an actual rise in temperature of the body of metal, i. e., a recalescence. The cooling will then resume a normal rate until the temperature of about 760° is reached, when a second evolution of heat takes place, but not so pronounced as in the first instance. The metal then cools normally to atmospheric temperatures. Thus, in pure iron there are two evolutions of heat, i. e., two critical points, both of which take place at a higher temperature than that noted for eutectoid steel and without actual rise in temperature. Carbonless iron, therefore, has no point of recalescence.

**Thermal Critical Points of Low Carbon Steel:** If the same experiment be now performed with a steel containing even a small per cent. of carbon, say .10%, the influence of this element is found to be very marked. Three thermal retardations will be detected, the first, the most marked, at about 850° C., the second near 760° C., and the third at the point of recalescence, near 700° C. The last two are very faint.

**Thermal Critical Points of Medium Carbon Steel:** If the experiment with low carbon steels be repeated with specimens containing higher and higher percentages of carbon, the upper critical points observed in the preceding experiment on .10% carbon steel and carbonless iron will be found to be lower and lower as the percentage of carbon is increased, until, finally, the determination of the rate of cooling of a steel containing .35% or .40% carbon reveals only two critical points, the upper one at about 740° C. and the other at the point of recalescence, 700° C. This fact means that the carbon has caused the two upper points observed in pure iron and low carbon steels to merge into one critical point. Furthermore, experiments on steel containing a higher per cent. of carbon than .40 show that the two lower critical points remaining also apparently merge into one on steels containing .60% carbon and over. Theoretically, this apparent merging should not take place till the steel is composed entirely of pearlite, that is, when it has the eutectoid composition and contains .85% to .90% carbon. The early merging is attributed to the difficulty of distinguishing by experiment two critical points so close together.

**The Carbon-Iron Diagram for Steels and Methods of Notation:** These critical points or ranges are indicated graphically in the accompanying diagram of Fig. 109, which is seen to be the same as that used in explaining the formation of pearlite. This diagram refers to the critical points on cooling, which occur at temperatures somewhat lower than on heating. All these critical ranges are denoted by the letter "A," followed by either the small letter r, an abbreviation for the French word "refroidissement," cooling, or the small letter c, which stands for "chauffage," signifying heating. These signs, Ar and Ac, are further modified by the numerals 1, 2, 3, indicating the point of recalescence, the second, and the third points encountered on heating, respectively. Thus, Ac1 means the first critical point passed upon heating the steel, and so on.



| %Carbon | .0 | .2 | .4 | .6 | .8 | | 1.00 | 1.20 | 1.40 | 1.60 | 1.80 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| %Cementite | 0. | 3. | 6. | 9. | 12. | | 15. | 18. | 21. | 24. | 27. |
| %Pearlite | 0. | 24. | 48. | 72. | 96. | 100. | 97.+ | 94.— | 90.+ | 87.— | 83.+ |
| %Free Ferrite | 100. | 76. | 52. | 28. | 4. | 0. | 0. | 0. | 0. | 0. | 0. |
| %Free Cementite | 0. | 0. | 0. | 0. | 0. | 0. | 3. | 6. | 10. | 13. | 17. |

FIG. 109. Diagram Showing Position of the Critical Ranges and the Relation of the Carbon Content to that of Pearlite and Ferrite and Cementite.

**The Position of the Critical Ranges** is affected in many ways. Attention has already been called to the difference between the ranges on heating and cooling. In commercially pure carbon steels, $Ar_1$ almost invariably takes place between 690° C. and 720° C. and $Ac_1$ 20 to 40 degrees higher. It has been well established that this lagging of the point on cooling and the point on heating behind the true point is a case of hysteresis, often observed in physical phenomena. Evidence of the correctness of this explanation is found in the fact that the slower the heating and cooling the nearer the two points approach each other. The speed of cooling or heating, then, is the first factor affecting the position of these points. A second factor influencing the positions of $Ar_1$ is found in the temperature to which the steel is heated before cooling begins. The higher this temperature and the longer it is held at the high temperature the lower the position of $Ar_1$ will be; but this change in position of the critical point is not pronounced and takes place very gradually and slowly. A third factor is that of chemical composition. In general the presence of impurities in the steel have a tendency to lower the position of Ac and Ar, and in some cases this tendency is very decided. Thus, manganese lowers the position of Ar some 25° C. to 50° C. for each per cent. of that element present in the steel. Nickel and copper also lower the Ar range. In the case of nickel and manganese the lowering is so pronounced that in a steel containing 13% Mn. and 25% Ni. no retardation is observed in cooling from a high to atmospheric temperature, but appears on cooling in liquid air, which indicates that the $Ar_1$ point has been lowered in this steel to below the temperature of the air. In the ordinary steel of commercial quality, the impurities are present in so small amounts that they can cause little variation in the position of the critical points.

**Changes at the Thermal Critical Points:** Besides the rise in temperature or retardation of cooling already explained, careful investigation has shown that other important changes take place in steels in passing through these ranges. For convenience these changes and their effects are summed up as follows:—

I. **Changes at $A_3$:** The point $A_3$, as already shown, applies to carbonless iron and steels containing less than .35% carbon. The passing of such steels through this point is accompanied by the following phenomena: 1. On cooling, the metal, which above $Ar_3$ was contracting, undergoes a sudden and marked expansion in volume on passing through $Ar_3$. In linear units the expansion amounts to about one one-thousandth of its length. This dilation is then immediately followed by normal contraction, again. 2. Above $A_3$ the metal has an electrical resistance about ten times greater than its resistance at ordinary temperatures. At $Ar_3$ a sudden drop in this resistance takes place, after which the decrease proceeds slowly at a uniform rate until atmospheric temperature is reached. 3. A change in crystalline form of iron takes place at $A_3$. Below this point iron crystallizes in the cubic form, but this form changes on passing $Ac_3$ to that of the octahedra. 4. The tensile strength of iron at the $A_3$ point has been shown to undergo a distinct discontinuity, (see page 337). 5. The dissolving power of iron for carbon is one of the most important changes which the properties of the metal undergo in passing the $Ac_3$ point. From what has been said in the preceding section it may be surmised that below this point, or at least as long as the iron is in the alpha form, it has no power of dissolving carbon, but it gains this power immediately the $Ac_3$ point has been passed. 6. An abrupt structural change accompanies the passage of all low carbon steels through this range. It is on reaching this point that the free ferrite begins to be set free, which continues till the residual austenite is of the proper composition for the formation of pearlite.

II. **Changes at $A_2$:** As indicated in the iron-carbon diagram, $A_2$ occurs as a separate point only in carbonless iron and in steels containing less than .35% carbon. Just as the retardation on cooling was found to be faint at this point, so the changes in properties are not so numerous nor so marked as at $A_3$. Thus, there is no dilation, no structural change, no change in crystalline form, and probably no change in the dissolving power of iron for carbon on passing through the range $A_2$. But the following three changes in properties on passing $A_2$ are to be specially noted. The magnetic properties undergo a marked change on passing $A_2$. Above this point steel is non-magnetic, or para magnetic, but in passing through $Ar_2$ it suddenly becomes strongly magnetic, and gradually becomes more so as the cooling continues, finally gaining its full magnetism at a temperature of about 500° C. A distinct discontinuity in both the tensile strength and specific heat of iron at the $A_2$ point has been shown to take place.

III. **Changes at $A_{3,2}$,** which point results from the merging of $A_3$ and $A_2$, are the same as those occurring in low carbon steels in passing through $A_3$.

IV. **Changes at $A_1$:** As previously explained, the point $A_1$ occurs in all steels containing from a mere trace to .90 per cent. carbon. It corresponds to the transformation of residual austenite into pearlite. At this point the following sudden changes in properties are noted: 1. A dilatation takes place which increases with the carbon content, reaching a maximum with .85% carbon. 2. Increased magnetism takes place for all steels on cooling through this point. 3. A marked decrease in electrical resistance is also noted on cooling through this range. 4. Below this point iron loses entirely its power to dissolve carbon. 5. The important changes from austenite to pearlite have already been shown to take place at $A_1$, but it is well to emphasize their significance here, for these changes give the key to the rational treatment of steel. The spontaneous transformation of austenite of eutectoid composition into pearlite, that is, a solid solution into an aggregate of the eutectoid, makes possible the refining of steel by heat treatment, because on being heated through its critical range, the steel is changed from a coarse aggregate to a fine, almost amorphous, solid solution. This fact is also the secret of hardening steel, as will be shown later.

**Causes of the Thermal Critical Points in Steel:** In seeking a cause for the existence of the thermal critical points in steel, all the phenomena exhibited must be considered. Starting first, then, with the thermal changes noted in the experiments previously described, it is well to note that there are but three well known causes of spontaneous evolution of heat in cooling bodies and of similar absorptions of heat on heating them. Briefly, these causes are (1.) the formation or decomposition of chemical compounds; (2.) changes of state, whether by solution or by the agency of heat; and (3.) allotropic or polymorphic transformations, which are always accompanied by either an absorption or evolution of heat when the substance of the body passes from one allotropic condition to another. As to the upper points, $A_3$ and $A_2$, it has been shown that at these points even carbonless iron either absorbs or evolves heat, depending upon whether the metal is being heated or cooled while passing through the ranges. The fact that the iron is pure, nothing being present with which it could combine, and the fact that it is in the solid state throughout the experiment, preclude the possibility of either a chemical change or a change of state having taken place to cause the thermal changes indicated. Only the explanation founded on the basis of allotropy, therefore, remains. According to the two thermal changes that occur, then, pure iron or ferrite exists in at least three allotropic forms. Below the point $A_2$ it is called **alpha iron,** between $A_2$ and $A_3$ it is known as **beta iron,** while above $A_3$ it is said to be in the **gamma form.** While it is not desirable to undertake a discussion of this theory here, it may be pointed out that all the changes in properties previously mentioned as accompanying these critical points are but additional evidence of the correctness of this view. Since the influence of carbon is to delay the separation of ferrite, it may be that beta iron is not formed on cooling steels containing .35% carbon or more, for since the temperature of the point $Ar_{3\text{-}2}$ in such steels is below that for the formation of beta iron, it is probable that just as iodine passes directly from the solid to the gaseous state by sublimation, or as amorphous sulphur at atmospheric temperatures passes to rhombic sulphur, so gamma iron passes directly to the alpha form. The fact that the point $A_1$ does not occur in carbonless iron and only faintly in low carbon irons, while with increase of the carbon it increases in intensity, is evidence that this point is due solely to the presence of carbon. Unlike the points $A_3$ and $A_2$, which are due to allotropic forms of iron, $A_1$ is not due to any change in the carbon itself, but merely to the formation of pearlite, which implies the crystallization or falling out of solution of cementite, $Fe_3C$, coupled with the complete change of the ferrite from the gamma to the alpha state as well. Above

$A_1$, the $Fe_3C$, being in solution with the gamma iron and thoroughly diffused, has the power of imparting its own properties, hardness and brittleness, to the steel in a more pronounced way than when in the segregated form in which it occurs below $A_1$. Hence, formerly due to the theories then advanced to explain the hardening effect of carbon, the term **hardening carbon** was applied to it above $A_1$, while below $A_1$ it was called **cement carbon.**

## SECTION III.

### THE CRYSTALLINE STRUCTURE OF STEEL.

**Crystals and Grains:** That the crystalline structure of steel exerts a deep influence upon its strength and ductility is a well known fact. Since this structure lends itself to refinement through proper heat treatment, a clear understanding of all the laws governing the crystallization of steel is essential to the art of heat treating steel. When steel, like many other substances, passes from the liquid to the solid state, the process of solidification is accompanied by crystallization, that is, the molecules of the various ingredients arrange themselves so as to form small bodies having regular geometrical outlines. Each of such bodies constitutes a crystal. In the case of iron in the gamma form the crystals are octahedra, or small eight sided bodies, but when the iron is in the alpha condition these crystals are cubic in form. Crystals have the remarkable property, called **cleavage,** of breaking most easily along certain planes usually parallel to the faces of the crystal. Hence, these planes of easy rupture are called **cleavage planes.** The direction of the cleavage planes constitutes the **orientation** of the crystal. Perfect crystals, called **idiomorphic crystals,** are formed only when the conditions are favorable. Thus, with high fluidity, absence of foreign particles, slow rate of cooling, and with the liquid at rest and undisturbed, perfect crystals of large size may form. Because of the unfavorable conditions that usually prevail in its manufacture, the crystallization of steel results in the formation of imperfect crystals with irregular forms and smaller in size than perfect crystals. These imperfect crystals are, scientifically, designated as **allotrimorphic crystals,** but the metallurgist speaks of them simply as **grains.**

**Crystallization of Steel:** As an aid to understanding the crystallization of steel it will, perhaps, be best to follow the crystallographic history of a steel casting that is allowed to cool slowly from the casting temperature to atmospheric temperature. For the present, let this steel be of any carbon content. During the solidification period, what has been termed the primary crystallization takes place, which consists in the formation of macroscopic tree-like bodies of austenite called dendrites. Each of these dendrites is composed of small octahedra, which is representative of the crystallographic form for austenite. Of these, Stead writes: "The fine fir-tree crystallites, containing probably a fraction of the amount of the carbon in the liquid steel, grow steadily forward from the cold surface of the containing moulds. The crystallites develop branches in three directions corresponding to the axes of the cube, and these branches throw out similar branches themselves. Eventually parts of the most fusible portions are trapped between the branches and are the last to solidify. When there is much phosphorus or some sulphur in the metal, they are always present together with an excess of the carbon in the last residue of metal that remains liquid, and although in cooling down, after the liquid has solidified, the excess carbon diffuses out of it into the purer part, the sulphides and phosphides do not, but remain fixed, and can generally be detected in the solid metal."

After the solidification is complete a crystalline transformation, called granulation, sets in and continues until the critical range is reached, where all steels are found to be made up of grains, each grain having its own orientation and being made up of small octahedra of crystalline matter. The size of these grains varies with the rate of cooling, just as the rate of cooling affects the size of crystal in any metal. In passing through the critical range the structural changes are affected by the amount of carbon present, and for this reason it is best to consider the three grades of eutectoid, hypo-eutectoid, and hyper-eutectoid steels separately from this point onward.

**Crystallization of Eutectoid Steels:** In the eutectoid steels the growth of the grains will continue down to the point $Ar_1$, where the metal will be made up of grains of austenite containing ferrite and cementite in proper proportions to form pearlite. Therefore, in passing through the critical point, $Ar_1$, each austenite grain changes bodily into a grain of pearlite. Hence, the coarse austenitic structure acquired by cooling from a high temperature gives rise to a correspondingly coarse pearlite structure.

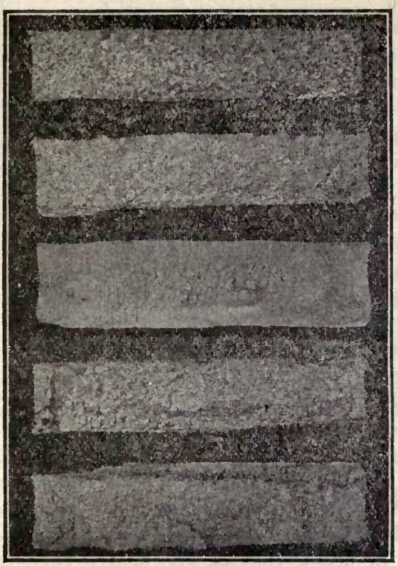
**Crystallization of Hypo-Eutectoid Steel:** As an example of the genesis of the crystalline structure of steels of hypo-eutectoid composition let a steel containing .60% carbon, corresponding to 72% pearlite and 28% free ferrite, be selected. In such a steel the granulation will proceed till the upper critical point $Ar_{3-2}$ is reached, where free ferrite begins to be rejected and continues till the point $Ar_1$ is reached, when the residual austenite, being of the proper eutectoid composition, passes into pearlite as described for eutectoid steels. An important point to be noted here is the fact that this setting free of the excess ferrite is brought about through the rejection of ferrite in excess of the eutectoid composition **by each individual grain of austenite,** either to its boundaries or between its cleavage planes. When each grain of austenite becomes a grain of pearlite, the ferrite previously rejected still remains as an envelope, thus forming the net-work mentioned under "Ferrite." Therefore, the structure of cast hypo-eutectoid steel is very coarse, for the following three reasons: 1. The slow and undisturbed cooling promotes the formation of large austenite grains and hence, later, of large pearlite grains. 2. The slow cooling between the upper and lower critical points favors the rejection of a maximum amount of free ferrite, which rejection makes for coarseness of structure. 3. The slow cooling from the upper critical point to atmospheric temperature promotes the crystallization of excess ferrite into large grains, especially when this excess is large in amount, i. e., in very low carbon steel. Because of its coarse structure, cast hypo-eutectoid steel is less tenacious and less ductile than forged, rolled or properly annealed steel of similar composition.

**Crystallization of Hyper-Eutectoid Steels:** In the case of hyper-eutectoid steels, the granulation proceeds to the point Acm, a temperature that is indicated by the line Acm in Fig. 109, where excess cementite is liberated—like the excess ferrite in hypo-eutectoid steels. This excess cementite is rejected either to the boundaries of the austenite grains or between their cleavage planes, where, after the transformation of eutectoid austenite into pearlite, it remains to form a network about the grains of the latter.

**The Effect of Work on Grain Size:** The effect of work on the mechanical properties of steel has been discussed in the second part of this book. It remains to be pointed out here that the greatest benefits of working as the steel cools to $Ar_1$ are due to a refinement in the grain size. The explanation for this refinement is found in the fact that, as each grain is distorted by the application of mechanical pressure, it endeavors to resume its original form, but being hindered in this by the rigidity of the mass, it breaks up into a number of smaller grains possessing the characteristic form. If the steel be worked at temperatures below $Ar_1$, cold working, no refinement of grain takes place, as the great rigidity of the metal or its lack of molecular energy prevents any readjustment of the grains at all. Hence, cold worked steel will show a pronounced distortion of grain.

**Crystalline Changes on Heating Steel:** Since the preceding discussions have been concerned mainly with steel under conditions of cooling, it may be profitable to review these changes from the standpoint of heating. Starting, then, with a low carbon steel, containing, say, .20% carbon, it will be found that, under normal conditions of manufacture and in its natural state, this steel consists of approximately 24% pearlite and 76% free alpha ferrite, the pearlite existing in small grains surrounded by the ferrite as a network. Upon heating through the point $Ac_1$, the pearlite changes into austenite, the iron of which is in the gamma form; but the free ferrite is still in the alpha form. As the heating continues throughout the zone bounded by $Ac_1$ and $Ac_2$ the austenite thus formed begins to absorb the free ferrite. Upon passing through the $Ac_2$ range the remaining alpha ferrite changes into beta ferrite; and the steel as a whole will be found to be hard and non-magnetic. As the heating progresses through the second zone, lying between $Ac_2$ and $Ac_3$, the beta ferrite, which is only a remnant of the original alpha ferrite, is gradually absorbed, so that as the range $Ac_3$ is passed the whole of the steel passes into the condition of austenite, or a solution of iron carbide in gamma iron. In a similar manner the changes in the constituents of steels of any carbon content up to eutectoid steel might be explained. In each case, however, it is to be noted that the temperature at which the transformations are completed falls as the carbon content is increased, being at its lowest when the eutectoid ratio has been reached. In the case of hyper-eutectoid steels, the free cementite is absorbed in a manner analogous to the absorption of free ferrite in hypo-eutectoid steels. But the final solution of the cementite takes place at a temperature range indicated by the line Acm, and much more slowly than ferrite. This latter point, being a matter of great practical importance, should be kept in mind.

**Crystalline Refinement on Heating:** Besides these structural changes brought about by heating the steel through the various critical ranges, there still remains a matter of extreme importance to be explained. This matter refers to the crystalline, or grain, refinement observed when a steel is heated through these ranges. Again assuming that the steel is in a normal condition after manufacture in the usual manner, no change on heating is observed to take place in the grain structure until the temperature has reached that of the lower critical range, $Ac_1$. At this temperature, which marks the point where the original pearlite grains are transformed into austenite grains, the maximum refinement, that is, the smallest grain size possible, occurs. This refinement is to be expected from the conditions of the formation of the austenite. Since the conditions favorable for the formation of large grains require slow cooling from a high temperature, the formation of the austenite at this low temperature permits no growth of the grain structure at all. Hence, it is found to be almost amorphous in respect to its grain structure. But it is to be especially noted that, as the temperature is raised above this critical range, grain growth begins, which fact results in a gradual coarsening of the grain of the austenite as the temperature is progressively raised above this range. It is also to be noted that this increase in grain size not only varies with the temperature above the critical range, but also with the length of time at which the steel is maintained at the high temperature. In eutectoid steels, then, complete and maximum refinement of the grain takes place immediately the point $Ac_1$ is passed. But if the steel contains free ferrite or free cementite, that is, if it is of hypo-eutectoid or hyper-eutectoid grade, then the steel as a whole is not refined on passing $Ac_1$, because the excess ferrite or cementite remains unaltered. In all cases it is only when all the constituents of the steel have passed into the state of a solid solution, or austenite, that complete refinement can be obtained. To bring about such a condition, it is necessary to heat such steels to a temperature a little above that of their upper critical ranges as indicated on the iron carbon diagram, on account of hysteresis previously discussed.



1. Heated to about 1300° C. and quenched in water.

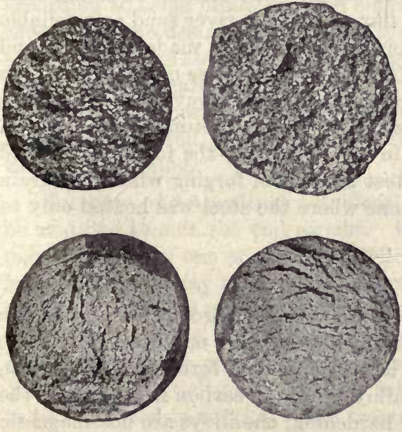
2. Heated considerably above the critical range and quenched in water.

3. Heated to just above the critical range and quenched in water.

4. Heated to just below the critical range and quenched in water.

5. Steel as forged and cooled in air to atmospheric temperatures.

**Fig. 110. Natural Size Photographs Showing Effect of Heat Upon Grain Size of a Rolled and Forged Steel, Carbon .75% (Metcalf's Experiment).**



1. Steel as cast and cooled naturally.

2. Heated to 927° C. and quenched in water.

**Fig. 111. Natural Size Photographs Showing Effect of Heat Upon the Grain Size of Cast Steel. Specimens, left to right, contain, .25% Carbon and .36% Carbon.**

**Practical Importance of Grain Structure:** The proper refinement of grain structure is of great practical importance. An illustration of the way in which the facts pointed out above in connection with the effects of mechanical work and heat upon the grain structure of steel may be practically applied is furnished by the welding of steel. If two steel bars are welded together by scarfing the ends slightly and hammering lightly over the weld only, as is the practice of most blacksmiths in welding iron bars, it is found that, while the weld itself is strong, the welded bar will be weak on each side of the weld. A bending test applied to such a weld generally causes the bar to break a short distance from the weld, which fact is responsible for the assertion, often made by some blacksmiths, that the weld is stronger than the bar. A careful examination of the whole bar, however, will usually show that the regions on each side of the weld are the weakest points in the entire bar. Evidently this weakness has been developed in the process of welding. The high temperature required in welding increases the grain size of the ends to be welded for a considerable distance along the bars. The subsequent hammering refines this large grain in the weld itself, but not in the areas on each side of it. By changing the manner of welding somewhat, the structure of the welded bar can be made almost uniform throughout, and these defective areas will not appear. This result can be accomplished by making the weld in the following manner, which is the usual practice in welding steel: The two ends to be welded are first heated to a moderate forging temperature for a distance of several inches back, the exact distance depending upon the size of the bar; these ends are then stove up, or upset, that is, the heated regions are shortened and thickened by hammering directly against the ends. Next, the ends are scarfed, but instead of a short, blunt scarf sometimes used, a well beveled scarf should be made. The scarfed ends are then heated to a welding temperature; a flux of common river sand or a reliable commercial welding compound is applied; the weld is made as usual; and the thickened portion of the bar is forged down to a size conforming to the remainder. This forging refines the grain which had previously been made coarse by the heating, and restores the uniform structure of the bar. If the bars have been stove up right in the beginning, the form of the weld will be such as to require the greatest amount of forging where the grain is the largest and will decrease to none where the steel was heated only to the critical range.

**Summary of Chapter I.** The conditions and properties of the iron carbon alloys and their constituents may be summed up about as follows: Above the critical ranges, the iron is in the gamma form, and the carbon is dissolved, thus imparting to the alloy, when the carbon is present to the amount of about .30%, the power of hardening; the alloys are non-magnetic and crystallize on cooling slowly, but mechanical working prevents the growth of the crystals and reduces their size. Below the critical range, the metal represents an aggregate of ferrite and cementite, $Fe_3C$, and it possesses little heardning power. Here the iron is in the alpha form, the alloys are magnetic, no crystallization takes place, and mechanical working distorts the grain structure.

# CHAPTER II.

## HEAT TREATING THEORY AND PRACTICE.

**Introduction:** While considerable time has now been spent in a discussion of subjects that may appear to be purely theoretical in nature and of little practical value, yet this course is justified, because the principles explained form the basis of all heat treating processes, and a clear understanding of them is therefore essential. The practical application of these principles will now be considered under the following headings, corresponding to the three chief processes of heat treatment as explained in the beginning.

### SECTION I.

### ANNEALING.

**The Annealing Operation** consists in (1) heating the steel to some predetermined temperature, (2) keeping the temperature constant at the predetermined point for a given length of time, and (3) cooling the steel according to some predetermined course to atmospheric temperature. To accomplish the desired result in the given steel to be treated requires that all three of these steps in the annealing operation be very carefully planned and as carefully carried out, for the success of the operation depends entirely upon the proper correlation of the rate of heating, the temperature to which the steel is heated, the time it is kept at the annealing temperature and the rate of cooling.

**Purpose of Annealing:** Evidently, then, the annealing operation will be modified to suit the end sought. In general, the purpose of annealing may involve any one or all of the following aims: 1. To soften the steel in order that it may meet certain physical requirements or be more easily machined. 2. To relieve internal stresses and strains induced by forging, rolling, or drawing, or by a non-uniform contraction in cooling. 3. To remove coarseness of grain and thus secure a more desirable combination of strength, elasticity and ductility for resisting the stresses to which it is to be subjected in service. The treatment is generally applied (1) to hot forged steel objects, because their grain structure is often more or less heterogeneous and, owing to high finishing temperature, relatively coarse; (2) to cold worked steel, such as sheets and cold drawn wire, which often must be annealed in order to increase or restore its ductility; and (3) to steel castings, which usually have so coarse a grain structure as to be very deficient both in strength and ductility.

**True Annealing and "Process" or "Works" Annealing:** To accomplish the results sought as expressed above in aims (1) and (2), it is not always necessary to heat the steel to the critical range. Thus, in the "process" or "works" annealing employed in wire drawing, it is only necessary to heat the steel, which contains less than .10% carbon, to about 550° C. in order to relieve the strained condition of the ferrite and restore the ductility. The same is also true in the case of the "white annealing" of cold rolled sheets. It is to be noted, however, that this treatment does not develop the maximum softness, because the pearlite is not affected. But as this constituent is present in so small amounts, its influence is scarcely evident. This method is also sometimes applied to tool steels in order to soften them for machining. All true or full annealing, however, requires that the steel be heated to a temperature above that of its upper critical range, and it is to this true annealing the following discussion is to be confined.

**Heating for True Annealing:** The first step in the annealing operation is to heat the steel past its critical range, for in so doing the previous structure is completely obliterated and a new one, nearly amorphous, is born. As has been previously explained, this important change is due to the passage of the steel structure from the state of an aggregate of ferrite and cementite to a homogeneous solid solution. Should the steel remain below the critical range, no structural change takes place, if the case of strain relief noted above in cold worked steel be excepted. The coarsening effect upon the grain size of steel, brought about by heating above this range, has already been explained. The proper temperature, then, for true annealing is one but slightly above the critical range of the steel, and this temperature must be maintained uniformly as near the range as possible during the time the steel remains at the annealing temperature.

The following ranges of temperatures are recommended by the committee on heat treatment of the American Society for Testing Materials.

TABLE 59. Annealing Temperatures as Recommended by the American Society for Testing Materials.

| **Range of Carbon Content.** | **Range of Annealing Temperature.** |
|---|---|
| Less than 0.12 per cent. | 875 to 925 degrees C. |
| 0.12 to 0.25 per cent. | 840 to 870 degrees C. |
| 0.30 to 0.49 per cent. | 815 to 840 degrees C. |
| 0.50 to 1.00 per cent. | 790 to 815 degrees C. |

These temperatures are shown diagramatically in the accompanying figure, together with recommendations by other authorities.

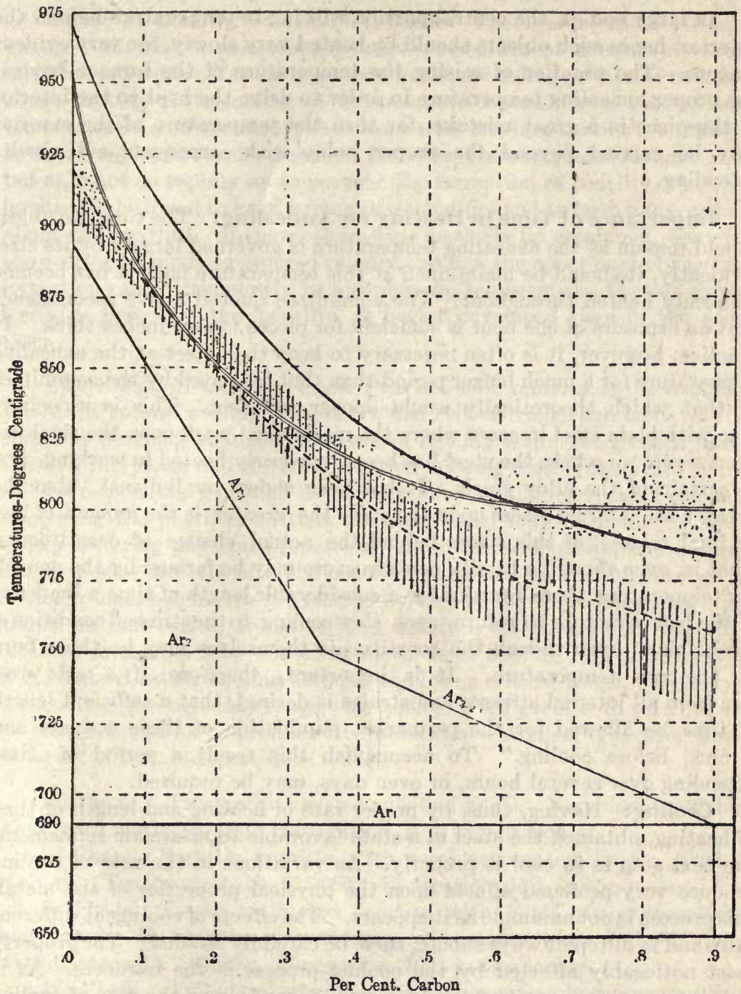


Fig. 112. Annealing (and Hardening) Ranges Showing Approximately the Temperatures Recommended by Different Authorities.

**Legend.**

═══ ........... Sauveur (for treating forgings).

⁚⁚⁚⁚ ............ American Society for Testing Materials.

‖‖‖‖ ............ Bullens (for annealing and hardening).

------ Stead's Lower Curve (for refining and hardening).

—— Stead's Upper Curve (for annealing and normalizing).

In large bodies, the central portion will lag in temperature behind the exterior, hence such objects should be heated very slowly, for very evident reasons. The practice of raising the temperature of the furnace beyond the proper annealing temperature in order to drive the heat to the interior of the piece is a great mistake, for then the temperature of the exterior may be carried beyond the proper point with consequent evil results attending.

**Importance of Time in Heating for Annealing:** The time the object should remain at the annealing temperature is governed largely by its size. Evidently, it should be maintained at this temperature until it has become uniformly heated throughout. The committee quoted above recommends that an exposure of one hour is sufficient for pieces twelve inches thick. In practice, however, it is often necessary to keep the object at the annealing temperature for a much longer period than that indicated by the committee or that which theoretically would appear sufficient. This is especially true with plain steel in cases where the mechanical work upon the steel has been severe, or where the steel has been improperly heated in working, and in certain of the alloy steels. It has been shown by Bullens[1] "that the greater the internal stress upon the steel the greater is the amount of lag, or final release, of this stress behind the actual change of constituents. That is, even though a totally new structure may be formed by the annealing temperature, there remains for a considerable length of time a tendency of the new structure to return, upon slow cooling, to the stressed condition of the original, even though the constituents themselves may be those born at the new temperature. It is important, therefore, if a soft steel free from all internal stresses and strains is desired, that a sufficient length of time be allowed for the permanent elimination of these stresses and strains, before cooling." To accomplish this result a period of time extending over several hours, or even days, may be required.

**Cooling:** Having, thus, by proper rate of heating and length of time of heating, obtained the steel in a state favorable to maximum refinement, the next step is to cool it properly. As variations in the rate of cooling produce very profound effects upon the physical properties of the metal, this process is not as simple as it appears. The effects of cooling at different rates and in different ways should, then, be carefully studied. The property most noticeably affected by the cooling process is the hardness. As is well known, this property in a given steel depends upon the rate of cooling from above the critical range. Thus, by the most rapid cooling, it is possible to develop the maximum hardness, or by the slowest cooling the greatest softness, and by varying the rate of cooling any degree of hardness between these extremes may be obtained. In searching for a reason for these changes in properties, it is not surprising that investigators have found that important structural changes accompany all cooling, and that these changes vary, in the effects they produce, with the speed of the cooling.

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[1] Steel and Its Heat Treatment, Second Edition, pp. 133 to 148.

**Effect of Cooling on the Net Work:** The first of these structural changes that may be mentioned is the effect of different rates of slow cooling upon the net work of ferrite described in the preceding section of this book. Thus, in very slow cooling of hypo-eutectoid steels from the annealing temperature a coalescence of the excess ferrite into large grains intermingling with coarse pearlite grains results. If the steel be now cooled rather rapidly, but still not so rapidly as to prevent the formation of pearlite, the excess ferrite will be found to be of a fine grain structure and to form a fine network about the pearlite. If, now, these two methods be combined, that is, if the cooling be made to proceed rapidly through the upper part of the transformation range then slowly to atmospheric temperature, the net work of ferrite is fine, but the pearlite is better developed than in the second case.

**The Effect of Cooling Upon Pearlite** now remains to be explained. While the rate of cooling from below the critical range can have no effect upon the pearlite, changing the rate of cooling while the steel is passing through this range and the solid solution is being transformed into pearlite will correspondingly change the arrangement of the ferrite and cementite composing the pearlite, so that the same steel may be made to exhibit widely differing physical properties. As mentioned before, the austenite does not pass directly into the pearlitic condition on cooling through the critical range, but makes the change by way of the three transition stages known as martensite, troostite, and sorbite. Of these, only sorbite is retained in the steel by annealing methods of cooling. In small sections it is retained by air cooling through the lower critical range. By varying the cooling through this range this change from sorbite to pearlite may be controlled so as to produce five phases, or varieties, of pearlite having different physical properties as follows:—

1st Phase. True Sorbite with emulsified $Fe_3C$. Very dark on etching. Tensile strength, 150,000. Elongation, 10% in two inches.

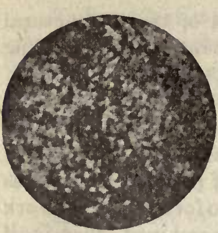
2d Phase. Sorbitic pearlite with semi segregated $Fe_3C$. Dark on etching. Tensile strength, 125,000. Elongation, 15% in two inches.

3d Phase. Finely laminated pearlite with $Fe_3C$ almost completely segregated. Exhibits a play of gorgeous colours when lightly etched. Tensile strength, 100,000. Elongation, 10% in two inches.

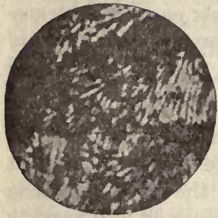
4th Phase. Fully laminated pearlite with completely segregated $Fe_3C$. Tensile strength, 85,000. Elongation, 8% in two inches.

5th Phase. Massive pearlite, consisting of coagulated $Fe_3C$ and ferrite. Tensile strength, 75,000. Elongation, 5% in two inches.

The second phase is the one sought in the process of patenting in wire drawing. So, it is seen that, having obtained the greatest possible refinement as to grain size and released all the internal stresses and strains in the metal by heating to the proper temperature, it still remains to adjust the physical properties by regulating the rate and the manner of cooling.

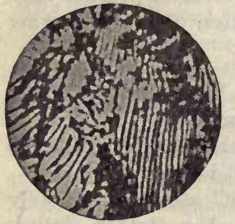


1. Sorbite. Cementite is emulsified. Obtained in steels of low carbon content by cooling rapidly to atmospheric temperatures.



2. Sorbitic Pearlite. Cementite is partly segregated. Obtained by cooling rapidly through the upper range only.

3. Pearlite. Cementite is largely segregated. Obtained by moderately slow cooling.



4. Laminated Pearlite. Cementite is completely segregated. Obtained by slow cooling.

5. Massive Pearlite. Cementite and ferrite are coagulated. Obtained by very slow cooling to atmospheric temperatures.

Fig. 113. Microphotographs Showing Progressive Segregation of Cementite in the Development of Pearlite from Sorbite. (White areas represent ferrite, black areas, cementite.)

**Other Factors** to consider in cooling are the carbon content and the size of the object. In general, the lower the carbon the more rapid may be the rate of cooling without affecting to any marked degree the softness and ductility of the metal. For example, steels containing less than .15% carbon may even be quenched in water, and those containing less than .30% carbon, in oil, without markedly decreasing their ductility. In order to secure the same rate of cooling in objects of different size, it is obviously necessary to regulate the external conditions in accordance with the dimensions of the objects treated. Thus, the cooling in air of a very fine wire may be equivalent to quenching in oil or water an axle of the same carbon content.

**Methods of Cooling:** In general, there are three methods of cooling, namely, furnace cooling, insulated cooling and air cooling. Of these, furnace cooling may be made the slowest, especially if the furnace is large and can be effectually sealed from air draughts. This method gives maximum softness and ductility. In other words, the tensile strength and elastic limit will be at their lowest, while the elongation and reduction in area will be at or near their maxima. Steel subjected to such treatment will resist severe distortions. In what has been termed above as insulated cooling, the object is removed from the furnace and covered with a blanket of lime, sand, ashes, etc., or it may be placed in a brick or concrete lined underground pit with a tight fitting cover, which in turn may be covered with ashes or loose earth. In cases where large amounts of steel are placed in a single pit, this method may be slower even than furnace cooling. In air cooling, the object is simply removed from the furnace and allowed to cool in the air. Evidently, the rate of cooling by this method will be affected by the size of the piece and the season of the year. In addition the physical properties imparted will depend somewhat upon the carbon content. Hence, the American Society for Testing Materials recommends that "Thick objects with less than 0.50% of carbon may be cooled completely in air, of course, protected from rain or snow. Objects with 0.50% of carbon or more, and thin objects with from 0.30% to 0.50% of carbon, may be cooled in air if their cooling is somewhat retarded, as for instance, by massing them together, as happens in the case of rails." The effect of the more rapid cooling in air is to increase the strength and elastic limit, but lower the reduction and elongation. In order to hasten the cooling, articles of low carbon content are sometimes immersed in water after they have become black in color. This method is then called water annealing.

**Combination Methods of Cooling:** Besides the three general methods of cooling described above, various combination methods have been employed with great success. Three of these, as directed by Bullens, are as follows:

1. "Heat to slightly over $Ac_3$, air cool to just over $Ar_1$, return to a furnace which is held at that temperature (about 725 °C.), heat until

uniform, and then cool slowly. The latter heating should not be any longer than is possible. This method will tend to prevent the formation of large amounts of free ferrite, but will affect the pearlite, as there will be slow cooling through the $Ar_1$ range. 2. Heat to slightly over the $Ac_3$ range, air cool to just under the $Ar_1$ range, return to a furnace and heat to 730° C. and slow cool. This method will effect a greater toughening, if the temperature has not been prolonged too greatly at the second heating. 3. Heat to slightly above $Ac_3$ air cool to below $Ar_1$, return to a furnace heated at a temperature slightly below $Ar_1$ (660° to 670° C.), hold at this temperature until uniformly heated, and slow cool (in lime or air). By permitting the steel to air cool to a temperature below the lowest transformation, advantage is taken of any 'hardening effect' or retardation in the transformation of austenite into a conglomerate of pearlite and ferrite. This effect will increase with the percentage of carbon and the smaller the size of the piece. The reheating to a temperature below the lower critical range, if not prolonged, will neither change the grain size nor allow of the coalescing of the excess ferrite or of the individual constituents of the pearlite, but will form a mass of irresolvable and intermixed pearlite and ferrite known as 'sorbite.' At the same time, however, it will give the maximum combination of large ductility, good strength and excellent machining properties. This method is of particular value in the annealing of tool steels, in which it has given most excellent results."

**Double Annealing** consists in heating the steel to a temperature considerably over the $Ac_3$ point, cooling rapidly to some point below the lower transformation range, then immediately reheating to a point slightly under or over $Ac_1$, and finally cooling slowly. This method is employed to relieve the most severe strains, which do not respond readily to ordinary annealing. The high first annealing temperature effaces the strains, while the rapid cooling prevents their returning. As this cooling tends to harden the metal, the second process is necessary to soften it and refine the grain, coarsened by the first operation, as much as possible. The second heating, of course, may be to a temperature just above $Ac_3$, when even better results should be obtained, provided softness is the chief end sought.

**Box Annealing:** In many instances, especially with tool steel, it is important that the surface be protected from oxidation, or decarbonization. Some furnaces are now designed so that the object being heated may be surrounded by a reducing atmosphere, and so oxidation is prevented. Where such furnaces are not provided, it is the practice to pack the object in a metal box, called an annealing box, with some refractory material, such as sand, ground mica, etc., in the case of low carbon steel, or with some reducing substances, as for example a mixture made up of a little charcoal with ashes, burned bone, etc., in the case of higher carbon steels, like the tool steels, for example.

**Annealing Hyper-Eutectoid Steels:** In annealing hyper-eutectoid steels, as in the case of hypo-eutectoid steels, one or more of these objects are aimed at; (1) release of strains, (2) softening in preparation for machining, and (3) change of structure. The first object may be accomplished by a simple reheating at temperatures considerably below those of the critical range. The second and third objects are more difficult to attain, for the treatment administered will be governed by the amount of the excess cementite and the form in which it exists. Thus, if the cementite is partly diffused, that is, does not exist as a net work or as spines and needles, and the grain size is small, conditions that may generally be expected in high carbon tool steels, the forging hardness may be largely removed by annealing at a temperature slightly under Ac. or between 600°C and 700°C. The steel should not be kept at this temperature any longer than is necessary to heat it thoroughly and uniformly throughout, as prolonged heating may cause the excess cementite to coagulate. Such treatment will release the strains and soften the steel sufficiently for machining. On the other hand, if the grain is coarse, making a complete change in structure desirable, it will be necessary to heat to a temperature in excess of the $Ac_{1-2-3}$ point, or above 725°C. For steels with a carbon content approximating 0.90%, such heating will bring about a complete change of structure and give the finest grain-size obtainable through annealing. For steels with a carbon content considerably in excess of the eutectoid ratio the annealing may be done at similar temperatures, provided the excess cementite is more or less in solution. If the cementite is not in solution and a maximum refinement is desired, the steel may be oil quenched from a temperature somewhat over the $Ac_{1-2-3}$ range, and subsequently annealed at a temperature just below that range, or it may be normalized and annealed.

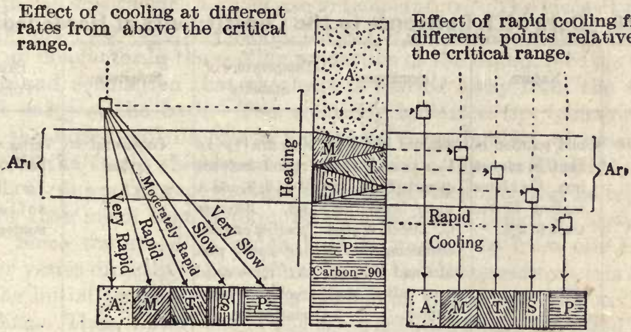
**Normalizing and Spheroidizing:** These are two processes applied to hyper-eutectoid steels in particular, though normalizing is often applied to hypo-eutectoid steels also. If the free cementite in the former steel exists as a network or as spines, which would make the steel difficult to machine, annealing at the usual temperatures ($Ac_{1-2-3}$) will not affect this cementite, but will simply refine the ground mass. In order to eliminate this free cementite, it is necessary first to normalize, that is, quench the steel from a temperature above that of the $Ac_{cm}$ range. Usually, air cooling from a temperature of, say, 960° C., or 1000° C., will not permit the cementite to recoagulate. Lower carbon steels are heated to about the same temperature, but quenching is never required. Hence, in practice, normalizing usually consists in heating the steel to the temperatures mentioned and cooling simply in air. The annealing may then be carried out at a temperature of 745° C. or over, to secure the refining of the grain size and complete softening of the steel. The heating for annealing should be just as short as possible in order to prevent the separation of the excess cementite again. The method given above may be modified for hyper-eutectoid steel by annealing at a temperature slightly under the lower critical range instead of over it. This method, however, is subject to the objection that the steel will not be refined, but will possess a large grain size on account of the high normalizing temperature. But on the other hand, the lower annealing temperature entirely prevents the formation of free cementite either as spines or as a network, and the excess cementite is thrown out, under these conditions, as little nodules or "spheroids," if the reheating temperature has been near the end of the lower critical range. Spheroidal cementite may also be obtained by cooling very slowly through the end of the $Ar_1$ transformation range. Spheroidizing is a great help in the machining of high-carbon steels.

## SECTION II.

### HARDENING.

**The Hardening Operation:** The operation of hardening as applied to steels containing a sufficient amount of carbon consists fundamentally of the two operations of heating to a suitable temperature and suddenly, or rapidly, cooling. The heating may be accomplished in a number of ways, varying from costly and specially designed furnaces and baths heated with gas or electricity to the simple forge fire of the blacksmith; but the cooling is always brought about by plunging the steel into a suitable liquid, a process called quenching. Let the means be what they will, in properly hardened steel the original structure, as it existed before the hardening process, such as coarse grain size, network, etc., has entirely disappeared and has been replaced by a new structure, totally different from that of the unhardened steel. To understand thoroughly the hardening process a close study of the two operations by which these changes are brought about should be made.

**Heating for Hardening:** The structural changes that accompany the heating of steel through its critical ranges have already been briefly described. Graphically, these changes are represented in the central part of the accompanying diagram (Fig. 114), depicting the heating and cooling of a steel with a carbon content of about .90%. From this evidence it will be seen that the function of the heating is to bring about the proper change in structure so as to obtain (1) the formation of the hard constituents of the steel and (2) the smallest grain size, or highest refinement of the crystalline structure. From what has already been said, these structural changes can be obtained only by heating the steel above its critical range. Any attempt at hardening it at a temperature inferior to this range results in only a very slight, if any, increase of the hardness. Again, the metal should not be heated much above the top range, for then its grain structure is coarsened, as has been previously explained, also, and no additional hardness is imparted. Clearly, the best temperature to which the steel should be heated is one just above the critical range. The proper temperature to which plain carbon steels should be heated is the same as for the true annealing of the same steels. What has been said about the rate of heating and the influence of size of section in annealing also applies to heating for hardening. If any difference, additional emphasis should be placed on the uniformity of heating. The rule for heating may be put thus: Heat slowly, uniformly, and thoroughly, to the lowest temperature, and no higher, that will give the desired results. To meet these requirements, the final heating of steel for hardening is often, and commendably so, conducted in baths of molten lead or of the chlorides of sodium, calcium, potassium or barium.



Legend: P=Pearlite, A=Austenite, M=Martensite, T=Troostite, S=Sorbite.

FIG. 114. Diagram Depicting the Different Methods by Which the Five Different Structural Constituents of Eutectoid Steel May Be Obtained. (After Sauveur.)

**Cooling for Hardening:** Thus it is seen that heating for both annealing and hardening are very similar, and that the changes wrought in the microscopic constituents of the steel are the same in both cases. The main difference in the two operations is found in the rate of cooling through the critical ranges, at least. For hardening, this cooling must be very rapid, whereas in annealing it was characterized as slow. The transitions attending the transformation of austenite to pearlite on slowly cooling through the critical ranges have been described. It will be recalled that this transformation is not instantaneous, nor is it direct, but takes place by stages through transitional structures called martensite, troostite, and sorbite, the order on slow cooling being from austenite, to martensite to troostite, to sorbite, to pearlite. On heating, this order is reversed. It now may be explained that the secret of the hardening process is revealed by the fact that rapid cooling through the critical range may prevent this transformation in part or in whole, depending on the rate of the cooling. Thus, by the most rapid cooling, the steel at atmospheric temperatures is found to consist almost entirely of austenite, while a little slower cooling produces martensite; still slower, troostite; slow, sorbite; and very slow, pearlite. Incidentally, it may be remarked that the constituents found in the steel after treating also depends on the temperature within the critical range at which the rapid cooling begins and the carbon content of the steel, because these constituents are formed at different temperatures and the presence of carbon retards the transformation. Since the properties of the cooled steel are imparted to it by the constituent which predominates, a study of the characteristics of these transitional constituents will, therefore, be of value. For the sake of brevity and convenience, this knowledge is here put down in tabulated form.

**Table 60. Data with Reference to the Constituents of Hardened Steel.**

| Name | Nature | Occurrence | Temperature of Stability | Structure | Physical Properties |
|---|---|---|---|---|---|
| Austenite | Solid solution of $Fe_3C$ in gamma iron, Carbon content from trace to 2%. | Obtained in 1.50% C. steels when quenched in ice water from 1050° C. Occurs in steel containing 12% Mn. and 25% Ni. even after slow cooling. | Normally in region between A-1, 2, 3, and A cm. Becomes pearlite on cooling slowly past $A_1$: more rapid cooling forms martensite. | Polyhedral grains | Varies with carbon content. Very hard but softer than martensite. |
| Martensite | Solution of $Fe_3C$ in beta iron, Carbon content from trace to 1%. | Obtained easily by quenching small bodies of hypereutectoid steel, in cold water. More difficult to obtain in low carbon steels. Chief constituent of hardened carbon tool steels. | Normally at slightly lower temperature than austenite. Changes into troostite. | Fibers or flat plates lying parallel to three sides of a triangle. | Varies with carbon content. Hardest constituent of steel of eutectoid composition. A little less hard than cementite. |
| Troostite | Mixture of $Fe_3C$ in beta iron crystallized $Fe_3C$ and crystallized alpha iron. | Obtained by reheating martensitic steel to 400° C. or on cooling relatively slowly through critical range. Found in center of large objects quenched in water. | Normally at lower temperature than martensite. | Slightly granular with sorbite and martensite intermingled and with ferrite and cementite in hypo-and hyper-eutectoid steels. | Intermediate between martensite and sorbite. Not so hard as martensite but stronger and more ductile. |

Neither pearlite nor sorbite are, strictly speaking, constituents of hardened steel, but the latter, on account of its position in the transformation scale, forms the connecting link between hardened and annealed steel, hence may occur in both. The nature and properties of sorbite have already been given, and it should here be recalled that it is the toughest constituent of steel. The transition from austenite to pearlite is admirably illustrated in the preceding diagram of figure 114.

**Cooling or Quenching Media:** Since the rate of cooling controls the hardening process, the selection of the proper quenching medium is a matter of much importance. The withdrawal of heat, the only function of a quenching liquid, from the metal immersed in it depends upon its quantity, its specific heat, its conductivity, its viscosity, its volatility, its latent heat of vaporization, and, to some extent, its initial temperature. The quantity and specific heat of the liquid control the quantity of heat the bath can absorb with a given rise in temperature. The viscosity affects the flowing properties of the liquid, hence the convection of heat by it, and therefore is a factor in the cooling properties of the liquid, for it is by convection and conduction that the heat is carried away from the steel to distant parts of the bath. The volatility indicates the temperature at which the liquid will become a vapor and form bubbles of gas on the surface of the steel, which tend to retard the cooling. Evidently, if the latent heat, or heat of vaporization, is high the volatility may be relatively low, for then much heat is required to change the liquid to the gaseous state. Since the speed at which heat is transferred from one body to another varies directly as the difference in their temperatures, it is evident that the initial temperature of the quenching liquid must affect the rate of cooling. Thus, water, one of the most efficient media for rapid cooling in use commercially, has high specific and latent heats, and its viscosity is very low, properties favoring its cooling power, while its volatility and conductivity are both low, properties against it as a quenching agent. Then just next to water in cooling power comes mercury, which has a lower specific heat, a lower heat of vaporization and higher viscosity than water; but it is less volatile and is a very much better conductor of heat. Thus, while the one owes its cooling power to one set of properties, the other is almost as efficient because of an altogether different set. A solution of salt in water, brine, is a little more rapid than water, while water sprayed under pressure upon the metal is a quicker cooling agent than either water or brine. After water, the chief quenching media in use commercially are the oils, all of which are much slower than water. An interesting experiment reported by Messrs. Matthews and Stagg[1] is intended to show the quenching properties of the various liquids that are employed in commercial hardening. In this experiment a suitable test piece of steel was carefully heated to 1200° F. and quenched in 25 gallons of the medium under examination, and the time required to cool the steel to 700° F. noted with a stop watch, as well as the rise in temperature of the medium. In each medium this operation was repeated successively until the medium had either reached its boiling point or a temperature of 250° F. The results of this experiment were then plotted somewhat as shown in the accompanying diagram.

**Combination Methods of Quenching:** Besides the straight water or oil quenching and water spraying, many special quenching methods and media have been tried. Many of the latter are fakes, but the three follow-

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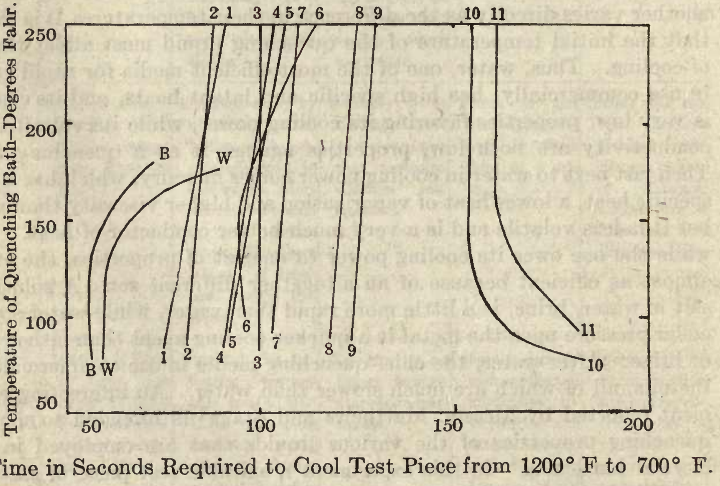
[1] See "Factors in Hardening Tool Steel" by Matthews and Stagg. American Society of Mechanical Engineers, 1915.

ing special methods of quenching have proved of great value. Thus, when high tensile strength is required, yet on account of the size of the piece or the chemical composition—manganese too high, for example—water quenching is unwise, the bath of water may be covered with oil to an equal depth, so that the piece upon being lowered into the bath is partly cooled in this oil, which then forms a film over the surface that retards the cooling by the water somewhat. This method is sometimes applied to large forgings, such as axles. For small tools a thin film of oil on the water suffices. Another method, used by some tool hardeners, consists of first plunging the tool into water to remove a part of the heat, then into oil till the cooling is complete. Information as to what is aimed at by this method is not at hand, but it is evident that the method is not so severe as straight water cooling. Where great toughness with little hardness is required, the article may be plunged into and forcibly submerged in molten lead, as this manner of quenching produces sorbite in steels under the eutectoid in composition.



**Legend:**

B—Brine.
W—City Water.
1—New Fish Oil.
2—No. 2 Lard Oil.
3—Lard Oil in Use Two Years.
4—Boiled Linseed Oil.
5—Raw Linseed Oil.
6—New Bleached Fish Oil.
7—New Cotton Seed Oil.
8—Tempering Oil $\begin{cases}\text{60\% Cotton Seed.}\\ \text{40\% Mineral.}\end{cases}$
9—Mineral Tempering Oil.
10—Dark Mineral Tempering Oil.
11—Very Viscous Tempering Oil.

NOTE. 10 and 11 are similar to cylinder oils.

FIG. 115. Diagram Illustrating Approximately the Quenching Power of Various Liquids. (Data by Messrs. Matthews and Stagg).

**Manner of Quenching:** Much skill is required on the part of the operator in the quenching of steel to prevent cracking and warping. Both defects are due to unequal or non-uniform cooling of the different parts of the piece, and are more liable to occur, for obvious reasons, in bodies of large size or of irregular section. It is to overcome this danger that large axles are hollow bored before treatment. All large sections, if solid, must be reheated immediately after hardening in order to relieve the internal stresses and strains, else incipient fractures will result. Warping will always occur in small sections, if the quenching is not uniform. As warping more often results when the piece is plunged into the quenching bath at an angle, it is always best to quench vertically, in the direction of greatest length, whenever such procedure is possible.

**Progressive Hardening:** Progressive, or differential hardening, is accomplished by quenching only a part of the object. In such a method the heat is slowly withdrawn from the part furthest from the quenching liquid, but more and more rapidly as the part quenched is approached, so that the steel becomes progressively softer and tougher from the hardened part. By withdrawal of the piece before cooling is complete, the heat in the unquenched part may be made to temper the hardened portion. In this method care is needed to avoid hardening, or quenching, rings, which form if the piece is held in the quenching bath at a uniform depth. To avoid them the piece should be raised and lowered during the quenching. This method is employed in treating such tools as anvils, die blocks, edged tools, pointed tools, etc.

**Hardening Eutectoid Steels (C. .80 to 1.00%):** Steel of eutectoid composition possesses the maximum hardening power, that is, the difference in hardness between the quenched and unquenched article of eutectoid composition is greater than that in any other grade of the plain steels. So, this statement does not mean that quenched eutecoid steels are the hardest steels, for hyper-eutectoid steels may show much greater hardness both before and after hardening than eutectoid steels, due to the presence of free cementite or to more highly carbonized martensite, but their gain in hardness on quenching is less. It is clear that eutectoid steels should be hardened from a temperature just above $Ac_1$, that is, 750° to 800° C., for at this temperature the carbon, being in solution and thoroughly diffused, possesses its full hardening power, and the grain structure is at its finest. For the maximum hardness, the metal should then be quenched as suddenly as possible in water, by which treatment the austenite is changed into a fine grained martensitic or troostito-martensitic structure, depending upon the size of the article and other incidental conditions. In order to avoid the danger of cracking, many operators will prefer to quench in oil, when troostite may be the predominating constituent if the piece is of large size.

**Hardening Hyper-Eutectoid Steels (1.00 to 1.50%):** Steels that contain more than .90% carbon are also hardened by heating just above

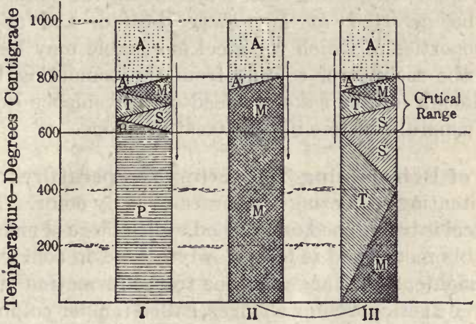
$Ac_{3-2-1}$, or in other words, at the same temperature as steel of eutectoid composition, the reason for which is readily seen by a little reflection. To cite an example, suppose the steel to be hardened has a carbon content of 1.30%. Such a steel in its natural state is composed approximately of 93% pearlite and 7% free cementite. To cause both pearlite and free cementite to change to austenite would require the steel to be heated above $Ac_{cm}$, about 950°, but such a high temperature would result in a decided and undesirable coarsening of the grain size, which is avoided by heating only above $Ac_{3-2-1}$. Besides, quenching from this lower temperature would give a harder steel than would be obtained in the first instance. For, supposing the quenching is such as to produce martensite, in the first case, the hardened steel would be composed of martensite only, whereas in the second instance it would be made up of 93% martensite and 7% free cementite, which being harder than martensite, would impart additional hardness to the quenched steel. When for any cause it is desirable to avoid the presence of any free cementite, the metal may be heated above $Ac_{cm}$ and cooled in molten lead, then reheated to slightly above $Ac_1$, and quenched as usual. The quenching in lead prevents the re-formation of free cementite and is not severe enough to cause cracking or warping, while the reheating to $Ac_1$ accomplishes the grain refinement so much to be desired in these steels.

**Hardening Hypo-Eutectoid Steels (C .30 to .80%):** Steel containing less than .30% carbon cannot be materially hardened by any of the ordinary commercial methods of quenching on account of the separation of ferrite from the solution, which takes place to some extent even with the most rapid methods of cooling. For hardening hypo-eutectoid steels with a higher carbon content, two methods may be employed. First, the metal may be heated slightly above $Ac_1$ and quenched, when only the pearlite of the steel will be affected, it being changed into martensite or troostite according to the rate of cooling, and the free ferrite will undergo no refinement at all. Evidently, the second and better plan is to heat the metal above $Ac_{3-2}$, when its entire bulk changes into hardenable austenite, which on quenching rapidly may be converted into martensite or at least troostito-martensite. While this martensite, because of its lower carbon content, is not so hard as the martensite formed from the pearlite in the first method, the steel as a whole will be harder and certainly more uniform and of a much finer grain structure, because the original network of coarse ferrite will have been absorbed and refined.

## SECTION III.

### THE TEMPERING OF HARDENED STEEL.

**The Tempering Process:** Tempering, sometimes spoken of as drawing-back or simply as drawing, consists in reheating the metal after hardening to some temperature below the critical ranges, and may have for its primary object (1) the regulation of the hardness and brittleness of the steel, (2) the toughening of it, or (3) the release of the hardening strains. In tempering, the release of the internal stresses and strains set up by the hardening process is always aimed at, whatever may be the other results sought, for the metal is incapable of giving its best service as long as these or similar strains exist. This result is usually accomplished by the heating in the tempering process, for even heating to the temperature of boiling water will relieve these strains to some extent. This fact is often taken advantage of to relieve strains when it is not desirable to soften the steel to the extent that higher heating would involve.



Legend A=Austenite, M=Martensite, T=Troostite, S=Sorbite, P=Pearlite.

I. Slowly cooled. (Annealed) II. Quickly cooled. (Hardened) III. Reheating Hardened Steel (Tempering).

Fig. 116. Diagram Depicting the Constituents Formed on Slowly Cooling and Quickly Cooling Steel and on Reheating Hardened Steel. (After Sauveur.)

**Nature and Theory of Tempering:** According to the retention theories of hardening, which are among the most plausible ones advanced to account for the hardening and tempering of steel, hardened steel is in a state of unstable equilibrium, or strain, and, therefore, is ever tending to assume a more stable form or condition, which tendency implies a return of the iron to the alpha form and of the carbon to the condition of cement carbon, or segregated cementite. In hardened steel, this transition is prevented by the rigidity of the metal, which is reduced by reheating. The extent of this reduction of the rigidity being in proportion to the extent of the reheating, the higher the temperature the greater will be the extent of the transformation. Thus, supposing the hardening operation has arrested the transition of austenite at the martensitic stage, this martensite will begin, at a temperature some 150° C. above that of the atmosphere to change into troostite, and the transformation will continue with the rising temperature until the martensite has passed entirely into troostite, which result is no sooner accomplished than the troostite in turn begins to change into sorbite. When the temperature has been raised to a point near that of the lower critical range, sorbite, to the exclusion of other constituents, will predominate the structure. Any higher heating, then, carries the transformation into the critical ranges, where the order of transition is reversed, sorbite passing into troostite and then to martensite, which, as the temperature, on rising, emerges from the range, becomes austenite. The preceding diagram, Fig. 116, copied after Sauveur, will aid in understanding these changes when they take place under different conditions. Evidently then, all heating for tempering is conducted below the critical range. By properly adjusting the temperature the transition described above may be arrested at any stage desired, and any combination of physical properties of which the steel is capable may be obtained. It is clear that the manner of cooling from the tempering temperature is immaterial, though for the sake of speed or convenience quenching or air cooling is the general practice in heat treating shops.

**Methods of Determining Tempering Temperatures:** The original method of estimating tempering temperatures is by color. Thus, if a piece of hardened steel is brightened or polished with a piece of emery, sand stone, or other suitable means and is then slowly heated in contact with air, the color of the brightened surface will, due to the formation of a surface film of oxide, undergo a series of color changes, called temper colors, ranging from faint yellow to blue, which will be characteristic of the different temperatures reached by continued application of heat. That these colors are indicative of a known temperature or at least a definite condition of the hardened steel is generally accepted; but it is evident that the method is subject to the objection that differences in distinguishing different colors, or shades of color, is bound to occur among different operators. Distinction of these colors is also affected by different light conditions. The same temper will not give the same color in a dimly lighted room as in a well lighted one. While these shades are hard to describe, the color corresponding to the same temperature often being differently described by different individuals, the following table will give some idea of the colors corresponding to the different temperature changes.

**Table 61. Tempering Colors and Temperatures Corresponding to Them.**

| | | | |
|---|---|---|---|
| Pale yellow | 220 deg. C. | Pale blue | 297 deg. C. |
| Straw | 230 " " | Dark blue | 316 " " |
| Golden yellow | 243 " " | Red in the dark | 400 " " |
| Brown | 255 " " | Red—indirect sunlight | 525 " " |
| Brown dappled with purple | 265 " " | Red in sunlight | 580 " " |
| Purple | 277 " " | Dark Red | 700 " " |
| Bright blue | 288 " " | | |

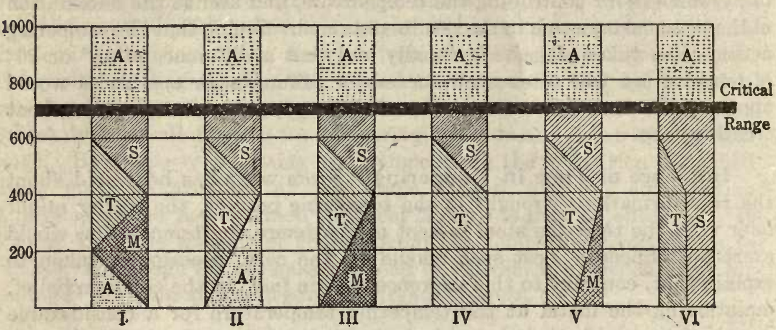
That the color method has its limitations is now well established, and so other methods are being developed on a more scientific basis. These methods involve the use of sand baths or liquid baths, such as oil, molten lead, or alloys, fused salts, etc., for heating the steel and the use of pyrometers for controlling the temperature, and aim at the elimination of the personal equation in the results obtained. Seeing that the tempering action often takes place very rapidly and that a difference of 15° or 20° of temperature will often spell success or failure, such appliances would appear to be a very necessary part of the equipment of the modern heat treating shop.

**Influence of Time in Tempering:** From what has been said about the transformations wrought in the tempering process, the reader might infer that the time the steel is kept at the tempering temperature would exert no influence. Lest such should be the case, occasion is taken to explain that, contrary to this inference and, in fact, to the common belief, maintaining the metal at the tempering temperature for a considerable length of time will result in producing additional tempering. This fact is evidenced by the change of the tempering colors at constant temperature. Thus, it has been ascertained that the temper color, instead of remaining the same at a given temperature, advances in the tempering color scale as it would if the temperature were being raised, which phenomenon would appear to indicate that the temper colors are indicative of the tempering condition of the steel rather than of the temperature. For example, by heating a steel to 277°, where its temper color is purple, and keeping it there till its color is bright blue, a temper corresponding to the temperature 288° is obtained. According to some investigators, however, the temper will not follow the color to the end. They maintain that each temperature has a maximum temper effect, which is reached quicker and quicker as the temper temperature is raised.

**Physical Properties Affected by Tempering:** It is to be remembered that besides the hardness, the other physical properties of the steel are likewise affected by tempering. Thus, as the hardness and brittleness are decreased, the tensile strength and elastic limit will follow the hardness closely and be correspondingly decreased, while the ductility, i. e., elongation and reduction in area, will be increased, though not following in the wake of the hardness with the same regularity as the tensile strength and elastic limit. (See table 62, page 561)

**Tempering the Steels of Different Structural Composition:** Seeing that the hardening process has developed a certain structure in the steel, it may be well, in turning to the practical application of the principles and theories of tempering the hardened steels, to consider this phase of the subject from the standpoint of their structural composition. The accompanying diagram is intended to depict the tempering of all the hardened steels.

**Tempering Austenitic Steels:** As has already been shown, austenite does not occur in steels hardened by any of the commercial methods. Hence, a lengthy discussion of the tempering of austenitic steel is out of place in this study. It may be pointed out, however, that instead of passing into martensite then to troostite, as shown at I in the diagram, austenite may on tempering, pass directly into troostite as indicated at II. The diagram shows that austenite begins to be transformed at a very low temperature, being completely converted into martensite at 200° C. or into troostite at 400° C.



Legend: A=Austenite, M=Martensite, T=Troostite, S=Sorbite.

FIG. 117. Diagram Depicting the Tempering of Hardened Steel. (By Sauveur.)

**Tempering Martensitic Steels:** If steel of high carbon content has been fully hardened by quenching rapidly, as in water, it consists mainly of martensite, if other conditions were at all favorable. This constituent is more stable than austenite, and on tempering will begin to change to troostite below 200° C. and this transformation is complete at about 400° C., as shown at III on the diagram. Recalling the properties of troostite, it will be seen, then, that tempering between these two points results in a material decrease of the hardness and brittleness accompanied by a decrease also of tensile strength and elastic limit, while some increase in the ductility will be noted. It is to be observed that just as martensite predominates in the structure of hardened steels, and pearlite, of annealed steels, so the presence of troostite indicates tempering, either as a separate reheating process or by regulating the cooling in the hardening operation, as for example, in oil quenching, which is often called oil tempering on this account.

**Tempering Troostitic Steels:** Commercially hardened steels, especially those quenched in oil, will sometimes show large proportions of troostite. From the diagram it will be seen that to temper this steel will require a temperature of at least 400°, the temperature at which it begins to be changed into sorbite. At 600° C. the transformation of troostitic sorbite is complete. Tempering here results in a marked toughening of the steel with loss of much of the hardness. Hence, as explained below, tempering between these temperatures is called toughening by many of the heat treating experts. However, troostite steels produced by quenching often contain considerable martensite. When such is the case the steel may be softened by reheating to about 400° C., when the martensite will be destroyed.

**Sorbite:** As this constituent occurs at the top of the tempering range, sorbitic steels cannot be tempered. Furthermore, as these steels are not produced by the regular hardening methods, they are not properly considered in connection with tempering.

## SECTION IV.

### THE TOUGHENING OF STEEL

**Toughening** is the term applied to certain treatments given usually to steels of medium carbon content (C. .35% to .60%) in which strength and toughness, rather than hardness and toughness, are the properties sought. It is a treatment applied to railroad axles, piston rods, and other articles subjected to fatigue, impact and dynamic stresses in service. As practiced by the Carnegie Company, toughening consists in heating the steel to temperatures varying from 775°C to 850°C, depending upon the chemical composition, quenching in oil or water, and then drawing back to such high temperatures, 450° to 650°C, that little, if any, of the hardness due to the quenching remains.

**Benefits of Toughening:** Compared with annealing, toughening has an advantage in that both the strength and ductility of the steel may be increased to the limits of which the steel is capable. In annealing, strength is sacrificed for ductility, but in toughening, the relation of these properties may be nicely controlled. The effect of the quenching operation is to give the greatest refinement of the grain and to develop the maximum strength of which the steel is capable. The effect of the draw back is to relieve all strains due to the quenching, and, without coarsening the grain, develop the ductility, which will gradually increase, with a partial loss in strength, of course, as the temperature of the draw back is raised. Between 500° and 600°C the draw back produces a steel composed entirely of sorbite, which is the structure that gives the highest combination of strength and ductility. The pearlite produced by the usual annealing methods is both less strong and less ductile than sorbite. One feature of the toughening operation is to increase the ratio of the elastic limit to the ultimate, or tensile, strength. Thus, while in natural and annealed steels of toughening grade this ratio is approximately 3:6, in properly toughened steel it is about 4:6. In view of the fact that it is the elastic limit that actually measures the working strength of the steel, this effect of toughening is worthy of careful consideration.

**Quenching for Toughening:** As indicated above, either oil or water is used as a quenching medium for toughening. Both media have their

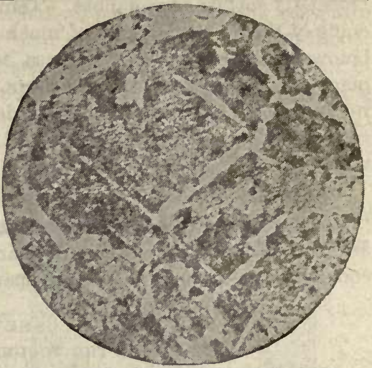
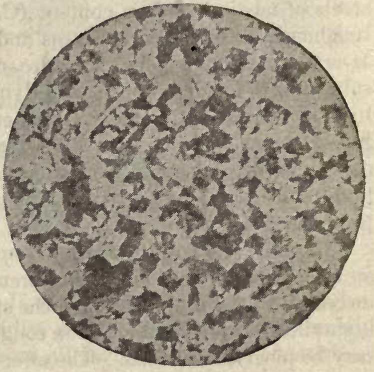
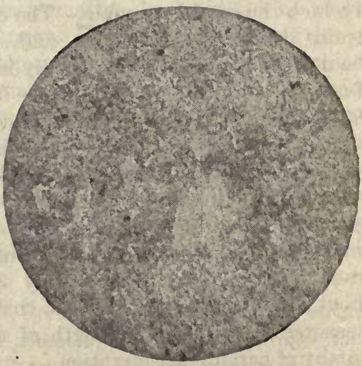
| Ladle Analysis | Treatment | Mechanical Properties | Structure |
|---|---|---|---|
| C. .49%<br>Mn. .66%<br>P. .020%<br>S. .026% | as forged | Ultimate Strength 96,370 lbs.<br>Elastic Limit 49,310<br>Elongation in 2″ 20.5%<br>Reduction of Area 34.7% |  x 100. Pearlite—Large Grain Size. |
| C. .48%<br>Mn. .54%<br>P. .020%<br>S. .036% | Annealed<br>Heated<br>to 830°C<br>and cooled<br>in air | Ultimate Strength 85,040 lbs.<br>Elastic Limit 44,920 lbs.<br>Elongation in 2″ 23%<br>Reduction of Area 37.8% |  x 100. Sorbitic Pearlite—Grain Size Good. |
| C. .49%<br>Mn. .66%<br>P. .020%<br>S. .026% | Quenched and tempered<br>Heated to 825°C and quenched in water<br>Drawn back at 585°C | Ultimate Strength 97,200 lbs.<br>Elastic Limit 62,720 lbs.<br>Elongation in 2″<br>25%<br>Reduction of Area 59.8% |  x 100. Sorbite—Grain Size Excellent |

Fig. 118. Showing Change in Structure and Condition of Constituents in Steel Due to Heat Treatment, with the Accompanying Changes in the Physical Properties. Specimens taken from large forgings, six inches in diameter, midway between center and outside, all from articles of the same size and design and forged in the same manner. (Micrographs by O. M. Ash).

advantages and disadvantages. Water is the more rapid and drastic medium, and on this account, is more liable to develop cracks in the steel, hence some heat treaters recommend that only oil be used. On the other hand, a deeper penetration of the effects of the quenching and greater tensile strength and elastic limit are obtained with water than with oil, thus making it easier to meet specifications calling for high tensile properties. Therefore, others will prefer water quenching under certain conditions. In selecting the quenching medium, it is evident that much depends upon the article, its shape, size, and the grade of steel it is made of, and much upon the skill of the operator. All these features of toughening are brought out in Fig. 118 and table 62.

**Table 62:[1] Illustrating the Effect of Various Heat Treatments upon the Mechanical Properties of Medium Carbon Plain Steels.**

Chemical Composition; C. .38%, Mn. .55%, Si. .05%, P. .024%, S. .050%.

Description of Pieces Treated; one inch rounds, 29 inches long; 14 pieces, all from same billet.

Description of Test Pieces; One test piece from each of the 14 pieces, turned to a diameter of ½ inch, as in Fig. 47.

| Heat Treatment | | Physical Tests | | | | | |
|---|---|---|---|---|---|---|---|
| Hardening and Refining Deg. C | Anneal and Draw, Deg. C | Tensile Strength | Elastic Limit | Elongation in 2″ % | Reduction in area % | Brinell Number | Scleroscope Test |
| As Rolled | .... | 85,000 | 50,000 | 30.0 | 48.9 | 163 | 25 |
| Heated to 760° and cooled in furnace | | 74,000 | 42,500 | 32.0 | 54.7 | 134 | 23 |
| Heated to 815° | 427° | 100,000 | 67,000 | 21.0 | 53.9 | 179 | 30 |
| quenched in oil | 482° | 98,000 | 66,000 | 23.5 | 52.8 | 170 | 29 |
| .............. | 538° | 90,000 | 59,000 | 26.5 | 54.7 | 170 | 29 |
| .............. | 593° | 89,000 | 58,000 | 26.5 | 63.5 | 170 | 29 |
| .............. | 649° | 75,000 | 53,000 | 33.5 | 64.7 | 156 | 27 |
| .............. | 704° | 71,000 | 51,000 | 34.0 | 59.3 | 137 | 25 |
| Heated to 815° | 427° | 110,000 | 81,000 | 19.0 | 46.0 | 223 | 35 |
| quenched in | 482° | 103,000 | 71,000 | 22.5 | 54.7 | 192 | 33 |
| water | 538° | 95,000 | 68,500 | 23.5 | 61.6 | 187 | 32 |
| .............. | 593° | 89,000 | 63,000 | 28.5 | 63.0 | 179 | 29 |
| .............. | 649 | 82,000 | 57,500 | 30.5 | 65.4 | 156 | 26 |
| .............. | 704° | 73,000 | 51,000 | 34.0 | 59.8 | 143 | 25 |

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[1] The data for this table, as well as that for tables 65, 68, and 69, were supplied by Henry Wysor, of the Bethlehem Steel Company.

## SECTION V.

### CASE HARDENING.

**The Process of Carburizing Iron:** It is a well known fact that if a bar of wrought iron or soft steel be heated to a temperature close to or above the critical range in contact with carbonaceous materials and within a suitable receptacle from which air is excluded after the heating is started, the bar of metal will absorb carbon, the amount so absorbed depending upon the time the bar is kept in contact with the carbon, the temperature maintained during the operation, the nature of the carbonaceous material, and the initial composition of the bar itself. This characteristic of iron with respect to carbon was first made use of in the manufacture of steel from wrought iron by the cementation process, then for the surface carburizing of armor plate, and finally for case hardening, or surface carburizing, smaller articles. Essentially, case hardening is but a special application of the cementation process, in which the articles treated are but partially carburized and the case extends but a short distance from the surface, leaving the central portions of the articles unchanged in chemical composition. Thus, while the chief principle of carburizing iron has been known and made use of for years, it is only within recent times that case hardening has become a process of commercial importance.

**Application of Case Hardening:** The result sought, in most cases where case hardening is employed, is the production of a hard, wear-resisting surface upon a tough, ductile core. It is, therefore, applied to many tools, to gears, to ball bearings and to various parts of automobiles, airplanes, bicycles and the like—in fact, wherever a combination of toughness and lightness with a wear-resisting surface is desired. On account of the wide application of the process and the fact that the art has not yet reached the stage of fullest development, a wide variation in the methods of applying the process is to be expected. This condition makes the subject a difficult one to deal with briefly and at the same time satisfactorily. In the following paragraphs, an attempt has been made to give a summary of the facts as revealed by the work of many investigators who have published or otherwise made known the results of their experiments and experience. Only general features are thus dealt with, because the working out of details is largely a matter to be determined by experience.

**The Two Periods of the Case Hardening Process:** In order to obtain the greatest benefits from case hardening, it is necessary that the carburization be succeeded by proper heat treatment, or that the carburizing process be considered as a part of a special heat treating process. The chief factors that control the carburization have already been enumerated. Since a relatively high temperature is employed in the carburizing process and the cooling, at the end of the carburizing period, is usually slow, the steel, as a whole, is in its softest condition, and has a large grain structure.

Therefore, the heat treating part of the process must combine a grain refining operation for low carbon steel with a hardening and grain refining treatment for high carbon steels.

**Kinds of Steel Suitable for Case Hardening:** In general, the composition of the steel for case hardening is limited by the desire to eliminate any elements that produce brittleness in the core, and also any that tend to retard the absorption of carbon by the steel. The elements that may be permitted and those that should be avoided in steel for case hardening will, therefore, be easily recognized after a study of the two succeeding chapters which are devoted to the effects of the elements upon the properties of steel. For convenience, however, a list of the elements with data concerning their case hardening properties is given here.

**Carbon:** Since the tendency of carbon, especially when present in any amount greater than .25 per cent., is to increase the brittleness, .30 per cent. is the limit to which the carbon in steel for case hardening may rise. Therefore, the carbon content of steels for this purpose ranges from .08 to .25 per cent. For ordinary purposes a carbon content of .08 to .15 per cent. is most satisfactory. However, as steel of this grade is difficult to machine so as to give a smooth surface, and a fairly strong core is desirable for some kinds of work, a carbon content of .15 to .25 per cent is frequently specified. Needless to say, the higher carbon grade requires more care in treatment than the low carbon grade.

**Manganese:** While manganese increases the ability of the steel to absorb carbon, on account of its tendency to make the case brittle and sensitive to shock, the per cent. of this element is generally kept below .50, though steel with a manganese content of .70 per cent. is sometimes employed.

**Silicon:** When the silicon content is raised to 2.0 per cent., the steel refuses to absorb carbon, hence the steel should be kept as free of this element as possible. The highest limit for silicon to give commercially satisfactory results is about .30 per cent.

**Phosphorus and Sulphur:** The phosphorus and sulphur content of the steel should be as low as possible, not over .05 per cent. for each of these elements.

**Nickel:** Nickel strengthens and toughens steel, but retards the carburization of the metal. The rate of penetration is lowered in proportion to the amount present, so that in a steel with a nickel content of 5 per cent., the rate of penetration, using solid carburizing materials, is about half that in the plain low carbon low manganese steels. But, offsetting this disadvantage, nickel steels possess certain peculiarities of structure and increased toughness, which make them desirable for carburizing purposes.

**Vanadium:** This element also lowers the rate of carbon penetration, but since it is present in very small amounts, its action in this respect is less pronounced than in the case of nickel.

**Chromium:** The low carbon chrome steels, especially those containing about 0.5 per cent. chromium, are well adapted to case hardening, for the chromium not only increases the rate of penetration and the concentration of the carbon in the case, but also materially reduces the grain size. Furthermore, this amount of chromium does not harden the case nor render it brittle beyond that which would be obtained by slightly increasing the carbon content of the plain carbon steel.

**The Carburizing Agent:** Many investigations have been conducted to determine just what the carburizing action is. Originally, it was held that the carbon was absorbed directly at the surface of the metal and there dissolved, the dissolved carbon being then disseminated towards the interior. That dissolved carbon may move about, or diffuse, within the metal is accepted, but it has been proved that carbon alone in contact with iron has only a slight carburizing action and that, for commercial carburization, the presence of carbon bearing gases is necessary. By diffusing into the steel where they may react with the iron, these gases act as carriers of the carbon. The gases available for this purpose are carbon monoxide, cyanogen, and gaseous hydrocarbons. Of these, carbon monoxide and cyanogen bearing gases are the most effective, but the former gives a much more uniform gradation of the carbon content from the exterior to the interior of the case, and is to be preferred on that account. The reaction by which carburization is effected with carbon monoxide is generally assumed to be the following: $2\,CO + 3Fe = Fe_3C + CO_2$.

**Carburizing Materials:** A great number of different carburizing materials, consisting of gases, liquids and solids, have been tested by the many investigators, and of these, solids are by far the most convenient for the purpose as well as the most effective, when they are of the proper composition. In the use of solid carburizers, the chief essentials to success are carbon in suitable form, a sufficiently high and properly regulated temperature maintained for a proper length of time, and reasonable care as to the details of preparing the carburizer and packing the articles therein. For supplying the carbon, many different substances may be employed, such as coke, wood charcoal, sugar charcoal, animal charcoal, charred bones, charred leather, etc. Coke and wood charcoal are not as rapid as these other forms of carbon. Care is required in using coke, bones, leather and animal charcoal to guard against imparting phosphorus and sulphur to the metal. The material selected should be ground or crushed to the proper degree of fineness and to a fairly uniform size, after which it should be sifted free of dust.

**Packing and the Action of Charcoal Carburizer:** Assuming that charcoal is selected, the article or articles to be case hardened are packed with the carburizer in a hardening pot or box of suitable size and shape. The boxes may be of soft steel, wrought iron or cast iron. The walls should be thin, about one-fourth inch in thickness, and of a size and shape that will permit the rapid penetration of the heat, so that the lag in temperature of the central part of the packed box behind the furnace temperature will be as small as possible. The best shape is one that conforms to that of the piece or pieces to be carburized. The article, or each of the articles, in a charge should be placed so that it will be completely surrounded by a layer of the carburizing material, about an inch in thickness. In case it is desired to carburize only certain parts of the article, the parts that are not to be carburized may be covered with asbestos cement, or slaked lime or fire clay in the form of a paste. When the packing has been completed, the open end of the box is closed with a neatly fitting lid, which is pressed down firmly against the top layer of carburizing material and fastened tightly in place, so that it will permit no displacement of the pack or packing in handling. The small opening about the edge of the lid is then luted with asbestos cement, clay, or a mixture of fire clay and sand; then, the box is ready for charging. When the contents of the box have reached a certain temperature in the furnace, the oxygen of the air that fills the interstitial spaces of the packing reacts with the carbon, giving carbon monoxide, which in turn reacts with iron to give iron carbide and carbon dioxide gas, as previously described. The iron carbide, of course, remains in the metal to form the case, while the carbon dioxide is given off. When it comes in contact with the carburizing material, CO gas is again generated, thus, $CO_2+C=2\,CO$. This CO then reacts with iron as before. This cycle is made again and again, until the process is stopped, or the iron becomes saturated with carbon. In the case of bones, leather, and other animal or vegetable matter, other more complicated reactions, due to cyanogen and hydrocarbon vapors given off by these substances, occur in addition to the simple reactions resulting from the carbon, as explained in connection with the use of charcoal.

**Carburizing Mixtures and Compounds:** These simple substances may also be used as the base materials for various carburizing mixtures designed to suit the conditions and the results desired. Thus, in the case of thin cases, where it is desired to increase the speed or rate of penetration and where the forming of a case of uniform thickness is essential, the following mixtures have been recommended:

1. Powdered wood charcoal with a little heavy hydrocarbon oil added.

2. Powdered wood charcoal, leather charcoal, and lampblack in the proportion of 5, 2, and 3 parts, respectively.

3. Powdered wood charcoal, 7 parts, and animal charcoal, 3 parts.

4. Powdered wood charcoal, charred horn and animal charcoal, in proportion of three parts of the first and two parts of each of the others.

The increased rate of carburization that may be obtained by the use of these mixtures is due to the fact that they give off volatile hydrocarbons and cyanogen compounds as well as carbon monoxide, and that these compounds are capable of causing carburizing reactions independent of and in addition to that involving carbon monoxide.

In addition to these, mixtures of wood charcoal with common salt or with barium carbonate have been found very efficient and desirable carburizing materials. Just what part common salt may play in the process is not known, but the action of barium carbonate is easily explained. At the higher carburizing temperatures it is decomposed according to the following reaction: $BaCO_3 = BaO + CO_2$. The $CO_2$ thus generated is immediately reduced by the hot carbon to CO gas, each volume of $CO_2$ giving two volumes of CO; thus, $CO_2 + C = 2\ CO$. The net effect of the barium carbonate, then, is to increase materially the amount of the CO available. By exposing the mixture, after use, to the air, the barium oxide takes up $CO_2$, forming barium carbonate again, so that with the occasional addition of small amounts of charcoal the same mixture may be used repeatedly. Another advantage secured in using the barium carbonate-charcoal mixtures is that the danger of contaminating the steel with sulphur is entirely avoided, as these materials may be obtained practically sulphur free. The mixture that has been found to give the best results is one composed of 40 parts of the carbonate to 60 parts of charcoal by weight.

When it is desired to obtain a thin case of high carbon content in a very short interval of time, quick acting mixtures are used. The substances employed in these mixtures are wood charcoal, bituminous coal, saw dust, charred leather, prussiate of potash, sal soda and common salt. From these substances mixtures that will give various speeds of carburizing may be made. For example, a mixture of 2 parts wood charcoal, 1 part salt, and 3 parts saw dust is relatively slow in its action while a mixture of 10 parts charred leather, 2 parts prussiate of potash and 10 parts saw dust is characterized as very rapid.

**Heating the Carburizing Pack:** For heating up the charged carburizing boxes, some form of gas fired muffle furnace is preferable. The essential requirements of the furnace are that it must be capable of giving a maximum temperature of at least 1000° C., any definite temperature lower than 1000°, and also be capable of maintaining these definite temperatures uniformly throughout the heating chamber for periods of several days at a time. In order to avoid the rapid oxidation and consequent destruction of the carburizing boxes, a reducing atmosphere should be maintained in the heating chamber, and furnaces constructed so as to effect this result are most desirable. The furnace should be cold, or nearly so, when the packed boxes are charged, and the heating, up to the carburizing point, should be very gradual. The steel will thus have time to adjust itself to the conditions; the pack will be uniformly heated throughout, so that carburization will begin in all parts of the pack at the same time; and the evolution and generation of gases, which begins at temperatures slightly below 700° C., will not be too energetic. The temperature and the length of time for carburizing depend on the depth and the carbon content of the case desired, the carburizing material, and the character of the raw iron or steel. In general, for a given set of materials, the higher the temperature and the longer the time of carburizing, the greater will be the depth of the carburized zone; and when solid carburizers are used, the same may be said with respect to the maximum carbon content or carbon concentration of the case. That the carburizing material may affect the speed of the carburization has already been intimated in discussing carburizing mixtures. A similar difference is also found in their action with respect to the concentration of the carbon. Thus, while one carburizer will give, for example, a case with a surface hardness corresponding to .80% carbon at 870° C., 1.05% carbon at 900° C., etc., another will give only a .70% case at 870° C. and a .90% case at 900° C. In treating ordinary carbon steel, a temperature between 875° and 900° is considered best to avoid large grain size and obtain the most satisfactory results. With this temperature determined upon, the depth of the case and the concentration of the carbon may be regulated by varying the time of carburizing and the composition of the carburizing material employed.

**Controlling the Temperature:** In regulating the temperature of the pack it should be kept in mind that the temperature of the furnace cannot be relied upon to give the actual temperature of the interior of the pack. The temperature of the latter, during the time it is being brought to heat, will tend to lag behind that of the furnace, and after a temperature of 700°C. is passed the chemical reactions within the pack itself may result in the liberation or absorption of a quantity of heat sufficient to maintain its temperature several degrees above or below that of the furnace. Evidently, then, some means of ascertaining the temperature of the interior of the pack is very desirable. For this purpose a pyrometer of the thermo-electric type is admirably suited, because with this instrument the hot junction of the thermo couple may be placed in the center of the pack as it is being made up, or inserted through a small tube so placed.

**Removal of the Articles from the Boxes After Carburizing:** In cases where it is desired to prevent the oxidation of the surface of the articles treated, it is necessary either to permit them to cool nearly to atmospheric temperature in the boxes or to quench them by emptying the entire contents of the box, inverted and with its opening very close to the surface, into the quenching liquid. Some materials are quenched from the carburizing temperature for the purpose of hardening them, but in order to refine the grain, which is coarse, due to the long period of exposure to a relatively high temperature, and secure the greatest toughness combined with greatest hardness, the carburized articles must be subjected to special heat treating processes, in which case the articles may be removed from the carburizing boxes at any convenient time and allowed to cool in the air to atmospheric temperatures or at least to a temperature that gives a black color.

**Heat Treatment of Case Hardened Articles:** The correct heat treatment of case hardened articles involves a combination of methods suitable to steels of different carbon content. Upon the core of low carbon content there is superimposed a layer of high carbon steel, which may be of hypo-eutectoid, eutectoid, or hyper-eutectoid composition, and the treatments should be varied to correspond to these three different cases and to the temperature at which the carburization was carried on. To secure maximum refinement of grain in the core it is necessary to heat the steel just above its $Ac_3$ point, which for a .15% to .20% carbon core, is a temperature near 900°, and quench, preferably, in oil. As this temperature is far above the Ac range of either a hypo-eutectoid or eutectoid case, this treatment hardens the case but leaves its grain structure relatively coarse. Therefore, the article should be reheated to a temperature slightly above the $Ac_{3-2-1}$ range of the case and again quenched in water or oil. Finally, to prevent brittleness in the case and to remove strains, it is desirable to temper the steel at once by reheating to 200° or over, depending upon the hardness it is desired the case shall retain. The temperature mentioned would relieve strains but would reduce the hardness very little, if any. Hyper-eutectoid cases require that the treatment described above be modified to the extent that either the first reheating shall be above the $Ac_{cm}$ range, or that the article be quenched from the carburizing temperature, in order that the excess cementite may be retained in solution. The further treatment may then be a repetition of that for hypo-eutectoid cases, or merely a quenching from above the $Ac_{3-2-1}$ range (750° C.). This last method leaves the core somewhat brittle, due to a large grain size, but produces a surface of exceptional wear resisting properties. In any of these cases, where the carburizing has been carried on at a high temperature and has occupied a considerable period of time, double quenchings are sometimes necessary to secure the best results.

**Superficial Hardening:** For the most superficial hardening and at the same time the most rapid, such as is sometimes desirable for hardening certain tools, cyanide of potassium or prussiate of potassium alone may be used in either one of two ways. In one, the salt is melted and the article to be hardened is brought to the quenching temperature by immersing it in the fused salt, held at that temperature for a few minutes, the exact time depending upon the amount or extent of the carburization desired, and then quenched as for ordinary hardening, except that lime water should be used to neutralize the poisonous cyanide. In the other method, the article to be hardened is heated to the hardening temperature and is then sprinkled with the dry salt or plunged into a quantity of the dry salt. It is then reheated to the hardening temperature and quenched, as in the first method. Although often spoken of as such, this treatment is not a true case hardening process.

## CHAPTER III.

## CONSTITUENT ELEMENTS OF COMMERCIAL CARBON STEEL AND THEIR INFLUENCE UPON ITS MECHANICAL PROPERTIES.

**Introductory:** Needless to say that a complete discussion of the effects upon the properties of steel of all the elements that naturally may be found in it or that may be added to it would be a very lengthy one, indeed. Even a thorough study of the subject as limited by the title of this chapter would involve an immense amount of labor on the part of the writer and much time on the part of the reader to peruse it. The most that is to be expected, therefore, in the following discourse is but a brief summary of the opinions of the different authorities as presented in the various text books, the trade papers, and the reports of conventions, and some deductions and conclusions arrived at through personal experience. In examining the information from these sources, the student is confronted with much difference of opinion, which often results in much confusion of thought. But a systematic search enables the student to arrive at the conclusion that certain elements, like manganese, for example, are beneficial; others, like oxygen, are harmful; some, like phosphorus and sulphur, are of doubtful influence; while others may be beneficial or harmful, depending upon conditions. In this regard, it is important to note that opinion at present is changing with respect to the influence of many of the elements. This is particularly true of phosphorus and sulphur, both of which were recently held to be injurious to steel under any conditions and at all times. Now, however, these elements, far from being considered as foes to good steel making, are, within certain limits, being looked upon as harmless to the steel, and even as aids for certain purposes. With these things in mind, an attempt has been made here to put down what appears to be the truth concerning these elements as revealed after a study such as that suggested above.

**Properties of Iron:** Since iron is the element that forms the base material for the steel, the discussion of this subject is naturally begun with a consideration of the properties of this element, though pure iron is unknown commercially. As the physical and chemical properties of the element will be found under the subjects of Physics and Chemistry and the Heat Treatment of Carbon Steel, it is not necessary even to tabulate them here. In this connection, special emphasis is to be laid upon the strength and ductility of the element. Seeing that it is almost impossible to obtain pure iron in sufficient quantity for testing, the determination of these properties cannot be made directly. However, figures that appear to be as near the true values as it is possible to get, have been assigned for these properties by calculating from results of pulling tests upon the purest forms of annealed or normalized commercial soft steels. After making what would appear to be a proper allowance for the influence of the small amounts of carbon that these steels contain, it has been established that pure iron has an elastic limit of about 20000 pounds, a tensile strength, or maximum stress, of 38000 to 40000 pounds, a reduction of area of 84%, and an elongation, measured in 8 inches, of 51%. From these values it is seen that pure iron is a very ductile substance, but weak as compared with steel.

**Effect of Carbon:** The influence of carbon upon iron is so characteristic and beneficial that it is employed as the controlling element in regulating the physical properties of all common steels. While this element is capable of changing most of the physical properties of iron by uniting and alloying with it, its most important influence is connected with the hardness, strength, and ductility of the metal. Its effect upon these properties may be varied in extent by heat treatment, as is fully explained in the chapter on that subject. It is to be noted here, however, that, with respect to its influence upon the strength and ductility of naturally cooled steel, the average results obtained by four eminent investigators show that for each 0.1% carbon added to steel up to .90%, these properties are affected approximately as follows:

| | | | | |
|---|---|---|---|---|
| Yield point is raised | 3987 | pounds | per | sq. in. |
| Maximum stress is raised | 9363 | " | " | " |
| Elongation is reduced | 4.33% | | | |
| Reduction of area is reduced | 7.27% | | | |

Above 1.00% in carbon content, the brittleness of steel increases so rapidly, due to the presence of excess cementite, that its use is then limited to articles, relatively few in number, requiring great hardness and little toughness or ductility. Hence, the carbon content of commercial steel will seldom exceed 1.10%.

**Influence of Manganese:** The chemical properties of manganese, which impart to it the power of combining with the oxygen of ferrous-oxide and of setting free the iron, make it invaluable as a cleansing, or deoxidizing agent, and have been referred to, time and again, in describing the various processes of making steel. It is here appropriate to consider the effect of the manganese that remains in the steel after deoxidizing. Of this residual manganese, it may be said that every one is agreed that its effects, when present up to certain limits, varying with conditions and the use to which the steel is to be put, are wholly beneficial. Aside from causing the steel to roll and forge better, it is a well known fact that manganese adds somewhat to the tensile strength, this beneficial effect depending upon the carbon content as well as that of the manganese. According to H. H.

Campbell[1] the tensile strength of untreated open hearth steel, containing .30% manganese and over, rises for each increase of .01% in manganese and with the carbon content as shown in the following table:

**Table 63. The Effect of Manganese Upon the Tensile Strength of Steel.**

Each increase of .01% Mn. above .30% or .40% raises the tensile strength in:

| CARBON CONTENT | BASIC OPEN HEARTH (MN. ABOVE .30%) | ACID OPEN HEARTH, (MN. ABOVE .40%) |
|---|---|---|
| .05 | 110 lbs. | ....... |
| .10 | 130 " | 80 lbs. |
| .15 | 150 " | 120 " |
| .20 | 170 " | 160 " |
| .25 | 190 " | 200 " |
| .30 | 210 " | 240 " |
| .35 | 230 " | 280 " |
| .40 | 250 " | 320 " |

When the manganese content is less than .30%, this law of increase is disturbed by other influences of an unknown character, which may even cause a complete reversal of tendencies and the tensile strength to rise when the content falls below .30%. Above 1.00%, manganese begins to produce undue hardness and brittleness which becomes very marked as the content reaches and passes 1.50%. Like the tenacity, these properties are similarly affected by the relation of the manganese to the carbon content.

**Influence of Manganese in Heat Treatment:** Relative to heat treatment, the effect of manganese upon the heat treating qualities of the steel are not to be overlooked. In the case of ordinary open hearth steels, this brittleness of the high manganese steels is associated with the tendency of such steels to crack just before or during the quenching. Much care, therefore, must be exercised in selecting steel for heat treatment to secure the proper proportion of carbon and manganese, for which purpose the following statements will be found to apply in a general way:

1. Steels containing 1.50% manganese cannot be quenched in water, whatever their carbon content may be, but with the per cent. of carbon no higher than .60 they may, depending on the design of the body and the condition of the steel, be quenched in oil.

2. Steels containing 1.00% manganese and of low or medium carbon content may be quenched in water, though the risk of cracking is still great.

3. A manganese content of .40% or less is required in high carbon steels near the eutectoid (.90% C.) composition, when such steels are to be hardened by quenching in water.

4. In hyper-eutectoid steels, such as high carbon tool steels, the manganese content should not rise above .25%.

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[1] See Manufacture and Properties of Iron and Steel. Published by McGraw Hill Book Co.

5. Each 0.1% of manganese lowers the critical range on heating by about 3° C.

6. According to one authority, electric steel permits a higher content of both the carbon and the manganese in heat treating than would be permissible with ordinary open hearth steel.

**Influence of Manganese on Sulphur:** Another great benefit to be gained from the use of manganese is due to its ability to neutralize, or offset, the evil effects of sulphur. Like oxygen, this element combines with both iron and manganese to form sulphides, but in the presence of both elements and at a high temperature it unites with the latter in preference to the former, thus producing manganese sulphide, MnS, which is practically harmless in steel for reasons that will be explained shortly.

**Influence of Sulphur:** The effect of this element upon the tenacity and ductility of steel, at least up to 0.1%, is so slight that it may be disregarded. One investigator asserts that it accelerates corrosion of the steel that contains it. Its most marked effects, however, are encountered in hot working, i. e., rolling or forging, the steel, and they were formally believed to be always evil ones. That in the form of ferrous sulphide, FeS, it is capable of doing great harm in steel by causing redshortness is conceded by all, but when neutralized with manganese in sufficient amount it may be comparatively harmless, even when present to the extent of a much higher content than one-tenth per cent.

**Why Manganese Neutralizes the Effect of Sulphur:** The only plausible explanation so far offered to account for the difference in the effect of the two sulphides is that the iron sulphide forms films, or cell walls, about the grains of the metal, and as this sulphide fuses at a red heat, these cell walls, by becoming fluid, interrupt the continuity of the mass and so render the steel hot short. Manganese sulphide, instead of forming envelopes about the grains of the metal, collects, or segregates, into globules at temperatures near that of the metal on solidifying, upon which the main body of metal then contracts. Manganese sulphide has a much higher fusion point than ferrous sulphide, hence does not melt at a rolling heat, but becomes merely plastic like the rest of the metal. In this form, it is rolled into fibers, which give to the steel, when present in sufficiently large quantities, a fibrous structure similar to that of wrought iron. In order to get the full benefit of the manganese, it is necessary that it should be present in the steel to the extent of about three times the theoretical amount required for the formation of the sulphide. Roughly, this means that the per cent. of manganese should be five times that of the sulphur.

**Uses for Sulphur in Steel:** This fibrous structure of high sulphur steel is made use of in the manufacture of free cutting steel, like screw stock, for example, because the free cutting properties of this steel are undoubtedly due to its fibrous structure. Thus, in this case, at least, sulphur is to be regarded as a friend rather than as a foe. In this connection, it should be observed that experiments conducted during 1914 and 1915 in both this country and England tend to show that sulphur, when accompanied with a sufficient amount of manganese, is not such an enemy as it is sometimes supposed to be. Extensive investigations by our own research department have shown that there is practically no difference in the rolling, forging or welding qualities, nor in the physical properties, of steels containing from .030% to .120% sulphur. It is interesting to consider how the unfavorable attitude toward sulphur came about. Up to within the present decade, most of the steel produced in this country was made by the acid Bessemer process in which the sulphur content would often range from .070% to .100%. Yet there was no complaint about this steel, and that it gave excellent service for nearly all purposes that steel is used cannot be denied. But with the advent of basic steel, the notion became prevalent, through academic discussions to explain why this steel should be better than Bessemer, that even a small quantity of sulphur was harmful to the steel; and consumers, also, naturally insisted on placing the limit for sulphur at the lowest possible figure, under .040 per cent. or even under .030 per cent., in order to secure the better steel. Evidently, however, such an attitude should be corrected now, for economic reasons, if no other. In view of the fact that it is becoming increasingly difficult to keep the sulphur content below .040%, it seems ridiculous to insist upon so low a limit, when the evidence points so strongly to .100% as a limit that may be made to serve as well, for many purposes, at least. As most basic steel made in this country appears to tend naturally toward a sulphur content of from .050% to .060%, even raising the limit to .080% would result in a great saving.

**Influence of Phosphorus:** Phosphorus is another element that has been painted a little blacker, perhaps, than it should. It has been everywhere charged with producing cold shortness, or brittleness when cold, but experiments and tests conducted by our research department, during the first half of the year 1917, seem to indicate that up to .10% at least, phosphorus does not produce brittleness in the metal to a degree that is noticeably harmful. In these experiments, steel with phosphorus contents ranging from .018% to .110% were subjected to severe cold bending, stamping and pressing tests that steel is called upon to withstand in shaping, with the result that the higher phosphorus steels stood up under the tests as well as the low phosphorus grades, otherwise of identical composition. That it does increase the hardness and tensile strength of the steel, causing at the same time a proportionate reduction in the ductility, is well established as a fact. In this respect it is very similar to carbon. Some authorities claim that it increases the tensile strength a little more than carbon with a less reduction in the ductility; others say that its effect is practically the same as carbon except that it increases the brittleness a little more. Campbell claims that the tensile strength of basic steel is increased 1000 pounds for each increase of .01% of phosphorus. It, also, benefits the wearing properties of the steel in much the same way that carbon does. In low carbon steels, it is used in many cases with entirely beneficial results. Thus, it is useful in sheet bar, as it is claimed that it prevents the sheets from sticking together in the pack during the rolling.

**The Two Evils of Phosphorus:** However, it is not to be inferred that the indiscriminate use of high phosphorus steel is advocated, because it has, according to Howe, Harbord and others, at least two evil tendencies that make it a dangerous element in steels for certain purposes. Speaking of these tendencies, Harbord states that, of all the impurities usually present in steel, practical experience has established the fact that phosphorus is the one that most prejudicially influences the physical properties of the metal by producing brittleness under shock, and hence for practical commercial purposes, phosphorus in steel should not exceed .080%. Again, Howe maintains that while phosphorus sometimes affects iron but slightly, at other times, under apparently similar conditions, it affects it profoundly. In view of this fact, which may be called the treacherousness of phosphoretic steel, it is difficult to define a limit for the maximum content of phosphorus which can be safely allowed in steel, but reasoning that the lower this is, the safer the material, many would insist upon a very low limit. That this limit may be unreasonably low is illustrated in the case of structural steel. Many users of this material refuse to accept any steel that contains a higher percentage of this element than .04%. Yet a class of material subjected to much more severe usage in service, namely, railroad rails made by the Bessemer process, is permitted to contain as much as .110% phosphorus. Furthermore, while structural material is subjected to static stresses mainly, a class of stress that phosphoretic steel is most capable of resisting, rails are required to withstand shocks and impacts, which the evidence shows, high phosphorus steels should be least capable of resisting.

**Influence of Silicon:** Apparently owing to the fact that all but traces of silicon may be removed in any and all of the processes for manufacturing steel, the attention of investigators has not been so universally directed to the effects of this element on steel as in the case of the other impurities. Besides, whatever evidence may be collected will be found to vary somewhat. Thus, while certain English investigators found that steels containing as much as 2.00% silicon, a content much higher than any employed in ordinary carbon steel, suffered a marked reduction in ductility, others maintained that the ductility is not markedly affected up to a content of .70%. All agreed that the tensile strength is increased, and some maintain that small percentages of silicon increased the resistance of the steel to shock. In short, it is generally accepted by all practical steel men that silicon up to .75% is beneficial, that it increases the yield point and tensile strength but does not materially impair the ductility.

This statement is in accord with the experience of our own Company, who found, for example, that in a certain specification calling for a tensile strength of 80,000 pounds with an elongation of 20% in eight inches, requirements that cannot be approached in plain untreated carbon steel, very satisfactory results were obtained by the addition of .50% silicon. Like manganese, silicon is a wonderful deoxidizer, or cleanser, of steel, and it is possible that the improvement in the quality of steel, and of basic steel in particular, which the addition of small quantities of the element produce, is due rather to this property than to any influence the residual silicon in the steel may have. Spring steel with the silicon ranging from .25% to .35% has greater resiliency than steels of lower silicon content, and without increased brittleness. In steel castings it is especially beneficial, as it tends to prevent blow holes and thus promotes soundness. In steels intended to be case hardened, silicon is an objectionable element, as it retards the absorption of carbon. Therefore, in such steels the silicon content should be low, as the retarding effect begins at about .04 per cent. In sheet bar, silicon is like phosphorus in that it tends to prevent the sheets in a pack from sticking together. For this purpose .06 per cent. is sufficient.

**The Influence of Oxygen** in steel has been thoroughly discussed and emphasized in connection with the various methods for manufacturing steel. It may, however, again be pointed out that its effects are all evil ones, causing both red shortness and cold shortness in steel, and that when present even in so small amounts as .03% it shows a marked tendency to produce brittleness under shock. The amount of oxygen steel is capable of retaining is small. That retained even by over-blown Bessemer steel without deoxidizing is less than .15%.

**Combined Effect of the Elements on Tensile Strength of Steel:** These elements, iron, carbon, manganese, sulphur, phosphorus, silicon and oxygen, are the ones found in all commercial grades of steel. Having discussed their effects separately, it may now be advantageous to consider their combined effect upon the metal. Of these elements only oxygen is to be looked upon as being always an enemy. The influence of manganese in steels that are not to be heat treated is always good, as is also that of silicon in small amounts. The tensile strength is raised by carbon, manganese, phosphorus, and silicon, while the ductility is decreased by carbon, manganese, and phosphorus. According to H. H. Campbell the influence of these elements varies in the different kinds of steels; and for the two kinds of open hearth steels in their natural state, that is, without any heat treatment, he sums up the combined effect of carbon, phosphorus and manganese on the tensile strength to be approximately as given in the following formulas:

First Method (of Least Squares):

A. Acid Steel $38600+1210\ C+890\ P+R=$ Ultimate Strength.

B. Basic Steel $37430+950\ C+85\ Mn+1050\ P+R=$ Ultimate Strength.

Second Method (by Plotting):

C. Acid Steel $40000+1000\ C+1000\ P+X\ Mn+R=$Ultimate Strength.

D. Basic Steel $41500+770\ C+1000\ P+Y\ Mn+R=$Ultimate Strength.

In these formulas 38600, 37430, 40000 and 41500 represents the initial strength of pure iron; C, P, Mn, stand for carbon, phosphorus and manganese expressed in hundredths of one per cent., respectively; X and Y represent variables changing with the carbon content as given under the heading, Influence of Manganese; and R is a factor that depends on the finishing temperature, and may be either plus or minus.

For low carbon plain basic steel, such as that used for plates and structural shapes, rolled at the ordinary temperature for hot rolling, the following simple formula is used by many inspectors:

T (Ultimate Strength)$=39000+950\ C+1050\ P+85\ Mn$.

The symbols in this formula have the same significance as the same symbols in Campbell's formulas.

**The Influence of Copper** upon the mechanical properties of steel, when present in small amounts, say up to .50%, is not very pronounced. In terms of tenths of one per cent., the effect of copper as determined by several different investigators is about as follows: The yield point is increased 1800 pounds in steels of low carbon, and 720 pounds in those of medium carbon content; the maximum stress, or ultimate strength, is increased 1200 pounds for low carbon, and 600 pounds for medium; the elongation is decreased .75% for low carbon, and .25% for medium; the reduction of area is decreased .45% for low carbon, and .50% for medium. From these results it is to be decided that the effect of small percentages of copper is slight, and what effect it has is beneficial. This declaration agrees, also, with the verdict of the American Society for Testing Materials. For years copper was looked upon as being very injurious to the steel, it being charged with making the steel red-short and unweldable. However, as early as 1899 A. L. Colby made an extensive series of investigations to determine what really were the effects of small percentages of copper upon the physical properties of the steel. Briefly, these investigations and the results obtained were as follows: A steel shaft 15 inches in diameter by fourteen feet long, corresponding in composition with the propeller shafts adopted by the U. S. Navy Board, but containing also .565% of copper, was forged without difficulty. Test specimens were doubled flat in the cold without showing cracks or flaws, and the tensile strength and ductility were well up to requirements of the Navy. In another series of tests the material, containing .553% copper, was forged into a gun-tube, and satisfied all the requirements for the U. S. Navy for a 6 inch gun. Mild steel in the form of ship-plates, containing .573% copper, passed all the tests required, except a quarter inch plate which was rolled too cold. The bending and quenching tests of the bars cut longitudinally were also satisfactory, but some, bent transversely to the direction of rolling, developed cracks. The material could be successfully welded, only one of the specimens tested breaking at the weld, and even then the breaking load was 61,630 pounds per square inch. Flanged cold, the material gave excellent results, and though most severely tested, developed neither defects nor flaws. Other investigations were directed to merchant bars, rails, and nickel steel all containing copper, and in no case was there any evidence of red-shortness, although the copper ranged from .089% to .486%. Colby's conclusions were that a good steel may contain as much as 1% of copper without suffering, provided that the sulphur content is not also high, in which case the metal is likely to crack in rolling.

Even small amounts of copper in steel causes the latter to resist corrosion by acids much better than steels that do not contain it. The research department of the American Sheet and Tin Plate Company has shown that .15% to .25% of copper in steel sheets of heavy gauge practically preserves them from general corrosion, and that the resistance to corrosion begins to be manifested by the steel with the copper content as low as .03%. While copper compounds occur in many iron ores, only traces, if any, are to be found in the Lake Superior Ores. Hence steels made from these ores are practically copper free, except in cases where it is added to produce the non-corroding steels. Occasionally, however, whether introduced through accident or from the ore, steels will be found to contain copper to the small amount of .01% to .02%.

**Influence of Tin:** While this element is not found in any of the iron ores, the use of detinned scrap may result in its introduction into the steel during the process of manufacture. Hence, the effects of small quantities of tin in steel are not to be overlooked, but unfortunately this matter does not appear to have been very thoroughly investigated. What work has been done shows that tin forms an alloy or a compound with iron, which has the property of making the steel very hard at rolling temperature. Thus, at one steel works it was impossible to roll a heat of steel into which there had accidently been introduced tin to the extent of .75%. Tin in steel increases the yield point and the ultimate strength of the metal, but to a less degree than carbon or phosphorus. So far as they have gone, investigations appear to indicate that .05% tin in steel would have little influence upon its mechanical or physical properties, but that larger quantities must be avoided.

**Influence of Arsenic:** This element does not occur in any of the iron ores from the Lake Superior region, and is, therefore, never found in steels made from these ores. When present, however, in small amounts, unless special precautions are taken in making an analysis of the steel, it is reported as phosphorus. Small amounts of arsenic do not affect the physical properties of steel; above .20% its effect is similar to that of phosphorus, causing cold shortness.

# CHAPTER IV.

# ALLOY STEELS.

## SECTION I.

### INTRODUCTORY.

**Definitions:** So many different elements may occur naturally in steel, or be added to it, in such varying amounts with corresponding variations in effects, that it is a difficult matter to determine just what constitutes an alloy steel even from the standpoint of chemical composition alone. When it is further considered that the different methods of manufacture also exert their influence, and that certain elements may be added or allowed to remain for widely different reasons, the difficulty of wording concisely an adequate definition becomes more apparent. The definition adopted by the International Association for Testing Materials is as follows: "Alloy steel is steel which owes its distinctive properties chiefly to some element or elements other than carbon, or jointly to such other elements and carbon. Some of the alloy steels necessarily contain an important percentage of carbon, even as much as 1.25%. There is no agreement as to where the line between alloy steel and carbon steel shall be drawn." In this connection it is well to note that elements other than carbon are always to be desired in steel of commercial grade, at least. Such elements may be added or permitted to remain for three distinct reasons, namely, (1) to correct or prevent defects that otherwise would be liable to occur in the final product; (2) to impart to the steel some distinctive property or to improve materially its natural properties; (3) to form alloys for the purpose of experimentation and investigation. The addition of silicon and manganese to steel illustrates the point it is desired to explain. In ordinary practice small amounts of these elements are added to deoxidize the steel, and incidentally the small amounts that remain in the metal may improve its properties. Large amounts of these elements, 1.50% to 3.50% in the case of silicon, and 11% to 14% in the case of manganese, may be added to impart properties to the steel that are distinctive and useful. Other proportions may be used, of course, which result in imparting properties that, while they are distinctive, are not useful, and so these iron alloys have only a scientific value. With these facts in mind, we agree with Henry D. Hibbard of the Bureau of Mines[1] who suggested the following definitions:

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[1] See Manufacture and Uses of Alloy Steels, Bureau of Mines Bulletin 100.

"**Simple steel**, which is often called carbon steel (or plain steel), consists chiefly of iron, carbon, and manganese. Other elements are always present, but are not essential to the formation of the steel, and the content of carbon or manganese, or both, may be very small."

"**Alloy steel** is steel that contains one or more elements other than carbon in sufficient proportion to modify or improve substantially and positively some of its useful properties." These steels, since they contain a special element, are sometimes called special steels.

"**Alloy-treated steel** is simple steel to which one or more alloying elements have been added for curative purposes, but in which the excess of the element or elements is not enough to make it an alloy steel."

All the alloy steels manufactured by The Carnegie Steel Co. are made either in the open hearth or the electric furnace, and the alloying elements chiefly employed are nickel, chromium and vanadium. While a large tonnage of steel, containing slightly higher percentages of copper, silicon or manganese than that prescribed by ordinary practice for carbon steels, is made, these elements in such small quantities are not to be considered as alloys but rather as curative or intensifying elements. A definition that would agree with the customs of this company, then, would appear to be the following: An alloy steel is steel, made by the open-hearth or the electric process, which contains, in addition to carbon, some element or elements added with the object of modifying and substantially improving its mechanical properties in such a way as to make it more suitable for the purpose for which it is intended. This definition does not include the addition of copper for obtaining non-corrosive steel, a chemical property, nor the addition of small amounts of phosphorus to basic steel for sheet bar, nor the sulphur in screw stock, nor manganese and silicon added for curative purposes.

**Carnegie Types and Grades:** To illustrate the importance of the elements mentioned above as being the ones chiefly employed in alloy steels, the types and grades of commercial alloy steels manufactured by the open-hearth process and fixed in 1919 as standards by the Carnegie Steel Company may be cited. They are as shown in table 63:

These types and grades are subject to change, of course, and except from the standpoint of tonnage represent only a small part of the whole field of alloy steels. They are, however, representative of the steels made from the three alloying elements that, up to the present time, have been found to be of greatest value commercially, namely, nickel, chromium, and vanadium. Since it is necessary to limit the scope of this chapter in some way, it seems appropriate to confine it to a discussion of the influence of these elements upon steel and of the general characteristics of the steels represented by the types given in this table.

### Table 64. Carnegie Standard Open Hearth Alloy Steels.

**Nickel Steel.**

| | |
|---|---|
| Carbon | .10 to .50% |
| Manganese | .50 to .80 |
| Phosphorus not over | .04 |
| Sulphur not over | .045 |
| Nickel | 3.25 to 3.75 |

**Low Nickel-Chrome Steel.**

| | |
|---|---|
| Carbon | .15 to .45% |
| Manganese | .50 to .80 |
| Phosphorus not over | .04 |
| Sulphur not over | .045 |
| Nickel | 1.00 to 1.50 |
| Chromium | 45 to .75 |

**Chrome Steel.**

| | |
|---|---|
| Carbon | .15 to .70 |
| Manganese | .25 to .50 |
| Phosphorus not over | .04 |
| Sulphur not over | .045 |
| Chromium | .60 to .90 |

**Chrome-Vanadium Steel.**

| | |
|---|---|
| Carbon | .15 to .55 |
| Manganese | .50 to .80 |
| Phosphorus not over | .04 |
| Sulphur not over | .04 |
| Silicon not over | .20 |
| Chromium | .80 to 1.10 |
| Vanadium not under | .15 |

**Chrome-Vanadium Spring Steel.**

| | |
|---|---|
| Carbon | .45 to .55, .50 to .60, .55 to .65% |
| Manganese | .80 to 1.00 |
| Phosphorus not over | .04 |
| Sulphur not over | .05 |
| Silicon not over | .20 |
| Chromium | 1.00 to 1.25 |
| Vanadium not under | .15 |

**Special Low Chrome Spring Steel.**

| | |
|---|---|
| Carbon | .80 to .95% |
| Manganese | .30 to .50 |
| Phosphorus not over | .04 |
| Sulphur not over | .05 |
| Silicon not over | .20 |
| Chromium | .20 to .40 |

## SECTION II.

### NICKEL STEEL.

**Manufacture of Simple Nickel Steel:** Nickel steel, said to have been used for the first time in 1888, may be made by any of the various processes for the manufacture of steel, but the greater portion is produced by the open-hearth process. At the steel-melting temperature nickel is chemically negative to iron, which is capable of reducing its oxides and preventing its oxidation, even when the bath is a highly oxidizing one. Nickel may, therefore, be added to the bath at any time practically without any loss or waste, but its addition is usually made just long enough before tapping to enable it to become properly diffused. For the same reason nickel cannot deoxidize iron, neither will it decompose carbon monoxide nor hold other gases in solution, though it is said to prevent, or hinder in a measure, the segregation of carbon and the other metalloids. It is not used, then, for a curative agent, but only for its beneficial effect upon the physical properties of the steel, for which purpose it is preeminently a strength giving element.

**The Different Nickel Steels and Their General Characteristics:** The nickel content of the useful nickel steels varies from 2% to 46%, which is a wider range than that covered by any other alloying element. Below 2% the benefits derived from its addition alone to steel are very slight and are not worth the extra cost. The great bulk of simple nickel steel, containing from two to four per cent. nickel, is used for structural purposes, such as bridges, gun forgings, machine parts, engines, large dynamos, steel rolls, and various parts of automobiles, because of the superior mechanical properties imparted by the metal when added in these amounts. Thus, for each 1% of nickel added above 2% and up to 4.00% an increase of approximately 6000 pounds in the tensile strength of this steel over the carbon steel is noted, while only a slight decrease, if any, in the ductility occurs, and all this improvement is secured without any heat treatment whatever. The best results, costs and benefits considered, appear to be obtained when the nickel content is between 3 and 4 per cent., the content aimed at for structural purposes being 3.25% to 3.50%. This steel also resists rusting and abrasion better than the plain carbon steels. Nickel steel of this grade lends itself well to heat treatment, and may also be used for case hardening, the only objection to its use for this purpose being the slight tendency of the nickel to retard the rate of penetration of the carbon. When the nickel content is raised above 5%, the metal becomes very hard, is difficult to work either hot or cold, and is rolled only by taking the greatest care. It is in demand where great resistance to shock is a prime quality, such as shield plates for protecting the ammunition of field artillery and the men serving the guns from rifle fire. Up to 8%, nickel increases the hardness of the steel to which it is added, but leaves the metal still amenable to heat treating. Steels containing 10% or more of nickel cannot be hardened by quenching, but become softer after being subjected to this heat treating operation. In 1914 a new alloy steel, containing 13% nickel and .55% carbon, was discovered by Arnold and Read. It is so hard that it cannot be machined or drilled, has a yield point of 134000 pounds, a tensile strength of 195000 pounds, and an elongation of 12% in two inches. Before this discovery, 15% nickel steel, tensile strength about 170000 pounds, was thought to be the strongest one of the series. This steel has been employed occasionally for shafting. Nickel steel containing 22% nickel is used when resistance to rusting is the prime consideration. Thus, it was employed in the valve stems of the salt water fire protective system installed by the city of New York, and in similarly exposed parts of the pumps used in the drainage system for the city of New Orleans. It is also said to be suitable for the spark poles in spark plugs for internal combustion engines. 24% to 32% nickel steel is used for electrical resistance, such as those employed in irons, toasters, and other household heaters. Nickel steels with a nickel content of about 24% are non-magnetic. 36% nickel steel is characterized by an extremely low coefficient of expansion, hence is used in balance wheels of watches, the pendulums of clocks, etc., in order to dispense with compensation. It is known as invar. Finally, 46% nickel steel, containing only .15% carbon, is known as platinite, because it has about the same coefficient of expansion as platinum and glass. Hence, it is employed in the lead wires of incandescent lamp bulbs, where formally platinum was held to be indispensable. Later, a 38% nickel steel wire, coated with copper, was found to give better satisfaction than platinite.

**Reasons for These Peculiarities of the Nickel Steels:** A study of the explanation offered to account for the peculiar influence of nickel upon steel is both interesting and instructive. Referring again to the 3.5% nickel steel, it is to be noted that nickel primarily influences the strength of the steel, and, to a less degree, the ductility. These facts are explained when the solubility of nickel in iron is considered. Thus, when nickel is added to steel, say of hypo-eutectoid composition, it dissolves in the iron to form an iron-nickel alloy. When this steel is cooled through the critical range, it is this alloy that replaces both the free ferrite and the pearlitic ferrite of the carbon steel. Naturally, a change in the physical properties due to this fact alone are to be expected. But it is in the influence of this alloy upon the formation of pearlite that the reason for the great increase in tensile strength of nickel steel is found. The separation of the cementite from the iron-nickel-carbon solution does not take place as readily as from a plain iron-carbon solution, hence the pearlite areas are larger and less clearly defined than in plain carbon steels. In other words, just as carbon and rapid cooling are obstructing agents to the transformation from austenite to pearlite, so also does the nickel act in a similar manner. As long as the nickel content is very low, not over 2%, this influence shows itself only in a slight change in the physical properties as noted. These changes become more marked with increase of nickel, as is to be expected, but the quick change in heat treating properties at 8% or 10% and at about 25% are not thus accounted for. A little reflection, however, shows all these characteristics to be due to the same cause, namely, the retarding action of the nickel upon the transformation ranges. One writer represents this influence of nickel upon the critical points in heating as follows:

.01% Nickel lowers the $Ac_3$ range .235° C.
.01% “ “ “ $Ac_{3-2}$ range .180° C.
.01% “ “ “ $Ac_2$ range .087° C.
.01% “ “ “ $Ac_1$ range .103° C.

No figures are given for the Ar points, but other authorities have established that the $Ar_1$ point is about 80° C. below the $Ac_1$ point. In addition to and in connection with these facts, the effect of nickel upon the eutectoid ratio should also be considered. The statement that nickel interferes with the free formation of pearlite has already been made, and it now remains to be pointed out that nickel, up to about 8%, reduces the eutectoid ratio below that for straight carbon steels. According to Bullens the eutectoid for a steel containing 3% nickel is reached when the carbon content is .75% and for one containing 7% nickel this value falls to .60% carbon. All these facts, as they relate to the 3% nickel steel, which is the one we are most interested in, have been assembled and are represented in the accompanying diagram copied after Bullens, who was the first to represent the effects of nickel in this way.

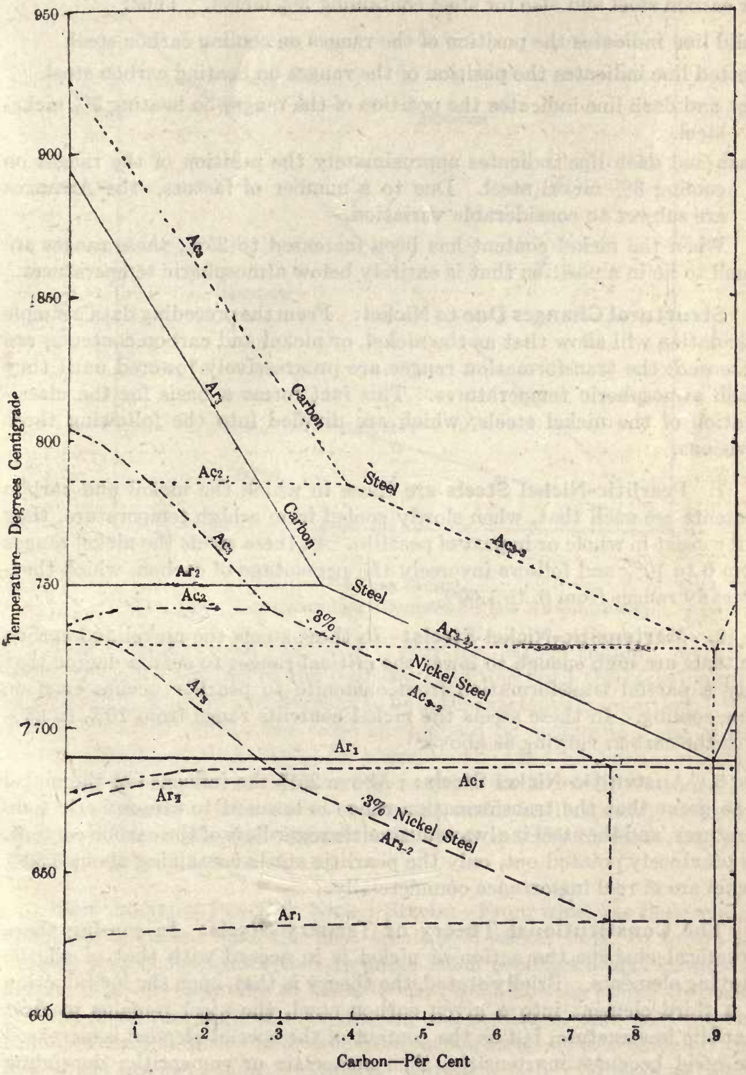

FIG. 119. Diagram Showing effect of Nickel Upon the Critical Ranges. Compared with Carbon Steel. (After Bullens, Steel and its Heat Treatment.

The preceding diagram is intended to depict the general effects of nickel upon the transformation ranges, which become lower and lower as the nickel content is increased, and the eutectoid ratio which decreases with increase of nickel. The diagram shows the position of the Ac and Ar points for carbon steel and also for steel containing 3% nickel. Thus:

Solid line indicates the position of the ranges on cooling carbon steel.

Dotted line indicates the position of the ranges on heating carbon steel.

Dot and dash line indicates the position of the ranges on heating 3% nickel steel.

Dash and dash line indicates approximately the position of the ranges on cooling 3% nickel steel. Due to a number of factors, the Arranges are subject to considerable variation.

When the nickel content has been increased to 25%, these ranges are found to lie in a position that is entirely below atmospheric temperatures.

**Structural Changes Due to Nickel:** From the preceding data a simple calculation will show that as the nickel, or nickel and carbon contents, are increased, the transformation ranges are progressively lowered until they reach atmospheric temperatures. This fact forms a basis for the classification of the nickel steels, which are divided into the following three divisions:

1. **Pearlitic-Nickel Steels** are those in which the nickel and carbon contents are such that, when slowly cooled from a high temperature, they will consist in whole or in part of pearlite. In these steels the nickel ranges from 0 to 10% and follows inversely the percentage of carbon, which theoretically ranges from 0. to 1.60%.

2. **Martensitic-Nickel Steels:** In these steels the nickel and carbon contents are high enough to lower the critical ranges to such a degree that only a partial transformation from austenite to pearlite occurs even on slow cooling. In these steels the nickel contents range from 10% to 25% with the carbon varying as above.

3. **Austenitic-Nickel Steels:** Above 25% the influence of the nickel is so great that the transformation range is lowered to atmospheric temperatures, and the steel is always austenitic regardless of the carbon content. As previously pointed out, only the pearlitic steels containing about 3.50% nickel are of real importance commercially.

**The Constitutional Theory of Ternary Steels:** In causing these structural changes the action of nickel is in accord with that of all the alloying elements. Briefly stated, the theory is that, upon the introduction of a third element into a given carbon steel, the steel remains at first pearlitic in structure, but as the content of the special element is increased the steel becomes martensitic, then austenitic or cementitic, depending upon the chemical action and alloying powers of the special element with respect to carbon and iron; and also that by keeping the amount of the special element constant, the same transformations may be effected by raising the carbon content. This statement, in so far as it relates to nickel, steels is expressed diagrammatically in the accompanying figure.

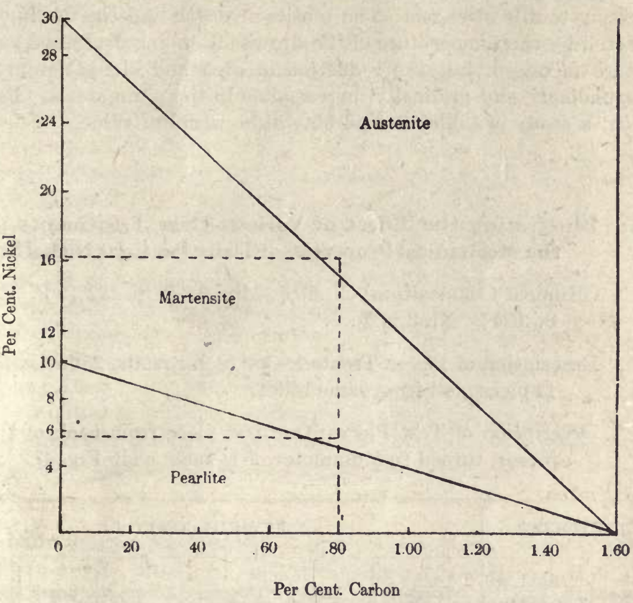

FIG. 120. Constitutional Diagram for the Nickel Steels.

This diagram shows that with a very low carbon content, say about .05%, the steel remains in the pearlitic condition until the nickel content reaches 10%, when it will be found to be in the martensitic condition. With a nickel content of 30% the same steel would be austenitic. But with a carbon content of about .80%, for example, the steel becomes martensitic when the nickel content exceeds 6%, and austenitic when it reaches 16% or 17%. Diagrams like the preceding are useful in illustrating the effect of the different alloying elements and will frequently be made use of in the discussions to follow.

**Heat Treating Pearlitic Nickel Steels:** From what has been said, it should be apparent that the heat treating of nickel steel, to secure the desired results, is an art that requires much experience and knowledge. Hence, it is only desirable to indicate what should be the proper treatment for this steel, and although the heating and cooling of this steel presents some phenomena quite distinctive from carbon steels, it is considered that this object has already been attained. However, a few remarks as to how the low nickel steels are benefited by heat treatment may not be out of place. A heat treated nickel steel has a lower reduction and elongation than a correspondingly heat treated steel without nickel, but the increase in strength is much greater. Thus, for the same strength, the nickel steel is much tougher, and on this account nickel is much to be preferred to carbon for increasing tensile strength. The tensile strength and elastic limit are both affected by the temperature of the drawback, being decreased as this temperature is raised, but the reduction in area and elongation are not so correspondingly and gradually increased as in the plain steels. In this connection, a study of tables 62 and 65 will be found of value.

**Table 65: Illustrating the Effect of Various Heat Treatments upon the Mechanical Properties of Three Per Cent Nickel Steels.**

Chemical Composition: C. .37%, Mn. .61%, Si. .22%, P. .022%, S. .034%, Ni. 3.27%.

Description of Pieces Treated: One inch rounds, 25 inches long; 14 pieces, all from same billet.

Description of Test Pieces: One test piece from each of the 14 pieces, turned to a diameter of ½ inch, as in Fig. 47.

| HEAT TREATMENT | | PHYSICAL TEST | | | | | |
|---|---|---|---|---|---|---|---|
| Hardening and Refining, Deg. C | Anneal and Draw, Deg. C | Tensile Strength | Elastic Limit | Elongation in 2′ % | Reduction in area % | Brinell Number | Scleroscope Test |
| As Rolled | .... | 113,000 | 69,000 | 22.5 | 47.7 | 229 | 32 |
| Heated to 760° and cooled in Furnace | | 99,000 | 60,000 | 26.1 | 48.3 | 183 | 26 |
| Heated to 815° quenched in oil | 427° | 168,000 | 150,000 | 13.5 | 47.2 | 331 | 48 |
| | 482° | 148,000 | 131,000 | 18.0 | 48.3 | 285 | 44 |
| | 538° | 133,000 | 118,000 | 21.0 | 57.3 | 262 | 40 |
| .............. | 593° | 110,000 | 90,000 | 28.0 | 64.7 | 217 | 33 |
| .............. | 649° | 104,000 | 70,000 | 28.0 | 63.0 | 207 | 27 |
| .............. | 704° | 95,000 | 62,500 | 28.5 | 51.7 | 179 | 26 |
| Heated to 815° quenched in water | 427° | 185,000 | 165,000 | 13.0 | 51.1 | 352 | 50 |
| | 482° | 150,000 | 136,000 | 17.5 | 47.2 | 311 | 44 |
| | 538° | 148,000 | 135,000 | 16.0 | 54.7 | 293 | 44 |
| .............. | 593° | 133,500 | 115,000 | 18.5 | 56.5 | 269 | 37 |
| .............. | 649° | 108,000 | 80,000 | 27.5 | 62.8 | 223 | 32 |
| .............. | 704° | 98,000 | 67,000 | 28.0 | 58.6 | 179 | 29 |

## SECTION III.

### CHROME STEEL.

**The Manufacture of Simple Chromium Steels** is carried on by the open hearth, the electric, or the crucible process. At the temperature of molten steel, chromium is capable of reducing iron oxides, hence it is oxidized to a great extent in the open hearth, especially during the melting and boiling of the charge. All simple chrome steel is made by the addition of ferro-chromium to the charge. When the steel is made in crucibles, the ferro-chromium is added with the original charge; if in the electric furnace, this addition may be made at any time; but if made in the open hearth furnace, the ferro-chromium is added to the steel just long enough before casting for the alloy to be melted and become well mixed through the charge, as otherwise great waste of the chromium results. Chromium, however, is not oxidized readily enough to be of any value as a curative or a deoxidizing agent, and is used only for its effect as an alloying element. Simple chromium steels are worked by the same methods and in the same way as carbon steels, but unlike nickel steels, they are seldom, if ever, used in their natural state, heat treatment being necessary to develop the beneficial effects of the chromium, which is most active in responding to this treatment. Simple chromium steel was one of the first alloy steels to be made.

**Influence of Chromium:** This element is preeminently a hardening agent in steel. Unlike nickel, which merely dissolves in iron, chromium forms a carbide. In steel, therefore, at least a part of the chromium will be in this form; but it never reacts with the carbon to the exclusion of iron, and in steel this carbide may exist either as iron-chromium carbide, $x\mathrm{Fe_3C}\cdot y\mathrm{Cr_3C_2}$ or as a solution of $\mathrm{Fe_3C}$ and $\mathrm{Cr_3C_2}$. Thus, while nickel is found in the ferrite of the steel, chromium is associated with the cementite, and imparts what might be termed a mineral hardness to the steel. But the great hardness of the chrome steels is due, also, to another cause. This iron-chromium cementite is not as readily dissolved or diffused as the ordinary cementite on heating the steel through the critical range, nor does it segregate, or separate to form pearlite, as readily on cooling. This fact accounts for the peculiar changes in the critical ranges of the steel that the addition of small amounts of this element brings about, for while it tends to raise the Ac range it also lowers the Ar range. Thus, in quenching it helps to prevent the transformation of the austenite, and so adds much to the hardness in this way. From these statements it is to be inferred that chromium may have no hardening power when not in the presence of carbon. Such a conclusion agrees with the facts, as it has been shown by Harbord that very low carbon chrome steels have practically no hardening power. It is now, also, easily understood why the degree of hardness of the steel is dependent, within certain limits, upon the carbon content as well as upon the chromium. An exceedingly fine grain structure is characteristic of heat treated chrome steels, which fineness of grain confers the valuable property of toughness. Thus, the net result from the influence of this element is to increase the tensile strength and elastic limit, without a noticeable loss in the ductility. One investigator has found chromium to be very efficient in retarding corrosion of the steel by neutral media, such as sea water, and, therefore, recommends its use in ship plates.

**The Microscopic Constituents of the Chrome Steels:** The influence of chromium and carbon in determining the constitution of the steel is shown in the accompanying diagram.

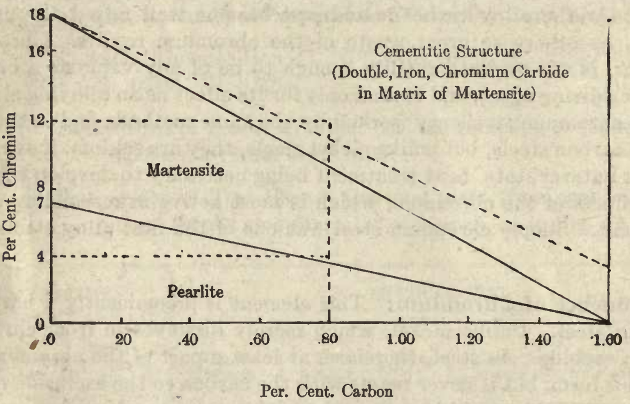

FIG. 121. Constitutional Diagram for Chromium Steels.

From this diagram it is seen that, when the chromium content exceeds 7% in steels of low carbon content or about 5% in steels of high carbon content, the steel is composed only of martensite, hence is very hard and strong, but is lacking in ductility and is inclined to be brittle. It can be neither hardened nor softened by heat treatment. It will be noted that unlike nickel, increasing the chromium content beyond a certain limit in a steel with a given carbon content fails to produce the austenitic condition, but gives a new structure made up of grains of the double carbide embedded in martensite. Between these two areas is a narrow range in which the carbide grains are somewhat less numerous than in the cementite region proper. This range marks the gradual transition from the martensitic to the cementitic condition with the gradual increase in the chromium and the carbon content. Like the martensitic condition, steel of cementitic composition is not affected by heat treatment. For obvious reasons, then, to produce steels of greatest usefulness, the chromium content will be restricted to that required to give the pearlitic condition only.

**Uses of the Simple Chrome Steels:** These steels are used wherever extreme hardness is desired. Thus, they have long been used for stamp shoes and dies for crushing hard ores, like some of the gold and silver ores. Another use is for five-ply plates for safes, where their great hardness is valued on account of the resistance they offer to the drilling tools used by burglars. Rolls for cold rolling metals are made of steel containing about .9% carbon and 2% chromium, while several thousand tons of steel containing about 1.30% carbon and .5% chromium are used annually for files. It is often used in steel for various special purposes, as for example the steel known by the name of "Crucia," which is nothing more than a good grade of spring steel to which has been added from .20% to .40% chromium. The Carnegie Steel Company manufactures this steel as a part of their regular product. A type for axes and hammers, which contains .60% to .70% carbon and .60% to .90% chromium; another for chains, containing .25% to .33% carbon and .65% to .95% chromium; and a third for track bolts with .25% to .40% carbon and .60% to .90% chromium are also manufactured by this company. But the most important use for these steels is in the balls and rolls for bearings. For this purpose they are employed in low carbons for case hardening and in high carbons for heat treating, i. e., quenching and tempering. Of the tonnage furnished by Carnegie Steel Company for this purpose, that for case hardening is made in the open hearth, while the high carbon material is produced in the electric furnace.

**Heat Treatment of Simple Chrome Steel:** To cite an example of the high grade of chrome steel: One large maker of bearings uses steel containing carbon, 1.10%; chromium, 1.40%; manganese, 0.35%; sulphur, 0.025%; and phosphorus, 0.025%. Sizes smaller than one-half inch diameter are heat-treated by being quenched in water from 774° C. and then drawn to 190° C. for half an hour. For larger balls, the quenching temperature is 802° C. The second heating does not produce even an oxide color, but is enough to relieve in some degree the internal stresses due to the irregular cooling of quenching, so that the balls are less liable to crack spontaneously or to be broken in use. The strength of a good, well-treated ball is prodigious; a ball three-fourths of an inch in diameter, tested by the three-ball method, sustained a load of 52,000 pounds. On the small area of contact the intensity of the pressure amounts to over one million pounds per square inch. The Society of Automobile Engineers recommends less chromium than that given above, or 1 to 1.2 per cent. The critical ranges for these steels containing .90% carbon, vary about as follows:

For a chromium content of .50%, from 720° C. to 745° C.

For a chromium content of 1.50%, from 760° C. to 785° C.

As indicating what may be expected by varying the treatment of the steels of this grade, the following will serve as an illustration:

**Table 66. Physical Properties of a Heat Treated Chrome Steel.**

Material: 1 inch rounds.

Analysis: C., .64%; Mn., .27%; Si., .18%; Cr., 1.01%.

Treatment: Heated to 870-871° C. Quenched in oil, and tempered as indicated.

| TEMPERING TEMPERATURES | TENSILE STRENGTH | ELASTIC LIMIT | ELONGATION IN 2 INCHES | REDUCTION IN AREA | BRINNEL HARDNESS |
|---|---|---|---|---|---|
| 400° C. | 228,000 | 170,500 | 5.2% | 13.7% | 478 |
| 500° C. | 212,500 | 155,500 | 8.4% | 19.8% | 445 |
| 600° C. | 186,500 | 128,000 | 10.3% | 22.2% | 389 |

## SECTION IV.

### CHROME—NICKEL STEELS.

**Influence of Chromium and Nickel When Combined:** Having considered the effects of chromium and nickel when added separately to the steel, the student is interested in knowing what their combined influence may be. In the words of Bullens, an impartial judge of high standing as an authority upon the subject of alloy steels, especially from a practical standpoint: "The chrome-nickel steels probably represent the best all-round alloy steels in commercial use for general purposes. Chrome-nickel steels of suitable composition appear to have combined in them the beneficial effects of both the chrome and nickel, but without the disadvantages which are inherent in the use of either one separately. Moreover, the presence of both chrome and nickel seems to intensify certain physical characteristics. To the increased ductility and toughness conferred by nickel on the ferrite there is added the mineral hardness given to the cementite and pearlite by the chrome, but with a greater resultant effect. Again, while the addition of nickel alone serves to diminish the susceptibility to brittleness in the steel upon prolonged heating or sudden cooling—in comparison with the corresponding straight carbon steels—and, on the other hand, the presence of chrome alone tends to the opposite effect, a suitable combination of the two alloying elements tends to neutralize the harmful effects and also to magnify the good points. This is not only brought out in the static strength and ductility, but also in the dynamic strength or fatigue resistance."

**Types of Chrome-Nickel Steel:** According to the testimony of some heat treating experts there appears to be a certain ratio of chrome to nickel which gives the most efficient combination of the physical properties. Thus, if the nickel and chromium are present in the right proportions, the lesser susceptibility of the nickel to brittleness, for example, will so modify the greater tendency to brittleness which is given by chrome alone, that a better steel is obtained than when this ratio is not observed. This ratio is said to be about 2½ parts of nickel to one part of chromium. Furthermore, it is claimed that if the chromium content greatly exceeds this relation to nickel, the temperature limits are so narrowed that the successful treatment of the steel is made very difficult. Thus, in the three standard types of these steels, known as low nickel-chrome steel containing about 1.5% nickel, medium nickel-chrome steel with about 2.50% nickel, and high nickel-chrome steel, in which the nickel content rises to that of the simple nickel steels with 3.5% nickel, the chromium content should be approximately .60%, 1.00% and 1.50%, respectively.

**Mayari Steel,** termed a natural chrome-nickel steel, is made from certain ores found at Mayari, Cuba. These ores contain enough nickel and chromium to give a pig iron with 1.3% to 1.5% nickel and 2.5% to 3.0% chromium. When this iron is converted into steel, for which purpose the open hearth or the duplex, Bessemer-open hearth, processes are employed, practically all the nickel remains in the steel, but a large part of the chromium is wasted. The steel is thus a species of low-nickel-chrome, containing roughly from 1.00% to 1.50% nickel and from .20% to .70% chromium. This steel is undoubtedly of excellent quality for certain purposes, but where the highest quality of chrome-nickel steel is required, most authorities agree that the synthetic alloy steels are superior.

**Uses of Chrome-Nickel Steels:** Low chrome nickel steel is the type more commonly employed because of its low price and the greater ease by which it is machined. In static properties it is nearly equal to the higher nickel grades, but in resistance to dynamic stresses, shocks, etc., the latter are superior. Besides, since the purpose to which it is adapted is about the same as 3.5% simple nickel steel, low-nickel chrome is being substituted for this steel, also on account of the price. All three grades are used in automobiles, the carbon content being varied about as shown in the following table:

TABLE 67: Grades and Composition of Nickel-Chrome Steels.

| GRADE | CARBON % | MN. MAX. % | SI. % | S. MAX. % | P. MAX. % | NI. % | CR. % |
|---|---|---|---|---|---|---|---|
| Low...... | 0.20 to 0.55 | 0.70 | Low | 0.050 | 0.04 | 1.25 | 0.60 |
| Medium.. | .20 to .55 | .70 | Low | .050 | .04 | 1.75 | 1.10 |
| High..... | .20 to .55 | .70 | Low | .050 | .04 | 3.50 | 1.50 |

An important use of these steels is in armor plate. Thick armor is face hardened by a carbonizing process, but the body has the original composition, which is approximately as follows: C., .33%; Mn., .32%; S., .03%; P., .014%; Si., .06%; Ni., 4.00%; and Cr., 2.00%. Medium armor, three to five inches in thickness, is not face hardened, but is given high properties throughout by the proper heat treatment. The composition of this armor is approximately, C., .30%; Mn., .34%; S., .03%; P., .03%; S ., .13%: Ni., 3.66%, and Cr., 1.45%. The nickel chromium steels are used in the manufacture of most armor piercing projectiles, also.

**Heat Treatment of Chrome=Nickle Steels:** The heat treatment of these steels is about the same in kind and method as that for simple nickel and chrome steels, and is varied to suit the kind of material and the purpose for which the steel is to be used. To give a general idea of the proper treatment for these steels, the recommendations of Bullens may be cited:

I. "For forgings:

  a. Quench in oil from about 175° to 200° F. (97° to 110°C.) over the critical range.

  b. Quench in oil from about 50°F (28°C) over the critical range.

  c. Anneal at about 75°F (42°C) under the critical range and machine.

  d. Quench in the proper medium from about 50°F (28°C) over the range.

  e. Draw the temper to suit the work in hand."

II. "For shafts and other structural parts in which the desired physical properties may be obtained by a drawing temperature of about 900°F (500° C.) or over, and which will leave the steel in a machinable condition, treatment I. may be modified at (c) as thus noted, and no further treatment will be required.

  a. Quench in oil from about 175° to 200° F (97° to 110°C) over the critical range.

  b. Quench in oil from about 50°F (28°C) over the critical range.

  c. Draw at 900°F (482°C) or more, as the work may require. Machine."

III. "The full treatment as given under (I) may be modified, if desired to the following, for parts to be drawn below 900° or 1000° F. (482° or 540°C.)

  a. Quench in oil from about 175° to 200° (97 to 110°C) over the critical range.

  b. Reheat to about 25° to 50° F. (14° to 28°C) over the critical range and cool slowly. Machine.

  c. Quench in oil from about 50° (28°C) over the critical range.

  d. Draw to the temperature required by the work."

The data supplied in tables 68 and 69 will serve as a basis for comparing the mechanical properties of the chrome-nickel steels, both in their natural and heat-treated states

**Table 68: Illustrating the Effect of Various Heat Treatments upon the Mechanical Properties of Low-Chrome-Nickel Steels.**

Chemical Composition: C. .39%, Mn. .52%, Si. .18%, P. .017%, S. .042%, Ni. 1.18%, Cr. .58%.

Description of Pieces Treated; One inch rounds, 25 inches long; 14 pieces, all from same billet.

Description of Test Pieces; One test piece from each of the 14 pieces, turned to a diameter of ½ inch, as in Fig. 47.

| HEAT TREATMENT | | PHYSICAL TESTS | | | | | |
|---|---|---|---|---|---|---|---|
| Hardening and Refining Deg. C | Anneal and Draw, Deg. C | Tensile Strength | Elastic Limit | Elongation in 2″ % | Reduction in area % | Brinell Number | Scleroscope Test |
| As Rolled | .... | 99,000 | 59,000 | 25.5 | 54.4 | 208 | 29 |
| Heated to 760° and cooled in Furnace | | 89,000 | 54,000 | 30.0 | 56.5 | 170 | 25 |
| Heated to 845° quenched in oil | 427° | 139,000 | 114,000 | 15.5 | 51.4 | 331 | 42 |
| | 482° | 130,000 | 113,000 | 15.0 | 53.9 | 321 | 44 |
| | 538° | 113,000 | 88,000 | 17.5 | 59.8 | 255 | 34 |
| ............. | 593° | 113,000 | 86,000 | 21.0 | 62.8 | 229 | 32 |
| ............. | 649° | 108,000 | 81,000 | 25.0 | 64.7 | 229 | 31 |
| ............. | 704° | 97,000 | 70,000 | 27.0 | 67.7 | 207 | 29 |
| Heated to 845° quenched in water | 427° | 174,000 | 158,000 | 14.0 | 47.2 | 363 | 46 |
| | 482° | 150,000 | 135,000 | 16.5 | 45.7 | 221 | 44 |
| | 538° | 140,000 | 125,000 | 20.0 | 55.2 | 285 | 44 |
| ............. | 593° | 124,000 | 108,000 | 22.0 | 60.8 | 255 | 40 |
| ............. | 649° | 110,000 | 91,000 | 26.0 | 66.0 | 229 | 33 |
| ............. | 704° | 90,000 | 70,000 | 34.0 | 69.2 | 187 | 25 |

**Table 69: Illustrating the Effect of Various Heat Treatments upon the Mechanical Properties of High-Chrome-Nickel Steel.**

Chemical Composition; C. .34%, Mn. .64%, Si. .20%, P. .010%, S. .036%, Ni. 3.65%, Cr. 1.24%.

Description of Pieces Treated; One inch rounds, 25 inches long; 14 pieces, all from same billet.

Description of Test Pieces; One test piece from each of the 14 pieces, turned to a diameter of ½ inch, as in Fig. 47.

| HEAT TREATMENT | | PHYSICAL TESTS | | | | | |
|---|---|---|---|---|---|---|---|
| Hardening and Refining Deg. C | Anneal and Draw, Deg. C. | Tensile Strength | Elastic Limit | Elongation in 2″ % | Reduction in area % | Brinell Number | Scleroscope Test |
| As Rolled | .... | 172,500 | 138,000 | 11.5 | 26.5 | 444 | 57 |
| Heated to 760° and cooled in Furnace | | 125,000 | 78,000 | 18.0 | 47.2 | 255 | 38 |
| Heated to 845° quenched in oil | 427° | 190,000 | 166,000 | 12.5 | 50.0 | 415 | 55 |
| | 482° | 170,000 | 154,000 | 15.0 | 44.3 | 341 | 41 |
| | 538° | 142,000 | 126,000 | 20.0 | 57.8 | 321 | 43 |
| .............. | 593° | 127,500 | 115,000 | 22.0 | 62.3 | 285 | 36 |
| .............. | 649° | 117,000 | 99,000 | 23.0 | 64.7 | 255 | 37 |
| .............. | 704° | 115,000 | 69,000 | 24.0 | 56.0 | 255 | 35 |
| Heated to 845° quenched in water | 427° | 164,000 | 152,000 | 17.5 | 56.0 | 375 | 51 |
| | 482° | 160,000 | 147,500 | 15.5 | 53.9 | 341 | 48 |
| | 538° | 145,000 | 130,000 | 21.0 | 58.6 | 321 | 43 |
| .............. | 593° | 124,000 | 100,000 | 22.5 | 62.8 | 269 | 40 |
| .............. | 649° | 120,000 | 99,000 | 24.0 | 63.7 | 248 | 36 |
| .............. | 704° | 120,000 | 69,000 | 17.0 | 50.0 | 269 | 36 |

## SECTION V.

### VANADIUM STEELS.

**Simple Vanadium Steels** do not at present have the standing they formerly had, and the only reason for mentioning them here is to enable the reader to get an idea of the effects of vanadium alone, so that he can better understand the reasons for chrome vanadium steel, to be considered later. Since 1917 the Carnegie Steel Company has manufactured but one grade of vanadium steel, known as type "F," which is used as a flux in oxyacetylene, oxyhydrogen, and electric welding.

**Influence of Vanadium:** Unlike nickel and chromium, vanadium is an intense deoxidizing agent, being capable of carrying the cleansing of the steel beyond the point obtainable by manganese, or even silicon and aluminum. Thus, this element performs the double function of a curative and an alloying element. It is added to the steel, in the form of ferrovanadium, containing about 35% of the element, at the time of tapping, if the steel is being made by the open hearth process, and preferably after the other ladle additions to avoid undue wastage. Of the vanadium that is retained by the steel, only very small amounts, from .15% to .25%, are required to affect the physical properties of the steel. Like most of the alloying elements, it tends to give a finer and denser structure than that of carbon steel, and for the most part its action is similar to other alloying elements. But in some respects, at least, it presents characteristic phenomena. Thus, there are good reasons to believe that, when present even in the small amounts noted above, it is both dissolved in the ferrite, like nickel, and exists as a carbide or a double carbide in the cementite, like chromium. It has a powerful influence upon the transformation ranges, as is seen from the fact that while steels containing .2% carbon and .7% vanadium, or .8% carbon and .5% vanadium, are pearlitic, any increase of the vanadium content over these limits renders the steel cementitic as shown in the following diagram:

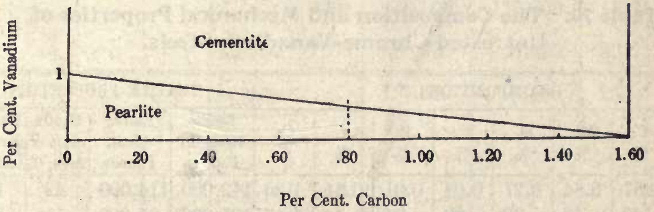

Fig. 122. Constitutional Diagram for Vanadium Steels.

As revealed by the static physical tests, the benefits from vanadium are somewhat similar to those for the pearlitic nickel steels, that is, it gives a combination of high elastic limit and ductility. With proper heat treatment, it is also said to resist shock, alternate stresses, wear and fatigue.

## SECTION VI.

### CHROME-VANADIUM STEELS.

**Effect of Combining Chromium and Vanadium:** In order that the influence of vanadium as indicated above may be realized to the fullest, the presence of another element as an intensifier is required. Just as chromium intensifies the influence of nickel, so does it also stimulate vanadium, but to a much greater degree, it is said, than with the former. Hence, though various combinations have been tried, such as vanadium-nickel, chrome-vanadium-nickel, etc., the tendency at present points to the general adoption of the one combination, chrome-vanadium.

**Properties and Uses of Chrome-Vanadium Steels:** The hot working of these steels presents no difficulties, the steel behaving in the press and rolls much like the higher carbon plain steels. In physical properties, they are similar to chrome-nickel steel except that their contraction of area for a given elastic limit is a little greater. They are also said to be more easily machined than chrome nickel steel and are more free from surface defects, such as scale-pits and seams. While some enthusiasts maintain that it is the steel best adapted to resist shock and fatigue, others hold that the chrome-nickel steel answers all requirements just as well. Perhaps the truth of the matter is that, while both steels are available for most purposes, there are limited fields in which one may excel the other and in which each has its own sphere of usefulness. Most of the chrome-vanadium steel made by the Carnegie Steel Company is used for driving axles and other forgings for locomotives, automobile springs and axles, compressed air flasks, torpedo tubes, and gun forgings. They are nearly always heat treated before being put into service, but in some automobiles the frames, and even part of the forgings and shafts, are made of the steel in its natural state. The composition and properties of three grades of this steel in the untreated condition are given herewith.

**Table 70. The Composition and Mechanical Properties of Untreated Chrome-Vanadium Steels.**

| | COMPOSITION | | | | | | | TENSILE PROPERTIES | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Grade No. | C. % | Mn. % | Si. % | S. % | P. % | V. % | Cr. % | Tensile Strength, Pounds | Elastic Limit, Pounds | Contraction of Area, % | Elongation in 2 Inches% |
| 1 | 0.57 | 0.84 | 0.27 | 0.04 | 0.01 | 0.31 | 1.36 | 142,000 | 114,000 | 42 | 14 |
| 2 | .46 | .48 | .20 | .03 | .01 | .14 | 1.17 | 125,000 | 95,000 | 55 | 20 |
| 3 | .18 | .32 | .18 | .03 | .01 | .20 | .74 | 65,000 | 47,200 | 62 | 23 |

Some idea of the general results obtained from heat treating the chrome vanadium steels and of the methods employed may be gained from the following table:

## Table 71. Physical Properties of Treated Chrome-Vanadium Steels. Tests made on Small Rolled Sections

| CHEMICAL COMPOSITION | | | | HEAT TREATMENT | | MINIMUM PHYSICAL RESULTS AFTER TREATMENT | | | |
|---|---|---|---|---|---|---|---|---|---|
| Carbon Per Cent. | Manganese, Per Cent. | Chromeium, Per Cent. | Vanadium, Per Cent. | Water Quenched, Deg. C. | Draw Deg. C. | Tensile Strength, Lbs. per Sq. In. | Elastic Limit, Lbs. per Sc. In. | Elogation in 2 in. Per Cent. | Reduction of Area, Per Cent. |
| * .19 | .49 | .96 | .23 | 850. | 749 | 101,400 | 91,200 | 27 | 69 |
| ... | ... | ... | ... | .... | 712 | 109,500 | 98,800 | 24 | 66 |
| ... | ... | ... | ... | .... | 675 | 121,200 | 113,100 | 22 | 66 |
| ... | ... | ... | ... | .... | 635 | 129,600 | 121,200 | 21 | 60 |
| ... | ... | ... | ... | .... | 596 | 136,000 | 125,700 | 20 | 60 |
| ... | ... | ... | ... | .... | 574 | 146,900 | 137,200 | 20 | 58 |
| * .25 | .30 | .85 | .14 | 850. | 748 | 88,640 | 78,960 | 29 | 77 |
| ... | ... | ... | ... | .... | 697 | 98,520 | 92,200 | 26 | 72 |
| ... | ... | ... | ... | . . . | 657 | 118,700 | 114,100 | 24 | 72 |
| ... | ... | ... | ... | . | 607 | 121,800 | 118,200 | 22 | 69 |
| ... | ... | ... | ... | ... | 574 | 132,400 | 125,800 | 20 | 64 |
| †.38 | .41 | .97 | .24 | 815 | 704 | 100,000 | 88,000 | 27 | 65 |
| ... | ... | ... | ... | .... | 649 | 118,000 | 101,000 | 23 | 60 |
| ... | ... | ... | ... | .... | 593 | 130,000 | 108,000 | 18 | 52 |
| ... | ... | ... | ... | .... | 538 | 130,000 | 108,000 | 16 | 50 |
| ... | ... | ... | ... | .... | 482 | 157,500 | 142,000 | 15 | 47 |
| ... | ... | ... | ... | .... | 427 | 177,500 | 155,000 | 11 | 36 |
| | | | | Oil Quenched | | | | | |
| ... | ... | ... | ... | 815 | 700 | 95,000 | 75,000 | 30 | 65 |
| ... | ... | ... | ... | .... | 650 | 117,000 | 98,000 | 20 | 57 |
| ... | ... | ... | ... | .... | 595 | 125,000 | 105,000 | 18 | 56 |
| ... | ... | ... | ... | .... | 540 | 133,000 | 113,000 | 18 | 50 |
| ... | ... | ... | ... | .... | 480 | 143,000 | 116,000 | 16 | 48 |
| ... | ... | ... | ... | .... | 430 | 149,000 | 120,000 | 15 | 49 |
| ... | ... | ... | ... | Annealed | 760 | 88,500 | 58,000 | 30 | 59 |
| ... | ... | ... | ... | As Rolled | ... | 127,500 | 96,500 | 20 | 48 |

*Silicon .05%. Phosphorus under .035%. Sulphur under .04%.

†Silicon .25%. Phosphorus .021%. Sulphur .041%. Tests on 1″ rounds.

# WORD INDEX