FUEL

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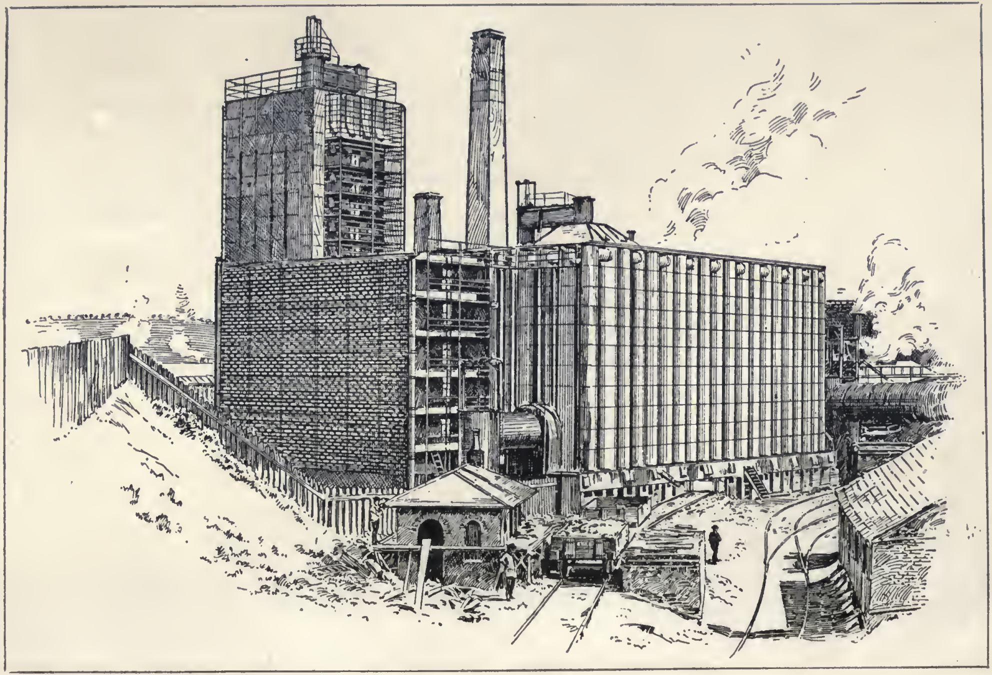

General View of the Alexander & M'Cosh Plant.

FUEL

AND

REFRACTORY MATERIALS

BY

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PREFACE.

THIS little book is intended to meet a want which the author has felt for many years, namely, that of a manual dealing concisely yet comprehensively with the subject of Fuel, and holding a place between such exhaustive treatises as those of Dr. Percy and Dr. Mills and Mr. Rowan and such brief outlines of the subject as may be found in manuals of Metallurgy.

The importance of a study of the subject, not only to the metallurgist but also to the engineer, can hardly be overestimated. Yet it has been very much neglected, and there are few books dealing with it at all completely in suitable compass. This book is intended mainly for the use of students, but the author has also kept in view the requirements of engineers and others who need information on the subject for practical purposes. For the convenience of these, British Thermal Units and Fahrenheit degrees have been used throughout, though Centigrade equivalents have almost always been given.

This is not the place to enter into a discussion of the best system of units, but as the British system—with all its theoretical absurdity—answers the purpose very well, and is still universally used in this country in practice, the writer of a technical manual is almost bound to adhere to it.

The author's thanks are due to very many friends for private information, and for drawings from which some of the illustrations are reproduced, as also to the councils of several scientific societies, the editors of technical journals, and firms of publishers, for permission to use illustrations from their respective publications. Every care has been taken that the source of these should be acknowledged in the proper place. The author has also to thank his assistant, Mr. John Buchanan, for much general help. That the book is not all that could be desired he is painfully aware, but he hopes that it will be of real use to those for whom it is intended, and that it may to some extent fill an existing void in technical literature.

GLASGOW.

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CHAPTER I.

COMBUSTION.

Combustion.—Heat is required in almost all metallurgical operations, and is always obtained directly or indirectly by the combustion of substances called fuels. A consideration of the phenomena of combustion and of the nature and methods of using fuel is therefore essential as an introduction to the study of metallurgy.

Chemical combination is almost invariably attended with the evolution of heat, and when this is sufficient to raise the combining bodies or the products of combination to the temperature at which they evolve light, combustion is said to take place. Combustion may therefore be defined as vigorous chemical combination, attended with the evolution of light.

In practice the combination is always between a combustible or fuel and the oxygen of the air, which is therefore said to support combustion.

Conditions which favour Combustion.—In order that combustion may begin, the fuel must be brought in contact with the air, at a suitable temperature; and in order that it may continue, this temperature must be kept up, a supply of oxygen must be maintained, and the products of combustion must be removed.

As a rule, the larger the surface of the combustible in contact with the air, the more readily will combustion take place, and as gases, by the mobility of their molecules, allow of the largest possible amount of contact, they, if combustible, usually burn very readily.

If a combustible gas be allowed to escape from a tube into the air at a temperature at which it will burn, combustion takes place with great facility; for as the gas comes into the air diffusion takes place, the gas molecules are brought into close contact with the oxygen molecules, and they combine, forming a zone of combustion surrounding a core of gas, and thus producing a flame.

If a combustible gas be thoroughly mixed with air and a light be applied, combustion takes place almost instantly through the whole mass, travelling very rapidly from particle to particle; heat is suddenly evolved, great expansion results, and an explosion of more or less violence takes place.

Liquids do not burn readily in mass, for the air cannot penetrate them, and there is therefore only contact at the, comparatively small, surface of the liquid. There are apparent exceptions to this, due to the fact that most liquids are volatile, and combination therefore takes place near the liquid surface, between the vapour and the air. If a combustible liquid be broken up into a fine spray by a steam or air jet, it will burn almost exactly as if it were a gas, and will form an explosive mixture with air.

Combustible solids usually burn readily when in pieces of such a size as to allow ready access of air, and at the same time expose a large surface of contact. If the lumps be too large the contact surface is too small and combustion is hindered, and if the substance be in a powder the air will be unable to penetrate, and therefore there will still only be a small surface of contact. If a finely-powdered solid fuel be projected at a high temperature into air, it burns very rapidly, almost exactly in the same way as a gas, and such a powder may even form an explosive mixture with air. It is quite certain that many colliery and other explosions, if not entirely due to, are at any rate very much intensified by the presence of coal or other combustible dust in the air.

Many examples of the influence of contact surface are familiar. A piece of charcoal of large size will burn readily, because being very porous air can find its way into it, and thus provide a large contact surface, while a large lump of anthracite, not being porous, will hardly burn at all. Paper and wood-shavings are employed to light a fire, though they have almost the same composition as the wood, because, owing to their thinness, they expose a large surface to the air, and ignite readily. These and such materials as light fabrics are very combustible, but books in which the paper leaves are pressed closely together, and bales of fabrics, are very difficultly combustible; and when a warehouse has been burned, whilst all the loose goods are destroyed, it is quite common to find bales of the same materials only singed on the outside. Heavy beams of wood make fireproof floors, and saw-dust or coal-dust thrown on a fire will often extinguish it.

Proportion of Combustible.—In order that combustion may take place the combustible and air must be present in—within certain limits—definite proportions. This is not so noticeable in the case of solid or liquid fuels, or of gas burned in a flame, because, owing to the circulation set up in the air, the proportions to some extent adjust themselves. It is, however, well seen in the case of mixtures of gases. If coal-gas and air be mixed in certain proportions a violently explosive mixture results; but there may be a large quantity of gas in the air, enough to be detected by the smell and to produce chemical and physiological effects, and yet the mixture will not explode on applying a light. The presence of a large quantity of inert matter in a fuel may much hinder or even prevent combustion, whilst the presence of a comparatively small quantity of carbon dioxide in the air will prevent it supporting combustion. Professor Clowes has recently shown that air which contains about 4 per cent of carbon dioxide, the oxygen being reduced by a like amount, will extinguish ordinary combustibles, such as candles or oil flames.[1] Marsh-gas

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[1] *J. S. C. I.*, vol. xiv. p. 346.

must be mixed with about at least ·75, and not more than 14·7 times its own volume of oxygen to form an explosive mixture.[1]

Temperature of Combustion.—For combustion to take place a certain temperature, varying with the nature of the combustible, is necessary. A mixture of hydrogen and oxygen in explosive proportions will remain inert for any length of time until a portion of the mixture is raised to about 1200° F. (650° C.), when ignition will at once take place. Coal-gas ignites in air at a bright red heat. Many of the metals are not acted on by dry oxygen at ordinary temperatures, but if they be heated to redness some of them burn, as in the case of magnesium, with great brilliance. On the other hand, phosphorus ignites at such a low temperature that for safety it is always kept under water or otherwise protected from contact with the air, and some substances have such affinity for oxygen that they take fire on coming in contact with it.

The temperature at which combustion can take place varies also with the condition of the combustible. Lead and iron can be obtained in such a fine state of division that they take fire spontaneously in air at ordinary temperatures.[2]

Continuous Combustion.—In some cases when a substance has been ignited it will continue to burn, in others it will go out as soon as the external source of heat is removed. This depends on the relationship which exists between the heat evolved by combustion and the temperature of ignition. If the heat evolved be sufficient to maintain the temperature above the ignition point the combustion will continue, if not it will cease.

Combustibles and Supporters of Combustion.—The fuel or substance which burns is usually called a combustible, and the oxygen of the air is called a supporter of combustion. These terms, though convenient, are not strictly correct, except in so far as they indicate an accident of position. Combustion is a mutual action in which both substances play

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[1] See *J. S. C. I.*, vol. xiii. p. 1155.

[2] These fine powders may be allotropic modifications of the metals.

an equal part, which being combustible and which supporter of combustion depending on circumstances. When a solid combines with a gas, the gas surrounds it, and is therefore regarded as a supporter of combustion. When a mixture of a combustible gas such as hydrogen, and air is exploded it is impossible to say that either is the combustible rather than the other; but when gas is burnt at a jet the flame is surrounded by the excess of air, which is therefore called a supporter of combustion. It is quite simple to arrange experiments so as to burn air in coal-gas or oxygen in hydrogen, and thus reverse their usual positions.

Complete and Incomplete Combustion.—All combustibles in common use are composed chiefly of carbon (C), usually combined with hydrogen (H), oxygen (O), and sometimes small quantities of other elements, but the carbon and hydrogen are always the valuable constituents.

When a combustible burns, the combustion may be either complete or incomplete. It is complete when all the combustible constituents are oxidized to their highest state of oxidation, and it is incomplete when any fuel is either left unconsumed, or passes away combined with less oxygen than the maximum with which it is capable of combining.

In the case of hydrogen, there is only one compound that can be formed—water, H_2O; and therefore, if the combustion be incomplete, some of the hydrogen must remain unconsumed.

In the case of carbon, the highest state of oxidation is carbon dioxide, CO_2; but there is also another oxide, carbon monoxide, CO, which contains, for the same amount of carbon, only one-half as much oxygen. When carbon is incompletely burned, therefore, either carbon may be left unconsumed, or carbon monoxide may be formed and pass away with the products of combustion. Both carbon dioxide and carbon monoxide are colourless gases, so that it is often not easy to decide whether combustion is complete or not.

The combustion of carbon commences at a comparatively low temperature; at about 752° F. (400° C.) the product is almost entirely carbon dioxide; as the temperature rises the rate of combustion increases, and the proportion of carbon monoxide formed increases till, at 1832° F. (1000° C.), the product is almost entirely this gas, which, if the air supply be sufficient, is rapidly burned to carbon dioxide. It is for this reason that carbon at low temperatures simply smoulders, whilst at very high temperatures it burns with a flame.

The combustion of hydrocarbons is much more complex. If the combustion be quite complete, the products are water and carbon dioxide; but if it be incomplete, what products will be formed depends on circumstances. Many hydrocarbons dissociate or split up into simpler hydrocarbons with separation of hydrogen, as, for instance, ethylene, $C_2 H_4$, which gives hydrogen and acetylene, $C_2 H_2$. The hydrogen burns to water, and the acetylene, partially escaping as such, imparts a most unpleasant odour to the products of combustion of incompletely-burnt hydrocarbon gases. The carbon will be burned to carbon dioxide, or a mixture of this and carbon monoxide. Under some conditions carbon may also be separated by dissociation in the solid form as soot.

Incomplete combustion of any kind always means considerable loss of heat.

Conditions of Complete Combustion.—In order to ensure complete combustion, three things are essential: the air supply must be sufficient, the air must be brought into intimate contact with the fuel, and the temperature must be kept up to ignition point until combustion is quite complete. Either insufficient air supply or too rapid cooling are the usual causes of incomplete combustion.

Flame.—Fuels burn in very different ways. Some, as, for instance, charcoal, at low temperatures, burn with a glow, evolving but little light; others, such as the metal magnesium, burn with a very brilliant light, but with no flame; others, like hydrogen, burn with a non-luminous flame; and lastly, some, like coal-gas, burn with a bright luminous flame. All combustible gases—and gases only—burn with a flame. There are some apparent exceptions to this, but they are only apparent; and whenever a solid or liquid seems to burn with a flame, it is because it is converted into gas either before or during combustion. "Flame is gas or vapour, the surface of contact of which with the atmospheric air is burning with the emission of light" (Percy). As combustion only takes place at the surface of contact, the flame must be hollow.

A simple flame is one in which there is only one product of combustion, and compound flames are those in which there are two or more. Almost all flames used in the arts are compound, the only examples of simple flames being those of hydrogen and carbon monoxide.

Fig. 1.—Gas Flame.

Simple Flame.—As an example of a simple flame a jet of hydrogen burning in air may be taken. As the hydrogen escapes from the jet it displaces the air and then diffuses into or mixes with it, and in the space where the gases mix combustion takes place. In the centre of the flame, therefore, will be a core of unburnt gas, outside will be the air, and between is the zone of combustion, or the flame.

Compound Flames.—With compound flames the reactions are much more complex, and it is often difficult to determine the exact changes which take place. The compound flames of most practical importance are those obtained by the combustion of various hydrocarbon gases. The fuel may be used in the form of gas from a burner, in the solid form as a candle, or in the liquid form as in the case of the burning oils. In the last two cases the combustible is drawn up by the wick by capillary attraction, gasified by the heat evolved during combustion, and the gas is burned; indeed candles and lamps may be regarded as combined gas producers and burners.

The structure of a compound flame is much the same as that of a simple one. In the centre is a core of unburnt gas, outside is the air, and between the two is the zone of combustion or the flame; but this zone is much more complex than in a simple flame, the combustion in the inner portions being usually incomplete.

Luminosity of Flame.—Most of the flames produced by hydrocarbons are more or less luminous, and the cause of this luminosity has given rise to a vast amount of discussion. Clearly the luminosity is not due to temperature alone, for a hydrogen flame, especially when formed by a mixture of hydrogen and oxygen, is intensely hot, but almost non-luminous; and it is quite possible to burn coal-gas, *e.g.* in the Bunsen burner, in such a way as to give a very hot, but non-luminous flame.

Davy suggested that the luminosity of flame was due to the separation of particles of solid carbon by incomplete combustion within the flame, which, being heated to intense whiteness, evolve light. This theory has been generally accepted, and in its favour many facts may be quoted:—

1. If solid matter be introduced into a hot, non-luminous flame light is evolved. A cylinder of lime, for instance, placed in an oxy-hydrogen flame gives the brilliant lime-light; a mantle of zirconia, suspended in a non-luminous Bunsen flame, is the Welsbach incandescent burner now so largely used for illumination purposes.

2. If a cold surface be held in an ordinary luminous flame

it becomes covered with a black deposit of solid carbon or soot.

3. Many substances which burn with the formation of solid products of combustion, *i.e.* magnesium or zinc, give an intense white light.

4. Luminous flames when examined with a spectroscope give a continuous spectrum.

5. When sunlight is reflected from hydrocarbon flames, it is polarized exactly in the same way as light reflected from solid carbon particles suspended in air.

On the other hand, Frankland contended that—at least in many cases—luminosity was due to the presence not of solid particles but of very dense gases or vapours. In support of this view it may be urged:

(1) That the luminosity of many flames is much increased under pressure, even a flame of hydrogen becoming luminous at high pressures, and that under reduced pressures the luminosity of ordinary luminous flames is much reduced.

(2) That many substances, *e.g.* phosphorus and arsenic, burn with a very luminous flame, though at the temperature of combustion the products are gaseous. Hydrogen produces water having a vapour density of 9 ($H = 1$), and the flame is non-luminous. Phosphorus produces phosphoric anhydride, P_2O_5, having a density of 72, and the flame is luminous; and arsenic, which produces arsenious oxide, As_4O_6—vapour density 198—also burns with a luminous flame. Therefore whether the flame will be luminous or not seems to depend on the density of the products of combustion.

(3) Soot is not pure carbon, but always contains hydrogen; and further, the fact that soot is deposited does not prove that it existed as such in the flame, as it may have been produced by the decomposition of dense hydrocarbons present.

(4) Gases under great pressure give much more complex spectra than under ordinary conditions, becoming banded, and ultimately tending to become continuous.

For these reasons it has been urged that luminosity of ordinary hydrocarbon flames may be due to the presence of very dense hydrocarbons, which under suitable conditions split up into carbon and hydrogen; or light hydrocarbons, which are then burned.

Profs. Lewes' and Smithells' Researches.—Professors V. B. Lewes and A. Smithells have recently investigated the question of the luminosity of coal-gas and similar flames, and whilst their work confirms the view that the luminosity is due to separated carbon particles, it has thrown fresh light on the reactions within the flame by which these are separated and the conditions under which luminosity can be produced.

Fig. 2.—Candle Flame.

Prof. Smithells describes[1] the structure of an ordinary luminous gas flame as consisting of four parts, which, for convenience, may be taken in the inverse order to that in which they are given by him:

(4) A dark inner core or region, consisting principally of unburned gas, mingled with some products of combustion which have diffused in from the surrounding parts (C).

(3) A yellow luminous portion, marking the region in which hydrocarbons are undergoing decomposition, the heat producing the dissociation being largely derived from the outer zones (A).

(2) An inner light-blue portion, visible at the base of the flame (D); and

(1) An outer sheath or mantle (B); these parts (1 and 2) corresponding to the outer and inner flame-cones of the Bunsen burner, and marking the region where the gas is undergoing combustion in presence of excess of air.

The explanation which has usually been given of the pheno-

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[1] *J. S. C. I.*, vol. x. p. 994.

mena of a flame is something like this: The gas coming into the air is at first mixed with only a very limited supply of air; the hydrocarbons cannot be completely burned, therefore the hydrogen burns, forming water, and the carbon is liberated and heated to incandescence by the heat evolved by the combustion of the hydrogen.

This description has been shown to be incorrect in at least two points: (1) the order of combustion, and (2) the source of the heat.

1. The hydrogen does not burn first, in the case of methane at any rate; the reaction being, as pointed out by Dalton, $CH_4 + 2O = CO + H_2O + 2H$—water, carbon monoxide and hydrogen being thus formed. But as carbon monoxide and water can mutually decompose each other, $CO + H_2O = CO_2 + 2H$, a further reaction may take place till the system attains equilibrium, the conditions of which, "according to Dixon, are expressed by the coefficient $\frac{CO \times H_2O}{CO_2 \times H_2} = 4$. This is subject to certain conditions of temperature and dilution."[1] These reactions, however, probably take place only to a small extent in the inner luminous part of the flame.

The source of the heat, therefore, is to be looked for not altogether in this partial combustion, but to transmission from the outer zone, where the temperature is very high.

2. The constituent of coal-gas to which the luminosity is mainly due is ethylene, C_2H_4, and perhaps some of its higher homologues. This at high temperatures (1472–1832° F.) splits up, yielding acetylene and methane, $3C_2H_4 = C_2H_2 + CH_4$, the acetylene then polymerizing into more complex hydrocarbons. At higher temperatures (above 2132° F.) no polymers are formed, but only acetylene, and at that temperature methane also dissociates, yielding acetylene and hydrogen, $2CH_4 = C_2H_2 + 2H$, so that all the hydrocarbons present will have split up into acetylene and hydrogen. At still higher temperatures acetylene itself splits up into carbon and hydrogen, this change taking place at about 2430° F.

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[1] *J. S. C. I.*, vol. x. p. 994.

The various hydrocarbons, as is well known, burn with very different degrees of luminosity. The flame of methane, CH_4, is very slightly luminous, that of ethylene, C_2H_4, is more luminous, whilst that of acetylene is intensely brilliant. That the luminosity is not due merely to the amount of carbon which the combustible contains is shown by the fact that in equal volumes of gas ethylene and acetylene contain the same weight of carbon, whilst benzene, C_6H_6, which burns with a luminosity much inferior to that of acetylene, contains, in the gaseous condition, three times as much carbon.

Neither is the luminosity due to temperature alone, as has been already shown.

It is now possible to form some idea of what actually takes place in a luminous gas flame. The inner blue core must be regarded as altogether unburned gas, for in it no combustion is taking place, but the temperature is rising, much heat being received by radiation from the outer zones of the flame, and the hydrocarbons being to some extent dissociated. As the temperature rises, dissociation takes place to a greater extent, till all the hydrocarbons, or nearly so, are converted into acetylene, and then the acetylene itself undergoes dissociation. This dissociation evolves heat, and at once brings the separated carbon up to vivid incandescence. As the products of these reactions pass outwards they are burned, the temperature therefore rising to the edge of the flame, and the combustion is completed in the very hot but feebly luminous mantle.

The luminosity, therefore, seems to depend not so much on the actual amount of carbon contained in the gas, or on the temperature, as on the readiness with which the gases present form acetylene or some other hydrocarbon which will similarly dissociate.

The luminosity of an acetylene flame is much reduced by the admixture of other gases, even though they themselves are combustible and evolve a large quantity of heat; as, for instance, hydrogen and carbon monoxide. The presence of such gases not only reduces the luminosity of the flame, but enormously raises its dissociation temperature, which is the point at which luminosity begins; thus—

Percentage of Acetylene.	Percentage of Hydrogen.	Temperature of Luminosity.
100	0	1436° F.
90	10	1645
80	20	1832
10	90	3092

Non-luminous Combustion.—If coal-gas, or any other gas which usually gives a luminous flame, be burnt in such a way that excess of oxygen penetrates into every part of the flame, and the acetylene burns before it can undergo dissociation, the flame will be non-luminous. Thus, if a gas flame be turned very low it is non-luminous, so also is candle flame when the wick is very short. The best means of obtaining a non-luminous flame is the Bunsen burner.

The Bunsen Burner.—This burner consists of a tube, usually about $\frac{3}{8}''$ in diameter and $3\frac{1}{2}''$ long, though the size may be varied within wide limits. Gas is admitted to the bottom of the tube, and just above the jet by which the gas enters are holes for the admission of air. The air mixes with the gas, and the mixture burns with a hot non-luminous flame.

"When a Bunsen burns under normal conditions it has a bluish central zone, but if the air supply be largely in excess of that required for non-luminous combustion, the flame becomes smaller and fiercer with the formation of a green central zone."[1]

The cause of the non-luminosity of the flame has usually been attributed to the more perfect combustion of the hydrocarbons due to the excess of oxygen in the interior of the flame. Professor Lewes has shown that this is not by any means necessarily the case, as nitrogen, carbon dioxide, and other inert gases also prevent luminosity, dilution, as already remarked, very much retarding the dissociation of acetylene, and therefore the production of luminosity. It is this dilution which is generally efficient in preventing luminosity in the

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[1] V. B. Lewes, *J.S.C.I.*, 1892, p. 231.

"Bunsen"; but if the air supply be too large then oxidation takes place rapidly, and the inner cone changes in appearance. The temperature of the flame is a little higher when the diluent is air than when it is nitrogen.

	Air.		Nitrogen.	
½ inch above burner, ...	54°C.	129°F.	30°C.	86°F.
1½ „ „ „	175	347	111	231
Tip of inner cone, ...	1090	1954	444	831
Centre of outer cone, ...	1533	2791	999	3630
Tip of outer cone, ...	1175	2147	1151	2104
Side of outer cone level with tip of inner cone, ...	1333	2334	1236	2275

If the supply of air be too small then a luminous point appears at the tip of the inner cone.

It does not follow that because the flame is non-luminous that combustion is complete; it frequently happens that the ingress of air has cooled the gases below ignition point, and not "inconsiderable portions of methane, carbon monoxide, acetylene, and even hydrogen escape unburnt", both from non-luminous and luminous flames.

Professor Lewes thus describes the structure of an ordinary luminous flame, and the actions which render it non-luminous in the Bunsen :—

"1. The inner zone, in which the temperature rises from a comparatively low point at the mouth of the burner to about 1000° C. (1832° F.) at the apex of the zone. In this portion of the flame various decompositions and interactions occur, which culminate in the conversion of the heavier hydrocarbons into acetylene, carbon monoxide being also produced.

"2. The luminous zone, in which the temperature ranges from 1000° C. (1832° F.) to 1300° C. (2372° F.). Here the acetylene formed in the inner zone becomes decomposed by heat with liberation of carbon, which at the moment of separation is heated to incandescence by the combustion of the carbon monoxide and hydrogen, thus giving luminosity to the flame.

"3. The extreme outer zone. In this part of the flame, the combustible gases meeting air, combustion takes place, making this the hottest part of the flame; but towards the outer part of this zone, combustion being practically completed, the cooling and diluting influence of the entering air renders a thin layer of the flame non-luminous, finally extinguishing it. This description of a luminous flame is of necessity far from complete."

"The various actions which tend to cause the loss of luminosity in a Bunsen burner may be summarized as follows:—

"1. The chemical activity of the atmospheric oxygen which causes loss of luminosity by burning up the hydrocarbons before they, in their diluted condition, can afford acetylene.

"2. The diluting action of the atmospheric nitrogen, which, by increasing the temperature necessary to bring about the partial decomposition of the hydrocarbons, prevents formation of acetylene, and in this way will by itself cause non-luminosity. In the normal Bunsen flame it acts by doing this until destruction of the hydrocarbons by oxidation has taken place.

"3. The cooling influence of the air introduced, which is able to add to the general result, although the cooling is less than the increase in temperature brought about by the oxidation due to the oxygen of the air.

"4. In a normal Bunsen flame the nitrogen and the oxygen are of about equal importance in bringing about non-luminosity; but if the quantity of air be increased oxidation becomes the principal factor, and the nitrogen practically ceases to exert any influence."

The amount of air supplied to the ordinary Bunsen is quite insufficient to support combustion without the air outside.

Propagation of Flame.—If a long glass tube, closed at one end, be taken and filled with an explosive mixture, say of coal-gas and air, and a light be applied at the open end, the flame will run down the tube with a definite and usually measurable speed, combustion not taking place instantaneously, but the ignition being transmitted from molecule to molecule at a comparatively slow rate. The speed at which the flame travels is called "the speed of propagation of the flame", and combustion thus taking place has been called an "explosion of the first order".

If, instead of a closed tube filled with gas, a tube open at both ends be used, and the mixture be made to flow through it —if the gas be lighted so that the ignition has to travel in the opposite direction to that in which the gas is flowing, its speed of transmission will be reduced, and will be the difference between the speed of propagation and the rate at which the gas is flowing, if the former be greater than the latter. If the rate of flow of the gas be very slightly in excess of the speed of propagation of the explosion, the flame will remain just at the mouth of the tube, and if it be much greater there will be a more or less long flame. Deville made a series of most interesting experiments on the rate of propagation of flames, and it is to his work, and that of Bunsen, that we owe most of our knowledge of the subject. He burnt a mixture of two volumes of carbon monoxide and one volume of oxygen—the gases therefore being almost exactly in the proportions required for complete combustion—at a jet having an area of 5 square millimetres. A flame 70 to 100 mm. high was formed, which consisted of two portions, an inner cold core, 10 mm. high, and an outer flame zone. It is obvious that in this case the inner core was not due to the absence of oxygen for combustion, but to the fact that the gases were travelling forward at such a speed that the ignition could not travel backwards, and ignite the mixture in the tube; and no doubt had the rate of flow been diminished the flame would have grown smaller and ultimately lighted back.

When a light is applied to an explosive mixture, an explosion usually takes place, the violence of which depends very largely on the speed at which the ignition is propagated. Bunsen found that in the case of a mixture of two volumes of hydrogen to one of oxygen the flame was propagated at the rate of 34 metres (37 yards) per second, the velocity being much reduced by the presence of inert gases. With marsh-gas (CH_4) and air the greatest velocity was ·56 metres (22 inches) per second, and this was attained with a mixture of one volume of marsh-gas to eight and a half volumes of air, a mixture which contains less oxygen than is required for complete combustion. A flame with a velocity of about four and a half metres (4·9 yards) per second will pass through the wire-gauze ordinarily used for safety-lamps.

Explosion.—If an explosion takes place its violence, as remarked above, depends on the rate at which the ignition is propagated. If it is in a closed vessel, vibrations may be set up which will enormously increase the speed of propagation of the ignition, sometimes bringing it up to many hundred feet per second. Explosions of this kind are called by Wright "explosions of the second order", and it is to them that most of the damage done by explosions is due.

Dissociation.—Referring back to Deville's flame with a mixture of carbon monoxide and oxygen, the fact that the ignition takes time to travel explains why the flame does not run back down the tube, but it does not explain why it spreads itself out into a flame of the ordinary form instead of at once igniting when it is released from the tube. This is due to dissociation.

The products in all ordinary cases of complete combustion are carbon dioxide and water, these being formed by the combustion of carbon, carbon monoxide, and hydrogen. If carbon dioxide and water be heated sufficiently strongly they are split up or dissociated into their constituents, water being broken up into hydrogen and oxygen, and carbon dioxide into carbon monoxide and oxygen. It is quite evident that if hydrogen and oxygen, or carbon monoxide and oxygen, be brought together at a temperature higher than that at which this dissociation takes place, combination will be impossible, and therefore there can be no combustion.

If a mixture of hydrogen and oxygen be inclosed in a strong vessel and exploded, from knowing the heat which will be evolved on combustion it is possible to calculate the pressure which the steam formed should exert. When the experiment is made it is always found that the pressure produced is less than the theoretical amount. The reason for this is: that combination is not instantaneous. As it progresses the temperature rises till the dissociation point is reached, when it can go no further, for this is the maximum temperature at which combustion is possible. As heat is lost by radiation, the gases cool and further combination takes place, and so on till combustion is complete.

Deville's experiment with the carbon monoxide and oxygen flame illustrates this very well. He carefully took the temperatures of all parts of the flame, and the results are recorded in the table.

Height above Burner.		Temperature.	Percentage of Gases.		
mm.	inches.		CO.	O.	CO_2.
67	2·638	Above melting point of silver, ...	·2	21·3	78·5
54	2·126	Melting point of gold,...	1·2	28·1	65·7
44	1·733	Commencing white-heat of platinum,......	10	20	70
35	1·378	White-heat of platinum,.......................	17·3	24·8	57·9
28	1·103	Strong white-heat of platinum,................	19·4	26·5	54·1
18	·708	Intense white-heat of platinum, ...	29	25·1	45·9
15	·591	Incipient fusion of platinum, ...	40	32·9	27·1
12	·472	Melting point of platinum,....................	47	36	17
10	·3937	Sparkling of melted platinum, ...	55·3	33·3	9·4
0	—	....	66·4	33·3	2·3

These figures at once explain the whole phenomena. As soon as combustion begins the temperature rises, and at the apex of the inner cone 10 mm. (·3937″) above the burner it has reached the melting point of platinum, which is above the dissociation point of carbon dioxide; so that no further combination is possible till the gases cool. This they do as they rise, and combustion again can take place, and this goes on till at the top of the flame all the carbon monoxide has disappeared and combustion is complete. From the very first the flame contains excess of oxygen, as some of the carbon monoxide is burned by the oxygen of the air. The length of the flame, therefore, is due to dissociation.

The dissociation temperature does not seem to be an absolutely fixed point, but varies with circumstances, it being in general raised by the presence of inert gases, and considerably lowered by contact with hot solids.

Dissociation plays a very important part in the practical applications of combustion.

Smoke.—Many hydrocarbon flames under certain conditions become smoky, the smoke being due to the separation of carbon under conditions which do not allow of its combustion. The cause of smoke is always imperfect combustion, due either to a deficient supply of air or to reduction of temperature. It is easy to see how the latter can be brought about. Air diffusing into a flame soon cools it; and if there be solid carbon in it this is likely to escape combustion. Smoke is always accompanied by other products of incomplete combustion.

Domestic Fire.—As an example of some of the causes which lead to smoke, an ordinary domestic fire may be considered. The whole question of the production and prevention of smoke will be discussed later.

Suppose, in the first instance, the fireplace to be full of glowing coke. As the air enters, combustion takes place and carbon dioxide is formed, $C + 2\,O = CO_2$, together with some carbon monoxide either formed directly, $C + O = CO$, or by the reduction of carbon dioxide, $CO_2 + C = 2\,CO$. This coming into the air at the top of the fire burns with its characteristic blue flame, carbon dioxide being produced, $CO + O = CO_2$, and the combustion is complete. If now the fire be made up in the usual way, by throwing cold coal on the surface, all is changed. The reactions at the lower part of the fire go on as before, but the carbon monoxide in passing through the coal is cooled below the point at which ignition can take place. At the same time the heat below begins to act on the coal, and destructive distillation commences, gases, and tarry matter which forms a dense yellow smoke, being given off; being cool, these do not ignite, but pass unburned to the chimney. After a time, as the heat penetrates, or perhaps when the fire is stirred, these gases ignite and burn with the bright flame characteristic of coal-gas. Smoke always indicates loss of fuel, not because of the actual carbon which it contains, but because the conditions which favour the production of smoke always favour the escape of combustible gases.

Heating by Contact or Radiation.—All fuels are burnt for heating purposes, and the methods of transferring the heat from the incandescent fuel to the object to be heated are of importance. Heat may be transferred in two ways—(1) by contact, as when a bar of iron is placed in a hot coke fire surrounded by the burning coke; (2) by radiation, as when an article is heated by being held in front of a fire. In many cases heating is necessarily by contact, as, for instance, in the blast-furnace, where the charge is heated by contact with the hot ascending gases, or with the hot fuel; and in others it is altogether by radiation, as when a room is heated by an ordinary house fire; and there are others in which both methods come into play.

Heating by contact of flame is not possible, except when the substance being heated is at a moderately high temperature. When flame is playing under a boiler it seems as if the heating were due to the actual contact of the flame. This is not the case, as the flame cannot touch the comparatively cold surface —kept cold by the contact of the water—but is separated from it by a thin cold layer, across which heat can only travel by radiation. Gases are, as a rule, very bad radiators; hence the Bunsen burner, though very satisfactory for heating small articles with which the flame can come into contact, is a very poor source of heat for heating by radiation, and when it is so used, as in many gas fires, iron, asbestos, or other material is fixed so as to be heated by the flame and made to radiate, usually at the cost of hindering complete combustion. Water vapour is a very good radiator, and its presence no doubt materially increases the radiating power of many non-luminous flames. Carbon is one of the best radiators, and therefore the luminous flame with its separated incandescent carbon is much more efficient for heating by radiation than the non-luminous Bunsen flame.

Amount of Air required for Combustion.—If we know the composition of a fuel it is an easy matter to calculate the amount of air which it requires for its complete combustion.

The air for all practical purposes may be taken as containing 21% by volume and 23% by weight of oxygen. When carbon burns to form carbon dioxide, 12 parts of carbon combine with 32 parts of oxygen to form 44 parts of carbon dioxide; so that 1 part of carbon will combine with 2·67 parts of oxygen to form 3·67 parts of carbon dioxide. If c be the percentage of carbon contained in a fuel which contains no other combustible material, then W, the weight of oxygen required for the combustion of one pound, will be

$$(1)\ \mathrm{W}=\frac{c\times 2{\cdot}67}{100}=c\times{\cdot}0267.$$

The weight of air A will be—

$$(2)\ \mathrm{A}=\frac{c\times 2{\cdot}67}{100}\times\frac{100}{23}=\frac{c\times 2{\cdot}67}{23}=c\times{\cdot}116.$$

One part of hydrogen when it burns combines with 8 parts of oxygen to form 9 parts of water, so that the weight W of oxygen required for the combustion of a fuel containing h per cent of hydrogen and no other combustible would be

$$(3)\ \mathrm{W}=\frac{h\times 8}{100},$$

and A, the weight of air,

$$(4)\ \mathrm{A}=\frac{h\times 8}{100}\times\frac{100}{23}=\frac{h\times 8}{23}=h\times{\cdot}348.$$

If the fuel contain $c\%$ of carbon and $h\%$ of hydrogen, then W, the weight of oxygen required for the combustion of one pound of the fuel, would be

$$(5)\ \mathrm{W}=\frac{c\times 2{\cdot}67+h\times 8}{100},$$

and the weight of air

$$(6)\ \mathrm{A}=c\times{\cdot}116+h\times{\cdot}348.$$

If the fuel contains $o\%$ of oxygen, then h must be taken to stand not for the total but for the available hydrogen $(h - \frac{1}{8}o)$.

As one cubic foot of air under the normal conditions of temperature and pressure may be taken to weigh ·0809 pound (566·3 grains), the volume of air required for combustion would be

$$(7)\ \mathrm{V} = \frac{c \times \cdot 116 + h \times \cdot 348}{\cdot 0809}.$$

If the air be at any other temperature and pressure, this must be taken into account.

The volume of a gas varies inversely as the pressure, so that if the normal pressure be taken as 29·922[1] inches of mercury (14·7 lbs. per square inch), the volume v under the normal pressure will become v' at the pressure p, and

$$(8)\ v' = \frac{v \times 29 \cdot 922}{p}.$$

If 760 mm. be taken as the standard, and the pressure p be measured in millimetres of mercury, the formula becomes

$$(8')\ v' = \frac{v \times 760}{p}.$$

The law according to which gases expand by heat may be expressed in various ways; probably the simplest is to say that the volume is proportional to the absolute temperature. The absolute zero is for the Fahrenheit scale -461, and for the Centigrade scale -273, so that any temperature t on the Fahrenheit scale will be $461 + t$ on the absolute scale in F. degrees, and t' on the Centigrade scale will be $273 + t'$ on the absolute scale in C. degrees.[2]

A volume of gas v at 32° F. would therefore become at t° F.

$$(9)\ v = \mathrm{V} \times \frac{461 + t}{461 + 32},\ \text{or}\ v = \mathrm{V}\ (1 + 0020276\ t).$$

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[1] For ordinary purposes 30 inches may be taken and 30 substituted for 29·922 in the equations.

[2] The absolute temperature may also be determined from thermo-dynamic principles, almost identically the same zero being obtained. (See Draper's *Heat*, p. 291.)

On the Centigrade scale the volumes would be

$$(9') \quad v = \mathrm{V} \times \frac{273 + t}{273} = \mathrm{V} \times (1 + {\cdot}003665\ t).$$

Combining the two equations, the volume of air v at 32° F., and 29·922 inches barometer, would become at t° F. and a pressure of p inches of mercury v', and

$$(10) \quad v' = \mathrm{V} \times \frac{29{\cdot}922}{p} \times \frac{461 + t}{493}$$

$$= \mathrm{V} \times \frac{29{\cdot}922 \times (461 + t)}{p \times 493}$$

$$\text{or } v' = \mathrm{V} \times \frac{29{\cdot}922}{p} \times (1 + 0020276\ t);$$

and for Centigrade degrees and millimetres

$$(10') \quad v' = \mathrm{V} \times \frac{760}{p} \times \frac{273 + t}{273},$$

$$\text{or} = \mathrm{V} \times \frac{760}{p} \times (1 + {\cdot}003665\ t).$$

The following formulæ are very similar to those given above, and are quite near enough for practical purposes. They are calculated for air containing an average amount of moisture.

c is the percentage of carbon in the fuel, and h the percentage of available hydrogen; A and V the weight and volume of air required as before; then

$$(11) \quad \mathrm{A} = {\cdot}12\ c + {\cdot}36\ h;$$

taking one cubic foot of such air as weighing ·07639 lb. the volume v would be

$$(12) \quad \mathrm{V} = 1{\cdot}57\ c + 4{\cdot}71\ h.$$

In practice excess of air must be used, so that the figures found as above must be multiplied by a factor. This will be, for gas furnaces about 1·5, for good grates about 2, and for defective grates 3 or more.

Products of Combustion.—The weight of the products of combustion will of course be the weight of the fuel consumed together with the weight of the air supplied; so that if W‴ is the weight of the products of combustion, A = the weight of air, F the weight of fuel, and a the weight of the non-combustible portion or ash, then

$$(13)\quad W''' = A + F - a.$$

The products of combustion will be carbon dioxide from the fuel, water partly formed by combustion of the hydrogen and partly moisture contained in the fuel, the nitrogen from the air and the excess of air; so that if c, h, o, and w be the percentages of carbon, hydrogen, oxygen, and water contained in the fuel, and E the excess of air, the weight of the products of combustion will be

$$(14)\quad W''' = \frac{c \times 3{\cdot}67 + h \times 9 + \{c \times 2{\cdot}67 + (h - \tfrac{1}{8}o)8\}\frac{79}{23} + w + E}{100}.$$

Heat carried away by Gases.—If it be required to know the heat carried away by the gases, this can be obtained by multiplying the products of combustion by their specific heats and the temperature at which they escape. All that is required in practice is to know the amount of heat lost which could be usefully employed, and as heat below 100° would be of no value no note need be taken of the latent heat of steam.

The heat carried away will be

$$(15)\quad H = \frac{\{3{\cdot}67c \times {\cdot}2387 + (9h + w) \times {\cdot}4805 + (2{\cdot}67 + 8h - \tfrac{1}{8}o) \times \frac{79}{23} \times {\cdot}2485 + E \times {\cdot}2375\}}{100} \times t;$$

and if it be required to take into account the latent heat of steam, then $\dfrac{(9h + w) \times 966}{100}$ must be added.

A simpler and sufficiently accurate method is to take the weight of the products of combustion by (13) and multiply this by ·25, which is about the average specific heat of the gases, and by the temperature, so that

$$(16)\quad H = (A + F - a){\cdot}25 \times t.$$

Volume of Products of Combustion.—When carbon burns to carbon dioxide the carbon dioxide formed occupies the same bulk as the oxygen consumed ($C + 2O = CO_2$).

When carbon monoxide is formed the volume is twice that of the oxygen $(C + \underset{\square}{O} = \underset{\square\square}{CO})$. When hydrogen burns, the volume of the gas is two-thirds of that of the component gases or twice that of the oxygen $(\underset{\square\square}{2H} + \underset{\square}{O} = \underset{\square\square}{H_2O})$. With gaseous fuels the reactions are more complex. Marsh-gas yields products which occupy the same volume as the gas burned and the oxygen used $(\underset{\square\square}{CH_4} + \underset{\begin{smallmatrix}\square\square\\\square\square\end{smallmatrix}}{4O} = \underset{\square\square}{CO_2} + \underset{\begin{smallmatrix}\square\square\\\square\square\end{smallmatrix}}{2H_2O})$. With ethylene, C_2H_4, the products also occupy the same volume as the gas and oxygen, and with acetylene three-quarters of the volume. In general, therefore, for solid fuels the volume of the products of combustion may be taken as being equal to that of the air supplied, and with gaseous fuels as being equal to the sum of the volumes of the gas and the air.

In either case allowance must be made for increased temperature by equations (10) or (10′).

CHAPTER II.

HEATING POWER OF FUELS.

Thermal Chemistry.—Combustion has been stated to be a case of chemical action, and as all chemical change is attended with evolution or absorption of heat according to perfectly definite laws, these laws must apply equally to combustion. A brief consideration of the laws of thermal chemistry is essential to a clear understanding of the way in which heat is obtained by combustion.

Unit of Heat.—As all thermo-chemical questions necessitate the measurement of quantities of heat, it is essential to select a unit in which the measurements can be made. The unit used for all practical purposes in this country is called the British Thermal Unit (B.T.U.), and is the amount of heat required to raise 1 pound of water 1° F. (from 60° F. to 61° F.).

The unit used in scientific work is the amount of heat required to raise one gramme of water 1° C. (from 0° C. to 1° C.), or sometimes the amount which is necessary to raise 1 kilogram of water 1° C.; this latter is usually called the *calorie*. Sometimes also the amount required to raise one pound of water 1° C. is taken; this may be called a Centigrade unit. The relationship between these units is easily calculated.[1]

Thermo-Chemical Notation.—Any chemical change which evolves heat is said to be exothermic and is indicated by the sign +, whilst one which absorbs heat is called endothermic and is indicated by the sign −. The thermal value of any reaction is the number of units of heat which would be evolved or absorbed by the formation of a molecular weight of the resulting compound. If the heat is measured in Centigrade units the weights are taken in grammes; if in B.T.U., the weights are taken in pounds. The formation of 36·5 pounds of hydrochloric acid by the combination of 1 pound of hydrogen with 35·5 pounds of chlorine evolves 39600 British Thermal Units, or if the weights be taken in grammes 22000 gramme Centigrade units (C.).

This may be written

$$H + Cl = H\,Cl^{*} \ (39600 +)\ \text{B.T.U.} \ (\mathit{22000} +)\ \mathit{C.}$$

It should not be written, as it often is, $H + Cl = H\,Cl + 39600$, as in that case the equation is incorrect, the two sides not balancing.

Laws of Thermal Chemistry.—There are three important laws of thermal-chemistry according to which thermal and chemical phenomena are connected.

1. The heat evolved or absorbed in any chemical change is fixed and definite, and depends only on the change. It is,

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[1] (1) To convert a quantity of heat in pound-Centigrade units into the corresponding value in B.T.U. ×1·8.

(2) To convert a quantity in B.T.U. into pound-Centigrade units × ·5.

(3) To convert a quantity given in (kilogramme) calories into B.T.U. × 3·968.

(4) To convert a quantity given in B.T.U. into (kilogramme) calories × ·252.

* Values in B.T.U. will be printed in ordinary type, those in gramme-Centigrade units in italics, which may be converted into calories by moving its point three to the left.

therefore, independent of any intermediate steps by which the change may be brought about; or to put it in another way, it depends only on the initial and final condition. Nernst[1] states the law: "The energy differences between two identical conditions of the system must be the same independently of the way by which the system is transferred from one condition to the other."

According to this law the heat evolution or absorption is as much an essential part of any reaction as the mass-change. One pound of hydrogen combining with 35·5 pounds of chlorine will necessarily form 36·5 pounds of hydrochloric acid, and also will necessarily evolve the 39600 B. T. units of heat.

In most cases the reaction is not merely the combination of two free elements, but is more complex, and in these the actual thermal result which can be measured will be the algebraic sum of the thermal values of the various parts of the reaction, and care must be taken not to overlook any of them, or any physical change which may accompany them, and which may itself evolve or absorb heat.

Thus, when hydrogen is made to combine with chlorine in solution, the heat of formation is 70767 + B.T.U., *39315 + C.*; but this is made up of two parts:—

Heat of combination of H, Cl, ...	39600 + B. T. U.	*22000 + C.*
Heat of solution of hydrochloric acid in water,	31167 +	*17315 +*
Total, ...	70767 +	*39315 +*

When hydrogen and iodine are made to combine, the result is still more striking. The two elements in the free state can be made to combine only with the greatest difficulty, their combination being attended with the absorption of heat, *i.e.* the reaction is endothermic. In solution, however, they combine readily enough:—

Heat of combination of H, I, ...	10872 – B. T. U.	*6040 – C.*
Heat of solution of hydriodic acid in water,	34578 +	*19210 +*
Total, ...	23566 +	*13170 +*

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[1] Palmer's translation of *Theoretical Chemistry*, p. 496.

2. "If a chemical change evolves (or absorbs) heat, the reverse change will absorb (or evolve) exactly the same quantity of heat." This is the law of reversibility.

To use the examples already given: If the formation of a pound-molecule of hydrochloric acid evolves 39600 units of heat, then to break up the molecule and liberate the elements will absorb exactly 39600 units. If the one reaction is exothermic, the other must be endothermic to the same amount.

In most reactions there are both combinations and decompositions, and the heat-value of both parts must be taken into account in obtaining the final result. If chlorine be brought in contact with hydrogen sulphide, decomposition at once takes place, and sulphur is separated, $H_2S + 2\,Cl = 2\,H\,Cl + S$. The reaction is thus made up of two parts: the formation of two molecules of hydrochloric acid, and the breaking up of one molecule of hydrogen sulphide:—

	B. T. U.	C.
Decomposition of one molecule of hydrogen sulphide,	8532 –	*4740* –
Formation of two molecules of hydrochloric acid, ...	79200 +	*44000* +
Resultant, ...	70668 +	*39260* +

Had the reaction taken place with a solution of hydrogen sulphide, the results would have been a little more complex:—

	B. T. U.	C.
Removal of a molecule of hydrogen sulphide from solution, ...	8209 –	*4560* –
Decomposition of hydrogen sulphide, ...	8532 –	*4740* –
Formation of two molecules of hydrochloric acid, ...	79200 +	*44000* +
Solution of the hydrochloric acid in water, ...	62334 +	*34630* +
Total heat change, ...	124795 +	*69330* +

3. Every chemical change effected without the intervention of extraneous force tends to produce those bodies the formation of which will evolve most heat.

This is called the law of greatest energy, and is of very great importance. From it it follows that reactions which are exothermic tend to take place more readily than those which are endothermic, and also that bodies which are formed with the absorption of heat are usually less stable than those in the formation of which heat is evolved.

Calorific Power.—The calorific power of any substance is the heat which is evolved by the union of one pound (or gramme) of it with oxygen. It is therefore the thermal value of the reaction which takes place divided by the weight of the substance taking part in it.

Combustion of Hydrogen.—The thermal value of the reaction $2H + O = H_2O$ is 123048 B. T. U., *68360 C.* As this is the combustion of two pounds (or grammes) of hydrogen, the calorific power will be half this, viz.:—

$$\text{C. P. of H} = 61524 \text{ B. T. U., } \mathit{34180\ C.}{}^{*}$$

liquid water being formed.

Combustion of Carbon.—The thermal value of the formation of a molecular weight of carbon dioxide from carbon and oxygen is $C + 2O = CO_2$, 174528 B.T.U., *96960 C.* As twelve parts of carbon take part in the reaction, the calorific power will be these numbers divided by 12:—

$$\text{C. P. of C to } (CO_2) = 14544 \text{ B. T. U., } \mathit{8080\ C.}$$

It will be remembered that carbon forms another, a lower oxide, carbon monoxide, CO, which contains, for the same amount of carbon, one-half the quantity of oxygen. What is the heat of formation of this oxide from carbon and oxygen? or, what comes to the same thing, what is the calorific power of carbon burning to carbon monoxide? This cannot be determined directly, for though carbon monoxide is readily formed from its elements, they cannot be made to combine under conditions suitable for the measurement of the heat evolved, but it can be ascertained indirectly by taking advantage of the known laws of thermal chemistry.

If twelve parts of carbon be burnt directly to carbon dioxide it evolves 174528 B.T.U., or *96960 C.* If twenty-eight parts of carbon monoxide (the weight which contains twelve parts

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* Thomsen's figures.

of carbon) be burnt to carbon dioxide it evolves 122328 + B. T. U., or *67960 C.*, and the heat of formation of the carbon monoxide must obviously be the difference between the two:—

$C + 2O = CO_2$	174528 + B. T. U.	*96960 + C.*
$CO + O = CO_2$	122328 +	*67960+*
$\therefore C + O =$	52200 +	*29000*

which, divided by 12, gives—

C. P. of C to C O = 4350 B. T. U., *2416 C.*

The figures may be stated in another way with the same result:—

	B.T.U.	C.
1 lb. carbon burning to carbon dioxide, ...	14544	*8080*
2⅓ lbs. carbon monoxide burning to carbon dioxide, ...	10194	*5664*
1 lb. of carbon burning to carbon monoxide, ...	4350	*2416*

It is important to notice that in this case the second atom of oxygen combining with the carbon evolves much more heat than the first. The probable reason for this is that in the free condition the carbon is solid, and in carbon monoxide it is gaseous, so that in the formation of carbon monoxide the carbon has been vaporized, and the difference between the heat evolved by the second atom of oxygen and that by the first may be taken as the latent heat of vaporization of the carbon, and this, therefore, can be calculated from the data given:—

	B. T. U.	C.
Heat evolved by combination of the second portion of oxygen with 1 lb. of carbon, ...	10194	*5664*
Heat evolved by combination of the first portion of oxygen with 1 lb. of carbon, ...	4350	*2416*
Latent heat of vaporization of carbon, ...	5844	*3248*

Evaporative Power (E. P.).—Engineers very frequently use a method of stating the heating power of fuels which has the advantage of being independent of any particular thermometric scale, and consists in stating the number of pounds of water at 212° which would be evaporated by the combustion of one pound of the fuel. Since the latent heat of vaporization of water is 537 Centigrade or 967 Fahrenheit units, the one is easily calculated to the other.

In the case of carbon,

$$(17)\ \text{E. P.} = \frac{14544\ \text{F.}}{967} = \frac{8080}{537} = 14{\cdot}9.$$

In the case of hydrogen the relationship is not quite so simple, for each pound of hydrogen forms nine pounds of water, which of course must be evaporated; and as by the conditions the products of combustion will remain in the gaseous condition, the latent heat of steam must be taken into account, and

$$(18)\ \text{E. P. of hydrogen} = \frac{61524}{967} - 9,\ \text{or}\ \frac{34180}{537} - 9 = 54.$$

Heat of Formation of Compounds.—When a compound is burned in oxygen or air, the heat evolved is not the same as would be evolved by the combustion of the same weight of the constituent elements in the free condition, but may be either greater or less, according as the body was formed with absorption or evolution of heat, and the difference will be the heat of formation of the body. It is easy to see why this must be the case, and, by taking advantage of it, it is possible to calculate the heat of formation of a compound. For example, what is the heat of formation of benzene, C_6H_6? Starting with $6 \times 12 = 72$ pounds of carbon and 6×1 pounds of hydrogen, and converting these into carbon dioxide and water, the heat evolution must be $174528 \times 6 = 1047168 + 61524 \times 6 = 369144 = 1416312$. *(96960 × 6) + (68360 × 3) = 785840.*

The formation of six molecules of carbon dioxide and three molecules of water from their elements must evolve this amount of heat, quite irrespective of the stages through which these combining bodies pass, so that, whatever be the nature of the changes, the algebraic sum must be 1416312. And if heat was evolved when the hydrogen and carbon entered into combination to form benzene, when the compound is burned, the heat of combustion will be less than 1416312 by the amount of heat evolved in the formation of the benzene; but if the benzene were formed with absorption of heat, then when it is burned it will evolve more heat than the elements would do in the free condition.

The heat of combustion of benzene, $C_6H_6 + 15\,O = 6\,CO_2 + 3\,H_2O$, is found to be 1418310 B. T. U. (*787950 C.*), so that

	B. T. U.	*C.*
Heat of combustion of benzene, ...	1418310	*787950*
Heat of combustion of carbon and hydrogen, ...	1416312	*786840*
Heat of formation of benzene, ...	1998 –	*1110 –*

So that, if we know the heat of formation of a body and the heat of combustion of its constituents, it is possible to calculate the amount of heat which it will evolve on combustion.

Calorific Power of Solid Fuels.—The heat of formation of the constituents of solid fuels is quite unknown, and therefore it is impossible to calculate exactly the heat of combustion of such fuels. It is usual, in calculating the calorific power of a fuel, to assume that the constituents give out in burning the same amount of heat that they would do if they were in the free condition. This assumption is manifestly incorrect, and the results given by it are sometimes higher and sometimes lower than those determined by experiment. Probably no two fuels have identical proximate composition, and therefore their heats of formation will vary, and may be either positive or negative. As the substances used for fuel are usually unstable, their heat of formation is small, and the results of these calculations for solid fuels are probably not far from the truth—at any rate, in most cases; but it must be remembered that, in the present state of knowledge, too implicit confidence must not be placed in them.

In the calculations which follow, c, h, o, s will stand for the percentage of carbon, hydrogen, oxygen, and sulphur contained in the fuel, and C. P. for the calorific power.

If the fuel contains no combustible but carbon the calculation is very simple.

$$(19)\quad \text{C. P.} = \frac{c \times 14544}{100} \text{ in B. T. U.}$$

$$(19')\quad \text{C. P.} = \frac{c \times 8080}{100} \text{ in C. units.}$$

If the fuel contains carbon and hydrogen the formula is also simple.

$$(20)\quad \text{C. P.} = \frac{c \times 14544 + h \times 61524}{100} \text{ in B. T. U.}$$

$$(20')\quad \text{C. P.} = \frac{c \times 8080 + h \times 34180}{100} \text{ in C.}$$

Since the calorific power of hydrogen is 4·265 times that of carbon these equations may be written—

$$(21)\quad \text{C. P.} = \frac{(c + 4{\cdot}265\,h) \times 14544}{100},$$

$$\text{or } (21')\quad \text{C. P.} = \frac{(c + 4{\cdot}265\,h) \times 8080}{100}.$$

Example.—Calculate the calorific power of a fuel containing 70% carbon and 30% hydrogen.

$$\text{By (18) C. P.} = \frac{70 \times 14544 + 30 \times 61524}{100} = 28637 \text{ B. T. U.},$$

$$\text{or by (18') C. P.} = \frac{70 \times 8080 + 30 \times 34180}{100} = 15910 \text{ C.}$$

Most fuels contain oxygen, and this has an important effect on the heating power. If the oxygen were free it would of course combine with the combustible matter just as the oxygen of the air does, and thus evolve heat; but it is not free, it is in combination with some of the other constituents of the fuel, and thus these, being oxidized, cannot burn again, and so are useless as fuel. The effect of the presence of oxygen in a fuel is therefore to render a certain portion of the carbon or hydrogen useless for combustion. It is not known in what form of combination the oxygen is present, but it is assumed to be present in combination with hydrogen in the proportions to form water, that is, eight parts of oxygen to one of hydrogen, so that the oxygen will render useless $\frac{1}{8}$ its own weight of hydrogen, and the hydrogen which is available for combustion will be $(h - \frac{1}{8}o)$; this therefore is called the **available hydrogen.**

The formula for calculating the calorific power of a fuel containing hydrogen and oxygen therefore is—

$$(22)\quad \text{C. P.} = \frac{c \times 14544 + (h - \frac{1}{8}\,o) \times 61524}{100} \text{ in B. T. U.,}$$

$$\text{or } (22')\ \text{C. P.} = \frac{c' \times 8080 + (h - \frac{1}{8}\,o) \times 34180}{100} \text{ in C.;}$$

or, using the form given in equations (21) and (21′),

$$(23)\quad \text{C. P.} = \frac{\{c + 4{\cdot}265\ (h - \frac{1}{8}\,o)\} \times 14544}{100} \text{ in B. T. U.}$$

$$(23')\quad \text{C. P.} = \frac{\{c' + 4{\cdot}265\ (h - \frac{1}{8}\,o)\} \times 8080}{100} \text{ in C.}$$

Example.—Find the calorific power of a fuel which contains 50% carbon, 26% hydrogen, and 24% oxygen,

$$\text{C. P.} = \frac{50 \times 14544 + (26 - \frac{24}{8}) \times 61524}{100}$$

$$= \frac{727200\ +\ 1415052}{100} = 21422 \text{ B. T. U.,}$$

$$\text{or C. P.} = \frac{50 \times 8080 + (26 - \frac{24}{8}) \times 34480}{100} = 12001 \text{ C.}$$

If sulphur be present, then $s \times 3996$ must be added to the numerator of the first fraction and $s \times 2220$ to the second.

Almost all fuels leave on combustion a non-combustible residue or ash. This has very little effect on the heating power, as it only absorbs a small quantity of heat in being heated to the resultant temperature. Similarly, nitrogen has no effect, nor has water, since it is assumed that the products of combustion are below 212° F. (100° C.), so that any heat absorbed when the water is converted into steam is given up again when it is condensed.

One inaccuracy in the calculations has been mentioned; there is still another due to uncertainty as to the thermal value of carbon burning to carbon dioxide. The figures given by Favre and Silberman are—

Wood charcoal, ...	8080 C.
Gas retort carbon, ...	8047 „
Native graphite, ...	7762 „
Diamond, ...	7770 „

The first value is always taken, though it is impossible to say in what form the carbon exists in fuels.

The number 61524 (34180) for the calorific power of hydrogen is based on the assumption that the hydrogen is gaseous, but in solid fuels it is in the solid condition, and therefore heat must be absorbed in melting it. Assuming that it combines with oxygen and then melts, the amount of heat absorbed would be 9 × 142 in B.T.U. and 9 × 80 in C. units, so that the calorific power of hydrogen in solid fuels would become—

(24) $\text{C. P.} = 61524 - (9 \times 142) = 59246$ B. T. U.

(24′) $\text{C. P.} = \mathit{34180} - (\mathit{9} \times \mathit{80}) = \mathit{33480}$ in C. units.

As the combined hydrogen is also present in the solid condition, the formulæ for solid fuels would become—

(25) $\text{C. P.} = \{c \times 14544 + (h - \frac{1}{8} o) \times 61524\} - 9\,h \times 142$ in B. T. U.,

(25′) or $\text{C. P.} = \{c \times \mathit{8080} + (h - \frac{1}{8} o) \times \mathit{34180}\} - \mathit{9}\,h \times \mathit{80}$ in C.

Calorific Power of Gaseous Fuels.—The value 8080 for carbon burning to carbon dioxide is for solid carbon, but in gaseous fuels the carbon is in the gaseous condition, and therefore will have a calorific power higher by the amount of heat which in the case of solid carbon is absorbed in gasifying it. That is—

(26) C. P. (gaseous carbon) $= 14544 + 5844 = 20388$ in B.T.U.

(26′) C. P. ,, $= \mathit{8080} + \mathit{3248} = \mathit{11328}$ in C.

It may be of interest to compare the numbers obtained by the usual formula with those obtained by direct experiment in the case of one or two of the well-known gases; this, as will be seen, is equivalent to calculating the heat of formation of the gases.

Marsh-gas (Methane), CH_4. This gas contains 75% of carbon and 25% of hydrogen, and its calorific power, as determined by experiment, is 24021 B. T. U., or *13345* C.

Calculated from the ordinary formula (20), taking the C. P. of carbon as 14544 (*8080*), the result is 26289 B. T. U., or *14605* C., which is somewhat higher than that found by experiment.

The result obtained by the correct formula for gases, taking the C. P. of carbon as 20388 B. T. U. *11368* C., is C. P. = 30670 B. T. U. or *17039* C., which is considerably higher than the experimental result; so that the heat value of the combination of ·75 lb. of carbon with ·25 lb. of hydrogen to form 1 lb. of marsh-gas is—

30670 − 24021 = 6649 + B. T. U.
17039 − 13345 = 3694 + C.

This may perhaps be better put—

	B. T. U.	C.
Heat of combustion of 12 lbs. of gaseous carbon,	244656	*136410*
,, ,, 4 ,, hydrogen,........	246095	*136720*
	490751	*273130*
,, ,, 16 ,, marsh-gas,.......	384336	*213280*
,, combination of 12 lbs. of gaseous carbon and 4 lbs. of hydrogen,..........	106415	*59850*

Ethylene, C_2H_4, is another important hydrocarbon which exists in coal-gas. When it burns, the reaction is $C_2H_4 + 6O = 2CO_2 + 2H_2O$, and its heat of combustion is 597600 B. T. U. (*332000* C.).

The figures for it stand—

	B. T. U.	C.
Heat of combustion of 24 lbs. of gaseous carbon,	489312	*272820*
,, ,, 4 ,, hydrogen,.......	246095	*136720*
	735407	*409540*
,, ,, 28 ,, ethylene,........	597600	*332000*
,, combination of 24 lbs. of gaseous carbon and 4 lbs. of hydrogen,..........	137807	*77540*

It is evident, therefore, that in the case of gases the heating power must be calculated not from that of the elements present, but from that of the constituent gases, any results obtained by calculating from the heat of formation of the products of combustion only being absolutely valueless.

Bodies with Negative Heat of Formation.—Bodies which have been formed with absorption of heat give on combustion more heat than the elements of which they are composed would do in the free condition, and the decomposition of such bodies without combustion will evolve heat. Among such may be mentioned acetylene, 86706 – B. T. U. (*48170* – C.) and carbon disulphide 46818 – B. T. U. (*26010* – C.).

The influence of the evolution of heat by the dissociation of acetylene on the luminosity of flames has already been discussed.

Calorific Power at Higher Temperatures.—The calorific power has been defined and used in the foregoing calculations in the form most convenient for comparison, though the conditions are not such as obtain in practice. It has been assumed that all the products of combustion are cooled below 212° F.; so that all steam is condensed to water and thus gives up its latent heat. In practice this is not the case; the temperature of the products of combustion is always above 212°, and therefore the steam remains as such. As the heating power which is important for practical purposes is that which can be actually obtained, the formula can be modified to give this.

Let the temperature of the products of combustion be 212° F. (100° C.), then the calorific power of hydrogen would be—

(27) $\text{C. P.}_{212^\circ} = 61524 - (966 \times 9) = 52830$ B. T. U.
(27′) $\text{C. P.}_{100^\circ} = \mathit{34180} - (\mathit{537} \times \mathit{9}) = \mathit{29347}$ C.

The higher the temperature of the products of combustion the less is the effective calorific power, because until the products of combustion are heated to this temperature, no heat can be utilized. The calorific power of hydrogen at t° Fahrenheit and t'° Centigrade becomes

(28) $\text{C. P.}_{t} = 61524 - \{(966 \times 9) + (\cdot 4805 \times 9 \times t)\}$ in B. T. U.
(28′) $\text{C. P.}_{t'} = \mathit{34180} - \{(\mathit{537} \times \mathit{9}) + (\mathit{\cdot 4805} \times t' \times \mathit{9})\}$ in C.

The carbon portion of the equation is not so much affected, and the calorific power for carbon at t° F. or t'° C. would become—

(29) $\text{C. P.} = 14544 - (3\cdot 67 \times \cdot 2163t)$
(29′) $\text{C. P.} = \mathit{8080} - (\mathit{3\cdot 67} \times \mathit{\cdot 2163}t')$,

and a fuel containing carbon, hydrogen, and oxygen—

$$(30)\ \text{C. P.} = \frac{[(c \times 14544) - 3{\cdot}67\, c \times {\cdot}2163 \times t] + 61524\,(h - \tfrac{1}{8}\, o) - (966 \times 9\, h) + ({\cdot}4805 \times 9\, h \times t)}{100} \text{ in B. T. U.}$$

$$\text{or } (30')\ \text{C. P.} = \frac{(c \times 8080) - (3{\cdot}67\, c \times {\cdot}2163 \times t) + 34180\,(h - \tfrac{1}{8}\, o) - (537 \times 9\, h) + ({\cdot}4805 \times 9\, h \times \text{C.})}{100} \text{ in C.}$$

Calorific Intensity (C. I.).—It is often not sufficient to know the actual heating power of a fuel, but it is required to know also the temperature which could be obtained by burning it, or, as it is called, the calorific intensity or pyrometric heating effect. The pyrometric effect and the absolute heating power are not identical or even proportional. It is obviously impossible to calculate a temperature attainable under any practicable conditions, since all the circumstances are too variable; but it is easy to calculate it under certain assumed conditions, which, though not attainable in practice, allow of the ready comparison of the heating power of various fuels. The calorific intensity may be defined as the rise of temperature which would be produced if one pound (or gramme) of the fuel were burnt in exactly the right quantity of oxygen under such conditions that combustion was perfect and there was no loss of heat.

The temperature would depend on the amount of heat liberated and on the nature and weight of the products of combustion which have to be heated. The products of combustion can readily be reduced to a water equivalent, *i.e.* a weight of water which would require the same amount of heat to raise it one degree. The water equivalent will always be W × S, where W is the weight of the product of combustion, and S its specific heat; and if C P be the amount of heat evolved, then T, the rise of temperature, will be—

$$(31)\ \text{T} = \frac{\text{C P}}{\text{W} \times \text{S}}.$$

If one pound of carbon at 32° F. (0° C.) be burned in 2·67 pounds of oxygen it will form 3·67 lbs. of carbon dioxide, which has a specific heat of ·2163; so that

$$(32)\quad \text{C. I.}_{\text{F}} = \frac{14544}{3{\cdot}67 \times {\cdot}2163} = \frac{14544}{{\cdot}7938} = 18297^{\circ}\ \text{F.}$$

This is rise of temperature, so that if, at starting, all the substances were at 32° the final temperature would be 18329° F.

In Centigrade degrees the figures would be—

$$(32')\quad \text{C. I.}_{\text{C}} = \frac{8080}{3{\cdot}67 \times {\cdot}2163} = \frac{8080}{{\cdot}7938} = 10178^{\circ}\ \text{C.}$$

The case of hydrogen is a little more complex. The heat evolution is 61524 B. T. U., which has to be distributed over 9 lbs. of steam produced by the combustion, having a specific heat of ·4805; but the 9 lbs. of water has to be converted into steam, which will absorb 966 × 9 units of heat, and thus reduce the heating power by that amount. But during the 180°, *i.e.* from 32° to 212°, the specific heat is not ·4805, but 1; so the difference must also be deducted, and the formula for the calorific intensity of hydrogen becomes—

$$(33)\quad \text{C.I.}_{\text{F}} = \frac{61524 - \{966 + (1 - {\cdot}4805)\,180\}\,9}{9 \times {\cdot}4805} = \frac{51988}{4{\cdot}3245} = 12021.$$

This is a rise of temperature, so that the temperature of products of combustion would be 12021 + 32 = 12053° F.

In Centigrade degrees—

$$(33')\quad \text{C.I.}_{\text{C}} = \frac{34180 - \{537 + (1 - {\cdot}4805)\,100\}\,9}{9 \times {\cdot}4805} = 6743.$$

These formulæ can readily be applied to fuels containing the ordinary constituents.

$$(34)\quad \text{C.I.}_{\text{F}} = \frac{c \times 14544 + (h - \tfrac{1}{8}o)\,61524 - \{966 + (1 - {\cdot}4805)\,100 \times (9h + w)\}}{(3{\cdot}66\,c \times {\cdot}263 + (9h + w) \times {\cdot}4805)\,100}$$

$$(34')\quad \text{C.I.} = \frac{c \times 8080 + (h - \tfrac{1}{8}o)\,34180 - \{537 + (1 - {\cdot}4805)\,100 \times (9h + w)\}}{(3{\cdot}66\,c \times {\cdot}263 + (9h + w) \times {\cdot}4805)\,100}$$

where, in addition to the symbols used above, *w* is the quantity of moisture in one pound of the fuel. To obtain the resulting temperature the figure obtained for the calorific intensity must be added to the temperature at which combustion takes place. To calculate the pyrometric heating power, using air in place of oxygen,

(35) $\{2{\cdot}66\,c + 8\,(h - \tfrac{1}{8}o)\} \times \dfrac{79}{23} \times {\cdot}244$ must be added to the denominator of the fraction, and if there be an excess of air e, then $e \times {\cdot}2377$ must also be added.

Comparison of Hydrogen and Carbon.—The calorific power and intensity of fuels are related, but they are not identical or proportional, as will be seen from the following tabular statement from Watts' Dictionary:—

	Weight.	Weight of Oxygen for Combustion.	Ratio.	Weight of Products.	Ratio.	Heat Units.		Ratio.	Thermal Effect.		Ratio.
Carbon, ...	1	2·67	1	3·67	1	8080	14544	1	10174	18297	1
Hydrogen,	1	8	3	9	2·4	34180	61524	4·265	6743	12021	·681

Other Formulæ.—Many other formulæ for calculating calorific power have been suggested. That of M. Cornu is very frequently used; it is—

$$\text{C.P.} = \frac{8080\,\text{C}' + 11368\,\text{C}'' + 34180\,\text{H}}{100},$$

where C′ is the percentage of fixed carbon, C″ the percentage of volatile carbon, and H the percentage of hydrogen in the fuel, and the results are given in Centigrade units.

This equation is readily modified to give the result in British units; it then becomes—

$$\text{C.P.} = \frac{14544\,\text{C}' + 20388\,\text{C}'' + 61524\,\text{H}}{100}.$$

The symbols having the same meaning as above.

The formulæ based on the calorific power of the elements necessitate for their use a knowledge of the ultimate composition of the fuel, and as this can only be obtained by a troublesome combustion analysis of the fuel, attempts have been made to devise formulæ which can be used with simpler data.

Of these, that due to Otto Gmelin is probably the best; it is:—

$$\text{C.P.} = [100 - (w + a)]\,80 - c \times 6w,$$

where w is the percentage of water, a the percentage of ash, and c a constant varying with the amount of water. The result is given in calories.

The value of c is, for coals with—

(1)	Water less than	3%			... ...	$c = 4$
(2)	„ between	3	and	4·5	... ...	$c = 6$
(3)	„ „	4·5	„	8·5	... ...	$c = 12$
(4)	„ „	8·5	„	12	... ...	$c = 10$
(5)	„ „	12	„	20	... ...	$c = 8$
(6)	„ „	20	„	28	... ...	$c = 6$
(7)	„ over	28%			... ...	$c = 4$

This formula seems to give good results with many coals.

It has been suggested by Welter that the heat evolved by a fuel when burned is proportional to the amount of oxygen with which it combines, and on this assumption (often called Welter's law) attempts have been made to estimate the heating power of a fuel by finding the amount of oxygen with which it will combine. The law is probably nearly correct where there is no change of state or chemical change except combination; but as in all solid fuels the solid carbon is converted into the gaseous form, the law breaks down and is of no practical use.

The amount of heat evolved per unit of oxygen taken up is:—

(1)	By combustion of hydrogen, ...	7705	B. T. U.	*4272 C.*
(2)	„ „ solid carbon to carbon dioxide,	6145	... „	*3414*
(3)	„ „ gaseous carbon,	7688	... „	*4271*

CHAPTER III.

FUELS—WOOD, PEAT, COAL.

Nature of Fuels.—All fuels in common use consist mainly of carbon and hydrogen, and all, with perhaps the exception of mineral oils and natural gas, are of vegetable origin.

Classification of Fuels.—The following classification of fuels will answer every purpose:—

- I. Solid fuels.
    - (*a*) Natural.
        - (1) Wood.
        - (2) Peat.
        - (3) Coal.
    - (*b*) Prepared.
        - (1) Charcoal.
        - (2) Peat charcoal.
        - (3) Coke.
        - (4) Briquettes.
- II. Liquid fuel.
    - (*a*) Natural.
        - Natural oils.
    - (*b*) Prepared.
        - Distilled oils.
- III. Gaseous fuel.
    - (*a*) Natural.
        - Natural gas.
    - (*b*) Prepared.
        - (1) Coal-gas.
        - (2) Producer-gas.
        - (3) Water-gas.
        - (4) Oil-gas.

Wood.—Wood may be regarded as the natural fuel of man: certainly it was the first, and for very many ages the only one, with which he was acquainted. It is still used in some minor operations, but has been abandoned for all metallurgical processes, except in regions where other forms of fuel are dear or unobtainable.

Wood is the more or less hardened vegetable tissue of trees. The stems and larger branches are called simply wood, while the smaller branches and all the wood of bushes and small trees is known as brushwood.

In the early days of its growth every plant is soft and herbaceous, but in time, in the case of those that live several years, the soft cells and tissues become hardened or filled up by the deposition of woody matter, thus converting the herbaceous plant into wood. As the plant grows, the older cells become more and more filled up, till after a time they cease to perform their functions, and may even decay without impairing the vitality of the tree. The hard centre of the tree is often called "heart-wood", whilst the younger and outer portion is "green or sap wood". Under the bark there is a layer of living and growing cells, by means of which fresh wood is formed and the tree increases in size.

The principal constituent of wood is cellulose—a substance which is seen very nearly pure in white cotton fibre—which has the formula $C_6H_{10}O_5$, and contains 44·44% carbon, 6·17% hydrogen, and 49·39% oxygen; the composition being the same whatever is the nature of the plant from which it is taken.

Composition of Wood.—The materials deposited in the cells as the tree grows vary in composition, but on the whole they are richer in carbon and hydrogen than cellulose, so that though pure cellulose contains no available hydrogen, wood always contains a small quantity.

The following analyses will give a sufficient idea of the composition of wood. The figures in the first column may be taken as an average; those in the other three columns are actual analyses, and are taken from Percy's *Metallurgy*, vol. i.:—

	Average.	Oak, 120 years.	Birch, 60 years.	Willow.
Carbon,	50	50·97	50·59	51·75
Hydrogen,	6	6·02	6·21	6·19
Oxygen,	41	41·96	42·16	41·06
Nitrogen,	1	1·27	1·01	·98
Ash,	2	1·93	2·10	3·67

Some plants and parts of plants are exceptionally rich in carbon and hydrogen, as, for instance, the spores of club-moss, which contain about,

Carbon, ...	61·5
Hydrogen, ...	8·4
Oxygen and nitrogen, ...	27·7
Ash, ...	2·4

Water in Wood.—Wood always contains a considerable quantity of water. In the growing condition the cells and vessels are filled with the sap fluids on the circulation of which the growth of the plant depends. Freshly felled wood contains 50 per cent or more of water—the amount varying with the kind of tree, the part of the tree, the age, and the season of felling. The young wood, branches, and leaves contain more than the stem; and the older the wood the less water it usually contains. The amount is greatest in spring, when growth is active, and least in winter. When a tree is felled and exposed to the air it loses water, and as the bark hinders drying it is usually removed, or the tree is "barked". After a few weeks' exposure, under cover, it loses as much water as it will do under the circumstances, and in this condition it is said to be "air-dried", but still retains 15 to 25 per cent of moisture. The following may be taken as the average composition of air-dried wood:—

Carbon, ...	40
Hydrogen, ...	4·8
Oxygen, ...	32·8
Nitrogen, ...	·8
Ash, ...	1·6
Moisture, ...	20·0
	100·0

Distillation of Wood.—When wood is heated in a closed vessel water and volatile matters are expelled, and a residue of charcoal is left, which consists of pure carbon and ash.

The following may be taken as an average result:—

Volatile,...	73%
Charcoal,	27%
Fixed carbon,	25%
Ash,	2%

Ash of Wood.—The ash which is left in burning away all the combustible portion of wood consists of the inorganic matters which were present. These constituents are not accidental, but are a necessary part of the plant; each plant containing the ash constituents in more or less definite proportions. The constituents of the ash are principally in the form of oxides and carbonates, depending to some extent on the temperature at which the wood was burned. This gives no clue to the way in which the elements were combined in the wood, since all organic compounds of the metals give oxides or carbonates on combustion. The ash is usually white, and consists chiefly of carbonates, potash, and lime, with smaller quantities of soda, magnesium, oxide of iron, alumina, and silica, the amount of the last-named varying much with the nature of the plant. The composition of wood ash is of no metallurgical importance.

Specific Gravity of Wood.—Wood floats on water, and bulk for bulk is therefore lighter. This is due to the fact that wood is very porous, and that the spaces are filled with air. If the air be removed and replaced by water, as when the wood becomes water-logged by long soaking, then the wood becomes heavier than water and sinks. The specific gravity of wood including the air-spaces varies from ·54 to over 1. Excluding air-spaces the specific gravity is about 1·5.

Wood as a Fuel.—Wood is not a good fuel. When air-dried it contains a large quantity of water, which has to be evaporated by the heat of combustion. It contains a large quantity of combined, but very little available hydrogen, so that its calorific power is low. Dry wood has only a calorific power of about 7000 B.T.U., and when air-dried only about 5600 B.T.U. The calorific intensity is also low.

Many attempts have been made to estimate the relative value of the various woods as fuel. The figures given by O. Pictet are:—

Lime (taken as unity), ...	1
Scotch fir, elm, aspen, ...	·98
Willow, horse-chestnut, larch, ...	·97
Maple, ...	·96
Black poplar, ...	·95
Alder, birch, hornbeam, oak, ...	·94
Ash, ...	·92

The heating power of the soft woods is therefore as great as that of the harder woods.

Wood is very light and bulky; it kindles easily, and burns with a long, luminous, often smoky flame. Long soaking in water seems to diminish the specific gravity and heating power of the wood, but there is little, if any, difference detectable in the composition.

Any vegetable matter that is sufficiently abundant and cheap may be used as a fuel under suitable conditions. Spent tan, straw, and many other substances have been successfully used. Dry straw has a calorific power of about 6300 B.T.U.

Peat.—Under certain conditions of moisture and temperature, various low forms of vegetable life flourish luxuriantly, and as they die down their remains accumulate faster than they decay, so that each generation helps to form the soil on which the next generation grows. In this way there gradually collects a mass of decaying vegetable matter, which may accumulate to a great thickness, forming beds of peat. These peat-mosses or peat-bogs are produced mainly in moist districts in temperate climates, sometimes occupying low-lying river-valleys, at others depressions in table-lands or among hills.

In this country the peat is composed almost entirely of the remains of mosses, those of the genus Sphagnum being far the most abundant. But in other countries these are sometimes quite absent, and therefore the peat is made up of the remains of other forms of plants.

As the plant-remains accumulate by growth and decay, it follows that the most recent peat must be at the top and the oldest at the bottom. The top layers will consist of the tangled roots and stems of the plants, only slightly decayed, so that the separate plants can be distinctly made out. It is usually light-brown in colour and of low specific gravity. Lower down it will be darker in colour and denser, the separate plants being less readily distinguishable, and at the greatest depth it may have passed into a nearly black, compact mass, in which all trace of the separate plants of which it is composed is lost.

Owing to the way in which the peat has been formed, it is usually very wet, often containing, when freshly got, as much as 80 per cent of moisture, and even after thorough air-drying it will usually contain 10 or 15 per cent.

Composition of Peat.—The following analyses of peat, from Percy's *Metallurgy*, may be taken as examples, but it must be remembered that samples from different beds in the same district, or even from different parts of the same bed, may vary so very much in composition that it is quite impossible to give anything like an average composition:—

	Kilbeggan.	Devonshire.	Philipstown, Ireland.	Abbeville, France.
Carbon,	61·04	54·02	57·53	57·03
Hydrogen,	6·07	5·21	6·83	5·63
Oxygen,	30·46	28·18	32·23	29·55
Nitrogen,		2·30	1·42	2·21
Ash,	1·83	9·73	1·99	5·58

A sample of Wicklow peat (dry) gave—

Volatile,	71·6
Coke,	28·4
Fixed carbon,	27·17
Ash,	1·23

Ash of Peat.—The amount of ash from peat is often very large; the tangled mass of roots and stems acts as an efficient filter, and retains much of the solid matter which the water carries in suspension. The ash, therefore, consists in many cases only to a very small extent of the remains of the inorganic matter in the plants from which the peat was formed, and its composition is different from that of wood. Alkalies are usually lower, and oxide of iron and earthy materials are much higher in amount; sulphates are often present in considerable quantity; and sometimes metallic compounds in such quantity as to be of value for the extraction of the metal they contain. Peat is often so impregnated with iron as to constitute a bog-iron ore; in Anglesea some of the peat contains so much copper that the ash yields about three per cent of the metal; while in other cases considerable quantities of iron pyrites have been found.

Density of Peat.—Peat varies much in density. It may be as light as ·25 or as heavy as 1·4. According to Sir Robert Kane:

1 cubic yard of light peat (as used for domestic burning) weighs....	500 lbs.
1 cubic yard of good peat weighs....	900 „
1 „ „ densest „	1100 „

Cutting and Preparing Peat.—For domestic use, where peat is employed as fuel, it usually undergoes no preparation except air-drying. It is cut from the moss by means of hand cutters in rectangular blocks, and these are allowed to dry in the air under cover till they are dry enough for use. Many attempts have been made to prepare a good fuel for manufacturing purposes from peat, but hitherto without much success. With this object the peat is first cut either by hand, or, better, by machinery—of which many kinds have been devised; it is then usually shredded or pulped, stones, pieces of wood, and anything else which will not pulp being separated, and the pulp is pressed into blocks under great pressure—these being often perforated to allow escape of moisture—and dried at a moderate temperature in air or superheated steam. As a rule, when fuel of fair quality has thus been made, the cost has been too great to allow it to come into extended use.

Peat as Fuel.—Peat is not a good fuel. It contains too much water, very often too much ash—and this usually of an objectionable kind. It contains very little available hydrogen, and has a very low calorific power, about 5000 B.T.U. or less, and its calorific intensity is also low. The evaporative power of dry peat may be taken as about 5·5, that of peat in its ordinary condition as 4·5, so that weight for weight its heating power is not more than half that of coal, whilst bulk for bulk it is much less. Peat has, therefore, all the defects of wood with the addition of the high ash, and as it burns it crumbles down, the residue or coke having no cohesive power whatever. The pressed blocks also have this defect, and are usually so soft that they will not bear handling.

Coal.—This is now the only important fuel, and practically all the energy required for metallurgical and manufacturing purposes is obtained directly or indirectly by its combustion, except in the localities where natural gas or oil is available. Common and well known as coal is, it is extremely difficult if not impossible to give a satisfactory definition; that is, one which, while including all varieties of coal, shall exclude all other substances. This was well shown in the Torbanehill case tried in Edinburgh in 1853, with the object of determining whether a certain mineral, torbanite or Torbanehill mineral, was or was not a coal. It was only after a lengthy trial, in which a great number of scientific witnesses were examined on both sides, that the substance in question was decided to be a coal.

The best definition of coal which has yet been framed is that due to Dr. Percy: "Coal is a solid stratified mineral substance, black or brown in colour, and of such a nature that it can be economically burned in furnaces or grates".

Exception may be taken to this because it makes the definition of coal depend on whether or no it can be economically used, and therefore to some extent on the nature of the grate; but it must be remembered that for practical purposes coal is only required for burning, and therefore the definition is quite sufficiently accurate.

Another definition which has been suggested is, "any mineral substance used as fuel which is mainly made up of the remains of plants".

Geology of Coal.—Coal is made up almost entirely of matter derived from plants. The plants lived in an age very much more remote than that in which the oldest peat was formed, and therefore their remains have undergone very much greater changes in composition and physical properties. So great has been the transformation, indeed, that composition alone would not be sufficient to prove the vegetable origin of coal. All the ordinary coals were formed *in situ*, the plants living and dying on the spots where the coal produced from them is now found. During the period when the British coal-measures were being formed, the whole of central England, Wales, Ireland, and part of Scotland, and part of the south of England, was covered with vast forests, was indeed probably made up of "broad swampy tree-covered flats", on which flourished a most luxuriant vegetation consisting not only of small plants like those of peat-mosses, but also of large trees, all, however, belonging to comparatively low forms of vegetable life allied to the living ferns, mosses, club-mosses, and horse-tails. Here the plants lived, shed their leaves and spores, and ultimately died; a mass of vegetable matter thus accumulating, and in time acquiring great thickness. The dead vegetable matter gradually underwent decay, the less stable portions going first, and those more stable—such as the bark and spores—resisting the decomposing agencies more powerfully. Gradually and very slowly the land then subsided, and at last the sea washed up over the morass, depositing layers of mud which afterwards became hardened into shale and sandstone. So gradually did this change take place that the soft mass of vegetable matter was not disturbed, many of the tree stumps remaining standing, and becoming embedded in the mud to be afterwards replaced by stone, the cast retaining the form of the tree. After the lapse of further ages the land ceased to sink, and again began to rise, the deposit became once more surface, trees sprang up, sending their roots down into the underclay and their stems up into the air, and once more an accumulation of vegetable matter commenced. In many instances this alternation was repeated a large number of times, giving rise to many layers of vegetable matter separated by beds of shale or sandstone, or in some cases, where the submergence had been greater, even limestone. In some places the land condition was more permanent than in others, and here beds of coal of greater thickness accumulated.

As to the time taken by the formation of these deposits it is impossible to form even the vaguest conception—it was a very long time, and that is all that can be said. In some cases the thickness of a bed of coal representing a distinct period of growth may be less than an inch, in others it may be many yards; so also the interbedded shales, &c., may be very thin or may attain great thickness.

After the formation of our chief coal-beds conditions underwent a more permanent change; the land sank again beneath the sea, and the regions where the luxuriant vegetation of the coal forests had flourished became sea-bottom, upon which beds of limestone, sandstone, &c., were deposited. Then other changes took place. The rocks were upheaved and broken, parts being thrown above the surface of the sea. Denudation at once commenced by the action of water and air, the rocks exposed were washed away and carried into the sea, the remains of them helping to form fresh beds. Thus what had before been continuous deposits became broken up into the series of isolated coal basins as we have them now, though in many cases they have been since covered by other deposits. The arrangement of the deposits is not the same in all localities. "The remarkable small scattered coal basins of France and central Germany were probably from the first isolated areas of deposit, though they have suffered, in some cases very greatly, from subsequent plication and denudation. In Russia, and still more in China and western North America, carboniferous rocks cover thousands of square miles in horizontal or only very gently undulating sheets."[1]

It must not be supposed that all coal is of exactly the same age, or that the conditions of its deposition were in operation at all places at the same time. When, for instance, much of

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[1] Geikie, *Text-Book of Geology*, p. 804.

England and Ireland was at the bottom of the sea during the carboniferous limestone period, coal-beds were being formed in Lanarkshire.

There is another variety of coal formed at about the same period as the ordinary coal, the origin of which is slightly different. This is the cannel coal, which consists of coaly matter often more or less intimately mixed with clay or shale. This coal "always occurs in basin-shaped patches thinning away to nothing on all sides",[1] and frequently merging into mere carboniferous shale, and it often contains fossil fishes. Cannel coal has probably been formed from vegetable matter drifted down the streams into ponds or lakes; this matter being mixed with other sediment, and ultimately undergoing decay till it was reduced to the condition of mere pulp. As the mud would tend to deposit first, near the mouths of the streams these would be carbonaceous shales; and, as the distance increased, the substances held in suspension by the water would gradually contain less mud and more vegetable matter, till ultimately the former would cease and the deposit become a mass of vegetable pulp.

Coal-beds occur in various parts of the world and, though as indicated above they are of various geological ages, they all belong to a very remote past. Wherever in any place there was a very luxuriant vegetation for a long period, followed by a time of depression, during which the sea flowed over the land and by depositing mud protected the vegetable matter from complete decay, beds of coaly matter might be formed. Some beds belong to very much more recent periods than the true coals.

Structure of Coal.—The vegetable matter of which coal is composed has undergone such complete mineralization that by the eye no trace of its vegetable structure can be seen. If ordinary coal be examined it is found "that it splits most easily in three directions nearly at right angles to one another, so that it comes away in rude cubical masses. Two of these planes are roughly at right angles to the planes of bedding of

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[1] *Coal*, edited by Prof. Thorpe, p. 30.

the rocks among which the coal occurs. The faces of the block on these sides are smooth and shining, and do not soil the fingers. One of the faces called the bord or cleat is very marked, the other called the end is less sharply defined. The third direction in which the coal naturally breaks is parallel to the bedding of the rocks above and beneath it; the planes of division in this direction are dull and greasy to the touch, owing to a thin layer or numerous patches of a dark black sooty substance which looks like charcoal, and is called mineral charcoal or mother of coal."[1]

"Thus coal may be said, speaking broadly, to be composed of two constituents: firstly mineral charcoal, and secondly coal proper. The nature of the mineral charcoal has long since been determined. Its structure shows it to consist of the remains of stems and leaves of plants reduced to a little more than their carbon. Again, some of the coal is made up of the crushed and flattened bark or outer coat of the stems of plants, the inner wood of which has completely decayed away."[2] A considerable proportion of the coal is made up of material, vegetable, it is true, but certainly not the remains of the stems or leaves of plants, and it is now pretty clearly made out that it is composed of the remains of a vast number of spores of a plant allied to the Lepidodendron. It must be remembered that the great trees of the coal period all belonged to the cryptogams or non-flowering plants which are propagated by means of spores.

When ordinary coal is ground into plates so thin that they become translucent and these are examined by means of a microscope by transmitted light, the coal is found to be composed of two parts, a yellowish translucent mass, and a dark opaque mass, and the yellowish mass is seen to be made up of small sac-like bodies which are the spores. Many coals seem to be almost entirely made up of spores, sometimes contained in sporangia, and the opaque matter is probably to a large extent also masses of spores which have undergone further mineralization. Coals which burn with a flame usually

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[1] *Ccal*, edited by Prof. Thorpe, p. 17.

[2] Huxley, *Collected Works*, vol. viii. p. 141.

contain a large amount of spore matter. Spores of cryptogamous plants are of a very highly resinous nature, and therefore would probably resist the decomposing action of water and air far better than ordinary wood, and they contain a large amount of free hydrogen, and thus would be likely to burn with a flame.

As metamorphosis goes on, the coal changes its character, the quantity of black opaque matter increases until in anthracite this is in such large proportion that it is impossible to get a translucent section at all. The black matter is probably only altered spore-matter, though Prof. Williamson regards it as altered "mother of coal".

"Professor Huxley states that all the coals he has examined agree more or less closely in this ultimate structure, spores are always present, and in the best and purest coals they make up nearly the whole of the mass, and he accounts very satisfactorily for the preservation of this part only of the plants on the ground that the resinous nature of the spores protected them from decay; while the wood rotted away, the bark, which is rather less destructible, was the only part of the stem which escaped, and thus appears in the mother of coal."[1]

Principal Dawson has pointed out that most of the coals of Canada are not composed mainly of spores, but of bark and other woody material.

Some carbonaceous shales seem to contain spores in abundance.

Distribution of Coal.—Coal is very widely distributed over the world. Fig. 3 shows, as far as is known, the relative quantities of coal available in different countries. It is of course only a very rough approximation.

Classification of Coals.—Coals may be classified in various ways. The following is convenient:—

Lignite or Brown Coal.
Bituminous or True Coals.
Anthracite.
Cannel Coal.

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[1] *Coal*, p. 23.

Lignite or Brown Coal.—This variety of coal is of more recent age than the true coal, occurring in rocks of tertiary age, and it is therefore, as might be expected, intermediate in composition between wood and coal. It is very widely distributed over Europe, the most important deposits being those in Bohemia, and as since their formation the rocks have undergone comparatively little disturbance, they do not lie in basins like true coal. There is only one British deposit, that of Bovey-Tracey in Devonshire, which is probably of oligocene age.

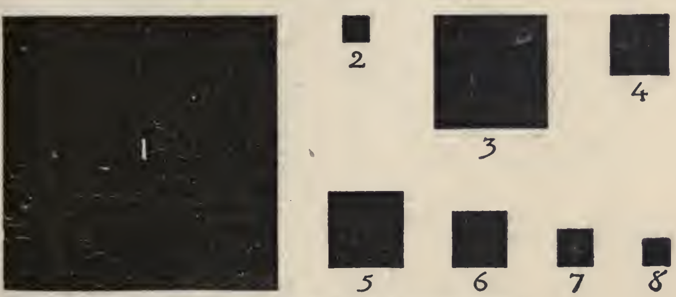

Fig. 3.—Superficial Coal Areas of various Countries.

1. United States: Bituminous coal,	133,132	sq. miles.
2. ,, ,, Anthracite coal,	15,437	,,
3. British America,	18,000	,,
4. Spain,	3,408	,,
5. Great Britain: Bituminous coal,	8,139	,,
6. Great Britain and Ireland: Anthracite, &c.,	3,720	,,
7. France,	1,719	,,
8. Belgium,	518	,,

There are several varieties of lignite.

Bituminous wood has a brown colour, and shows its woody structure very distinctly, whence it is often called wood-coal.

Brown coal or lignite proper is harder and more compact, shows the woody structure less distinctly, and has a brown colour.

Pitch Coal is brownish-black or black in colour, breaks with a conchoidal pitch-like fracture, may be dull or shiny, and shows no woody structure.

Freshly got lignite often contains a large quantity of water, and some samples are very high in ash. The following analysis of Bovey lignite given by Dr. Percy may be taken as a type:—

	Bovey.	Average.
Carbon, ...	66·31	68
Hydrogen, ...	5·63	5·5
Oxygen, ...	22·86	26-5
Ash, ...	2·27	2·0

EXAMPLES OF LIGNITES.

	1.	2.	3.	4.
Volatile matter, ...	54·02	48·30	45·6	40·2
Coke, ...	45·98	51·70	54·4	59·8
Fixed carbon,..........	36·08	50·74	41·86	51·6
Ash,.......................	9·9	1·23	12·54	8·2
Sulphur, ...	—	—	3·12	—
Moisture,.................	—	24·64	—	1·21

1, Bovey. 2, Pitch-coal, Servia (J. I. and S. I.). 3, Austria (Schrötter). 4, Colorado (cretaceous age), Klose.

Lignite kindles easily, burns with a long smoky flame, and has a low calorific power. If the powder be heated it does not cake.

Lignite is very little used for metallurgical purposes, except in districts where no other fuel is available.

Bituminous Coals.—Bituminous coals burn with a yellow luminous smoky flame resembling that of the mineral bitumen, whence the name. They are mostly black in colour, though some are brown, and they mostly soil the fingers. All bituminous coals of Great Britain belong to the carboniferous period.

When a powdered coal is heated in a closed crucible or retort gaseous and liquid products of destructive distillation are given off, and a solid residue of coke is left. According to the nature of this coke coals are divided into two great groups.

Caking Coal.—Some coals when heated soften, appear to fuse, and the particles become aggregated into a continuous mass, so that the residual coke is hard, compact, and shows no trace of the original coal particles. If such a coal be charged into a retort in lumps, the lumps will fuse together and yield a solid coherent mass.

Non-Caking Coal.—With the extreme varieties of this class the coals undergo little apparent change on heating. They do not soften or fuse, and if the coal be powdered the particles do not cohere, but the coke is a powder. In less extreme cases the particles cohere, but the mass does not swell up as a caking coal does, and the coke is soft and friable. If such coals be coked in lumps the pieces of coke retain the form of the coal, and if they cohere at all it is only slightly.

There is every gradation between caking and non-caking coals, so that in many cases it is impossible to say where one ends and the other begins, but a coal is not usually spoken of as a caking coal unless it yields a fairly hard and coherent coke.

Cause of Caking. — On what the property of caking depends has not yet been thoroughly made out. No doubt it is on the chemical composition, but certainly not merely on the relative quantities of carbon, hydrogen, oxygen, &c., which the coal contains, for two coals may have the same ultimate composition and yet one may cake and the other not.

There are two classes of coal which do not cake—those poor in oxygen and rich in carbon, approaching therefore to the anthracites, and those rich in oxygen and poor in carbon, which approach more nearly to the lignites. As examples the following analyses given by Dr. Percy may be quoted :—

	Non-caking, poor in oxygen. Dowlais.	Caking. Northumberland.	Non-caking, rich in oxygen. S. Stafford.
Carbon,	89	78·66	76·12
Hydrogen,	4·43	4·65	4·83
Oxygen,	3·25	13·66	16·72
Nitrogen,	·55	·55	1·00
Ash,	1·20	2·49	2·33

These figures do not seem to indicate any except the most general relationship between the composition and the caking property. Ash, sulphur, and nitrogen vary much in coals, and as they may vary between very wide limits without in any way affecting the caking properties, they may be left out of account. In order to get at the relationship existing between the three essential elements the analyses should be written in such a way that the others do not interfere with the result. This may be done, as also suggested by Dr. Percy, by calculating, not the percentage of the whole mass, but the quantities combined with 100 parts of carbon. Written thus the three coals would give—

	1.	2.	3.
Carbon, ...	100	100	100
Hydrogen,	4·43	4·65	4·83
Oxygen,...	5·28	14·52	22·52

Dr. Percy suggested as a generalization from a large number of experiments and analyses that when the quantity of oxygen, stated as above, as a percentage of the carbon present, fell between 8 and 18, the coal would cake, whilst if it were lower or higher it would not.

This cannot be taken as an absolute rule, for there are many exceptions to it, but it holds good in a very large number of cases.

Classification of Bituminous Coals.—Many attempts have been made to form a good classification of bituminous coals, but owing to the great variety among them, and to the fact that many of their properties seem to vary independently of the rest, no very satisfactory classification is possible. That due to Grüner is probably the best which has been proposed, and answers very well for practical purposes. Grüner's names for the classes are not in harmony with those in general use in this country, so it will probably be most convenient to translate them into their equivalents—

Grüner's Names.		Equivalent Names.
1. Dry coal.	Long flame.	Non-caking coal. Long flame.
2. Fat coal.	„ „	Gas coal.
3. „ „	Caking coal.	Furnace coal.
4. „ „	Short flame.	Caking coal.
5. Lean coal.	... ...	Anthracitic coal.

The following table gives the characters of the different coals:—

	Carbon %.	Hydrogen %.	Oxygen %.	Proportion of Oxygen to Hydrogen.	Products of Distillation.			Coke %.	Nature of Coke.
					Ammonia Liquor.	Crude Tar.	Gas.		
1. Non-caking coal. Long flame.	75	5·5	19·5	4	12	18	20	50	Pulverulent or only slightly coherent.
	to	to	to	to	to	to	to	to	
	80	4·5	15	3	5	15	30	60	
2. Gas coal.	80	5·8	14·2	3	5	15	20	60	Caked, but with many crevices, soft.
	to	to	to	to	to	to	to	to	
	85	5·0	10	2	3	12	17	68	
3. Furnace coal.	85	5·0	11	2	3	13	16	68	Caked. Moderately compact.
	to	to	to	to	to	to	to	to	
	89	5·5	5·3	1	1	10	15	74	
4. Coking coal.	88	5·5	6·0			10	15	74	Caked. Very compact and hard.
	to	to	to	1	1	to	to	to	
	91	4·5	5·5			5	12	82	
5. Anthracitic coal.	90	4·5	5.5		1	5	12	82	Pulverulent or slightly adherent.
	to	to	to	1	to	to	to	to	
	93	4	3		0	2	8	90	

1. **Non-caking Coal. Long Flame.**—These coals contain a large quantity of oxygen and hydrogen. On destructive distillation they yield a large quantity of gas, and leave a residue or coke which usually retains the form of the lumps of coal heated, and if such a coal be coked in powder the coke has little cohesion, and therefore is soft and friable. The coals are black or brown in colour, often hard and stony in appearance, and give a distinctly brown powder.

This class includes most of the hard splint coals used for blast-furnaces in Scotland and Staffordshire. These coals contain a considerable quantity of nitrogen, from 1 to 1·5 per cent, and on distillation in the blast-furnace yield ammonia equivalent to about 25 pounds of ammonium sulphate per ton of coal consumed.

The specific gravity, unless the ash is very high, is about 1·25, the available hydrogen is very low, and the heating power therefore is also low. They burn with a long smoky flame, and yield on distillation large quantities of tarry matters.

These coals occur in abundance in the coal-fields of Scotland and also in Derbyshire and Staffordshire.

EXAMPLES OF COALS OF CLASS 1.

	1.	2.	3.	4.	5.	6.
Volatile matter,............	42·3	42·05	39·27	38·90	42·18	39·95
Coke,..........................	57·7	57·95	60·73	63·10	57·82	60·05
Fixed carbon,................	54·9	54·00	43·03	48·10	55·27	56·30
Ash,............................	2·8	3·95	17·70	15·00	2·55	3·75
Sulphur,.......................	·88	1·15	·6	·648	·53	1·65
Moisture, ...	7·1	8·1	10·40	8·95	—	—

1, Govan, splint. 2, Russell, splint. 3, Overton. 4, Woodhill, wee. 5, S. Staffordshire (E. W. T. Jones). 6, S. Staffordshire, bottom coal (E. W. T. Jones).

2. **Gas Coals.**—These coals are black in colour, usually hard and dense, and have a specific gravity of about 1·3. On distillation they yield a large quantity of gas, often as much as 17 to 20 %, or 10,000 to 11,000 cubic feet per ton; they contain a considerable quantity of nitrogen, and yield a good deal of ammonia. The coke left when the powdered coal is heated is more coherent than that of Class 1, but is still friable and too soft for blast-furnace use. If coked in lumps, the lumps fuse together but do not entirely lose their identity. On heating, the coals soften somewhat, whence the name "fat" coals has been given to them. These coals are in great demand for various purposes. They are used for gas-making, and are very suitable for use in reverberatory furnaces, as they burn with a long luminous flame; the varieties which approach nearly to Class 1 are used in the blast-furnace, and many of the Scotch splint coals belong to this class.

3. **Furnace Coals.**—These coals are among the most valuable for general use. Many varieties are used for domestic purposes, and are commonly called house coals. They are suitable for reverberatory-furnace use, and are used for gas-making, but are too strongly caking for use in the blast-furnace. They are black, have a bright lustre, are often soft and brittle (cherry coal). They burn with a bright luminous flame. On heating, they soften and swell up, the separate pieces adhering and forming a dense gray coke, in which almost if not quite all trace of original pieces is lost. The amount of coke left on distillation may amount to 75 per cent.

Examples of Coals of Classes 2 and 3.

	1.	2.	3.	4.	5.	6.
Volatile matter,	30·60	31·60	33·30	26·40	25·18	28·60
Coke,	69·40	68·40	66·70	73·60	74·82	71·40
Fixed carbon,	63·20	64·27	65·29	69·06	67·47	69·98
Ash,	6·20	4·13	1·41	4·54	7·35	1·42
Sulphur,	—	·91	·749	—	·803	—
Moisture,	5·85	8·85	6·44	2·10	—	—

1, Auchenairn, splint. 2, Ell No. 1. 3, Dungarvie, Blackband. 4, Rawkiston No. 2. 5, Berlin, Penn. (J. I. and S. I.). 6, N. Wales (Mushet).

4. **Coking Coals.**—These coals are black and shining, and are usually harder than those of Class 3, which, however, they resemble. On heating, they soften, swell up, and apparently fuse into a solid coherent coke, which is harder and more compact than that left by coals of Class 3, and may amount to as much as 80 per cent of the weight of the coal. They burn with a shorter flame than those of the preceding groups, and give less gas. They are used for household and furnace purposes, and for making coke.

5. **Anthracitic Coals.**—These coals are bright black, and soil the fingers very slightly if at all. They are hard and compact, have a specific gravity of 1·35 to 1·4, ignite with difficulty, and burn with very little flame or smoke. On distillation they yield about 90 per cent of a powdery or slightly coherent coke, and give off very little gas. These coals are largely used for heating boilers, and are called Blind-coals or Smokeless Steam-coals.

Examples of Coals of Classes 4 and 5.

	1.	2.	3.	4.	5.	6.
Volatile matter,	24·90	21·12	20·15	23·70	14·2	10·43
Coke,	74·00	78·88	79·85	76·30	85·8	89·57
Fixed carbon,	72·71	77·38	72·99	73·56	81·5	83·34
Ash,	1·39	1·50	6·86	·74	4·3	6·23
Sulphur,	—	—	·880	—	1·6	1·03
Moisture,	—	—	—	—	—	1·29

1, Garesfield (Richardson). 2, Blaina, S. W. (Mushet). 3, Pittsburg, steam (J. O. Weeks). 4, Brymbo, S. W. (Mushet). 5, South Wales, steam coal. 6, Pennsylvania, anthracitic coal.

Anthracite.—This coal represents a stage of mineralization beyond ordinary coal. It contains up to 98 per cent of carbon. On heating in a closed vessel it gives off very little, if any gas, and leaves a residue of 96 to 98 per cent of its weight, which is apparently quite unaltered, and shows no sign of caking. Anthracite is very hard and brittle; it is bright, usually with a metallic lustre, and often shows iridescent colours (Peacock coal). It is extremely difficult to ignite, burns without flame or smoke, and gives a very intense local temperature. It is used for furnace purposes, and sometimes for iron-smelting blast-furnaces.

Anthracite is usually regarded as being coal which has been metamorphosed by the action of heat or other agencies. This is no doubt the case in many instances, but there is evidence that under some conditions ordinary coal may pass into anthracite where no heat has been applied, and some coals tend to become anthracitic on exposure to the air.

The same coal-field may yield both anthracites and bituminous coals, as in the case of that of South Wales, where bituminous coals occur at the east end of the field and gradually pass into anthracites at the west end.

Cannel Coals.—These coals differ so much from the ordinary coals that they cannot be placed in the same group with them, but must be considered apart. Not only do they differ from ordinary bituminous coals in properties and composition, but their mode of formation was probably also different. They are close and compact in texture, dull black in colour, break along joints, or with a conchoidal fracture, and often appear like black shales. They burn with a very long luminous or smoky flame, whence the name cannel (candle) coal. When heated they decrepitate with a cracking sound, and therefore are sometimes called parrot coals. On distillation they yield a very large quantity—10,000 to 12,000 cubic feet per ton—of highly illuminating gas, leaving a residue which often consists mostly of ash, and contains but little fixed carbon. Cannel coals are used entirely for gas-making.

Examples of Anthracites and Cannels.

	1.	2.	3.	4.	5.	6.
Volatile matter,	3·96	4·07	4·13	71·06	66·30	50·8
Coke,	96·04	95·03	95·87	28·94	33·70	49·2
Fixed carbon,	89·74	94·10	89·72	7·10	28·90	47·76
Ash,	6·30	·93	6·15	21·84	4·80	1·44
Sulphur,	·585	—	·58	·24	1·32	1·76
Moisture,	3·71	—	3·71	·4	—	3·15

1, Pennsylvania. 2, Cwm-Neath, S. W. (Mushet). 3, New Zealand. 4, Boghead Cannel. 5, Kentucky Boghead (G. Macfarlane). 6, Longton Cannel.

The difference between ordinary bituminous coals and cannels is no doubt due to difference in the mode of formation, and the latter pass by insensible stages into mere bituminous shales.

Passage from Wood to Coal.—The transformation of woody material into coal, and ultimately into anthracite, has taken place by a series of very complex changes, the exact nature of which is unknown. As decomposition goes on, in presence of a very limited supply of air, all the constituents of the wood are removed in the form of gases, but at very different rates, the oxygen being removed the fastest, next the hydrogen, and the carbon most slowly, so that the ultimate result is to increase the percentage of carbon in the residue as decomposition goes on. The relative rates of removal of oxygen and hydrogen are such that though the percentage of hydrogen falls, that of the available hydrogen increases up to a certain point, when it also begins to decrease. Much of the gas which is evolved cannot escape, and is therefore imprisoned in the coal, to be released when the coal is cut into in mining operations. The nature of the gases in coal-mines therefore gives some indication of the forms in which the lost constituents have escaped from the coal.

The following may be taken as examples of the gases found in coal-mines:—

	1.	2.	3.	4.
Marsh-gas (CH_4),	77·5	91·8	66·3	7
Nitrogen (N),	21·1	6·7	6·32	11
Oxygen (O),	—	·9	—	—
Carbon dioxide (CO_2),	1·30	·7	4·03	—
Air,	—	—	23·35	82·00

It is quite impossible to form any idea of the actual amount of material lost, or the relationship which it bears to that which is left, but probably the amount lost is enormously greater than that which remains.

The following table, from Percy's *Metallurgy*, illustrates the nature of the changes by which woody matter has been transformed into coal. Ash, sulphur, and minor constituents are omitted, and the figures are calculated to 100 parts of carbon.

	Carbon.	Hydrogen.	Oxygen.	Available Hydrogen.
1. Wood,	100	12·18	83·07	1·8
2. Peat,	100	9·85	55·67	2·89
3. Lignite,	100	8·37	42·42	3·07
4. South Staffordshire 10-yard coal,	100	6·12	21·23	3·67
5. Steam coal, Tyne,	100	5·91	18·32	3·62
6. Pentrefelin coal, S. Wales,	100	4·75	5·28	4·09
7. Anthracite, U. S.,	100	2·84	1·74	2·63

Water in Coal.—All coal as raised from the pit contains water in considerable quantity. On exposure to the air it loses most of this, till in the ordinary air-dried condition it usually retains from 2 to 4 per cent. On heating to 100° this water is expelled, but oxidation begins almost immediately and the sample increases in weight; it is therefore impossible to be quite sure of the exact amount of water in coal.

Sulphur in Coal.—Sulphur is always present in coal; the amount usually varying from ·5 to 3 per cent. The sulphur is present in at least three forms.

The largest quantity is usually in the form of iron pyrites, $Fe S_2$. This is almost invariably present in coal, either in thin layers along the planes of bedding or in irregular distributed masses scattered through the coal, constituting what are called "coal-brasses". Sometimes it is so abundant that it can be picked out and used as a source of sulphur for the manufacture of sulphuric acid. When coal containing pyrites is burned oxide of iron is formed, which remains in the ash, $2 Fe S_2 + 11 O = Fe_2 O_3 + 4 S O_2$. When such coal is heated without access of air, the pyrites is split up, $Fe S_2 = Fe S + S$, the iron sulphide remains in the coke, and the liberated sulphur combining with the carbon forms carbon disulphide, which escapes with the gas. Other reactions, however, also take place, so that it is not possible to calculate from the amount of pyrites the quantity of sulphur which will escape as gas and that which will remain with the coke.

It is the sulphur present in the form of pyrites which is most objectionable for iron smelting and other purposes.

Some sulphur is often present as calcium sulphate, $Ca\,SO_4$. If it remained in this condition it would probably not be objectionable for most purposes, but, heated to a high temperature with excess of carbon, it is decomposed and calcium sulphide is left, which is very deleterious in a coal to be used for iron smelting, $Ca\,SO_4 + 4\,C = Ca\,S + 4\,CO$.

A third portion of the sulphur is present in some unknown state of combination with organic matter.

Chlorine in Coal.—Chlorine is almost always present in coal, though it is usually overlooked, as, unless special care be taken in burning, it cannot be detected in the ash. The chlorine is probably present in the form of sodium chloride, which when the coal is burned is decomposed by the silica of the ash, evolving chlorine or hydrochloric acid, usually the latter. The following quantities have been found by the author in samples of coal:—·069, ·099, ·217, ·094, ·118, ·113, ·207, ·084. These quantities may seem small, but they are quite enough to rapidly corrode the interior of brass or copper boiler tubes. This is shown by the fact that the deposit from the interior of such tubes usually contains a considerable quantity of copper-chloride or oxychloride. The presence of chlorine is of little importance to the metallurgist, but it is of vital importance to the engineer who uses the coal for firing boilers fitted with brass or copper tubes.

Phosphorus in Coal.—Phosphorus is always present in coal, usually as calcium phosphate; the quantity of phosphoric acid, P_2O_5, ranging in ordinary cases from ·1 to 1·25 per cent of the ash.

Nitrogen in Coal.—All coals contain nitrogen in small proportion, though in many analyses this is not stated, the nitrogen being taken with the oxygen. The amount is largest in the long-flame coals such as the splints, and least in the anthracites. When the coals are distilled about 15 per cent or more of the nitrogen is evolved as ammonia, the rest remaining in the coke or escaping in the free state. Splint coals contain on an average about 1·5% of nitrogen and anthracite coals about ·7%.

Ash of Coal.—All coals leave when burned a quantity of non-combustible residue or ash, varying in amount from 1 to 10 per cent or more. The ash is quite different in composition to that of wood, and can only to a very small extent be regarded as being derived from the original plants from which the coal was formed, but mostly as foreign matter which has been carried in.

The following may be taken as examples of the composition of coal ash:—

	1.	2.	3.	4.
Amount of Ash,............	5·52	6·94	2·91	14·72
Silica,..................................	40·00	28·87	34·21	53·00
Alumina,............................ Oxide of iron,......................	44·78	86·95	52·00	35·01
Lime,..................................	12·00	5·10	6·19	3·96
Magnesia,............................	trace	1·19	·66	2·26
Sulphuric acid (SO_3),................	2·22	7·23	4·12	4·89
Phosphoric acid (P_2O_5),............	·75	·74	6·63	·88
	99·75	98·08	97·82	99·92

It will be noticed that the alkalies, which were very abundant in the ash of the plants, have disappeared, and that the bulk of the ash seems to be made up of clayey matter. It is, however, noteworthy that the plants which approach most nearly to those of the coal-measures are the only ones the ash of which contains any considerable quantity of alumina.

This residue or ash does not represent the forms in which the mineral constituents were present in the coal, as combustion breaks up all organic or volatile compounds containing metals, and leaves the metals as oxides. Any iron pyrites is converted into ferric oxide, and this imparts a reddish colour to the ash, and, other things being equal, the more pyrites is present the redder will be the ash. In the case of coals containing a very high ash, the large amount of white residue may completely hide the red colour of the oxide of iron.

The amount of ash is of great importance, and for many purposes so is its quality, as, for instance, whether it fuses into a clinker or whether it is infusible.

Amount and Composition per cent by Volume of the Gas evolved from certain Coals of Northumberland and Durham (? at 20° C.).

	Number of Cubic Centimetres of Gas yielded by 100 Grammes of Coal.	Composition of the Gas.			
		CO_2.	O.	N.	CH_4.
1. Low Main Seam—Bewicke Main Colliery,	25·2	5·55	2·28	85·65	6·52
2. Maudlin Seam—Bewicke Main Colliery,	30·7	8·54	2·95	61·97	26·54
3. Main Coal Seam—Urpeth Colliery,.........	27·0	20·86	4·83	74·31	—
4. Five-quarters Seam—Urpeth Colliery (30 fathoms from surface),.	24·4	16·51	5·65	77·84	trace
5. Five-quarters Seam—Wingate Grange Colliery (74 fathoms),......	91·2	·34	trace	13·86	85·80
6. Low Main Seam—Wingate Grange Colliery (108 fathoms)......	23·8	1·15	·19	14·62	84·05
7. Harvey Seam—Wingate Grange Colliery (148 fathoms),.....	211·2	·23	·55	9·61	89·61
8. Upper or Harvey Seam—Woodhouse Close Colliery (25 fathoms),......	84·0	5·31	·63	44·05	50·01

Rarer Elements in Coals.—Arsenic has been found in coal in small quantities up to ·2%. So has copper. Galena and zinc blende have been found, and more recently vanadium.

Gas in Coal.—Coal, when freshly won, usually contains occluded in it a certain quantity of gas. On exposure to the air, especially if warm, the gases are slowly given off, and on heating to 50° C. they are rapidly expelled. The quantity of gas may be many times the volume of the coal, and may vary very much both in quantity and composition, as is shown by the analyses from Percy's *Metallurgy* on p. 77.

It will be seen that the gases are much the same as are usually found in coal-mines, which indeed is exactly what would be expected. It will also be noticed that the gases are of two classes, the one containing little or no marsh-gas, and therefore non-explosive, and the other containing a considerable quantity of this, and therefore explosive; and the nature of these gases is sufficient to explain why some pits are fiery and others are not. The evolution of these combustible gases in a closed space may account for many explosions on shipboard or in other places where coals are stored.

Weathering of Coal.—When coal is exposed to the air it undergoes changes which are called weathering. They are mostly due to oxidation by the action of atmospheric oxygen, and often have a serious effect on the value of the coal, reducing its calorific power and diminishing its power of coking. Both the carbon and the hydrogen undergo oxidation, and the available hydrogen is reduced. Iron pyrites present is also readily oxidized, especially in presence of moisture, the expansion thus produced often causing the coal to fall to pieces.

These changes take place more readily the warmer the coal, and as they all evolve heat, once they start, they are likely to go on at an accelerating rate, unless the temperature can be reduced. Under certain conditions, as, for instance, when the coal is stored in close, unventilated chambers, especially if much pyrites be present, the temperature may rise to ignition point, and the mass then take fire. This is usually spoken of as the spontaneous ignition of coal.

Chemical Composition of Coal.—The ultimate composition of coal is easily determined by the ordinary methods of organic analysis, but this throws no light whatever on its constitution. If the coal be heated in a closed vessel, part of the carbon—the fixed carbon—is left in the residue, the remainder—the volatile carbon—goes off in the gases. The relative amounts of the two forms of carbon are not fixed for a particular specimen of coal, but vary somewhat with the temperature and rate of heating; and as they are the results of destructive distillation, by which complex substances are broken down into simpler forms, they do not represent in any way the form in which the carbon is present in the coal.

Many attempts have been made to ascertain the proximate composition of coal by the action of solvents, but they have not been very successful. The most elaborate researches in this direction were those of Frémy. He found that in the case of lignites the brown varieties were partially soluble in alkalies, and almost completely so in nitric acid and hypochlorites, whilst the black varieties were not acted on by alkalies, but dissolved in nitric acid and hypochlorites. The bituminous coals did not dissolve in alkalies or in hypochlorites, but both bituminous coals and anthracites dissolved completely in a mixture of sulphuric acid and nitric acid, producing dark-brown solutions containing ulmic compounds, which were completely precipitated by water.

Valuation of Fuels.—The value of a fuel will obviously be a function of its calorific power; but it will not vary directly with this, for there are many shales and similar substances which have a measurable calorific power, but no value as fuels. The value of a fuel therefore falls much more rapidly than the calorific power.

No absolute rules can be given for calculating the actual money value of a fuel, but the following points must be taken into account; and it must be remembered that a coal may have more value for some one special purpose than it would have for any other:—

1. Calorific power or absolute heating effect.
2. Calorific intensity or pyrometric heating effect.
3. The amount of ash. A large amount of ash is very objectionable; it reduces the amount of combustible material present, and its removal and disposal entails trouble and

expense. The carriage of the ash has to be paid for at the same rate as that of the combustible portion of the coal, and the ash or clinker will also have to be carted away, and for a given amount of heating power more coal will have to be supplied to the furnace, and this entails more labour. The ash usually falls from the furnace hot, and carries with it a certain amount of heat. The specific heat of ash being taken as ·2, and it being heated, say, to 1000° F. for each pound of ash, the loss of heat will be $\cdot 2 \times 1000 = 200$ units.

4. The nature of the ash, whether it clinkers or not.
5. The coking power of the coal.
6. The length of the flame.
7. The amount of sulphur, chlorine, &c., which it contains.

These last do not so much alter the value as render it unfit for special purposes.

Pyrites as Fuel.—In some metallurgical operations where pyrites is present no additional fuel is necessary, the heat evolved by the burning sulphur being all that is required. In this case the pyrites must be considered as a fuel. The calorific power of sulphur is 4000 B.T.U., or 2222 C. units; but the combustion of pyrites is not a simple combination. The equation $2\,FeS_2 + 11\,O = Fe_2O_3 + 4\,SO_2$ shows it to consist of at least three parts—

1. Decomposition of two molecules of pyrites.
2. Formation of four molecules of sulphur dioxide.
3. Formation of one molecule of ferric oxide.

The heat values of which will be:—

The heat of formation of FeS_2 is not known. Assuming it to be the same as FeS, *i.e.* that the separation of the second atom of sulphur neither evolves nor absorbs heat—an assumption which cannot be correct, but which will not be far out—then, in C units,

1. $23800- \quad \times 2 \quad = \quad 47600-$
2. $71000+ \quad \times 4 \quad = \quad 284000+$
3. $199400+ \quad \times 1 \quad = \quad 199400+$

=Total heat of reactions, 531000+

which, divided by 240, the weight of the two molecules of pyrites (FeS_2), gives 2212 as the calorific power of pyrites, and divided by 128 gives 4148 as the calorific power of sulphur when present as pyrites.

In B. T. U. the figures would be—

1. 42840 − × 2 = 85680 −
2. 127800 − × 4 = 511200 +
3. 358920 × 1 = 358920 +

Total heat of reactions, 955800 +

or the calorific power of pyrites is 3982, and of sulphur in the form of pyrites 7467.

Table of Calorific Powers.

	C. units.	B. T. U.
Carbon solid to carbon dioxide, ...	8080	14500
Carbon gaseous to carbon dioxide, ...	11368	20388
Carbon to carbon monoxide, ...	2400	4320
Hydrogen, ...	34180	61524
Marsh-gas (CH_4), ...	13349	24021
Ethylene (C_2H_4), ...	11823	21343
Sulphur, ...	2220	3996
Pyrites FeS_2 to ferric oxide and sulphur dioxide,	2212	3982

CHAPTER IV.

SOLID PREPARED FUELS—CHARCOAL PEAT, CHARCOAL COKE.

Charcoal.—When wood is heated in closed retorts a black residue of charcoal is left. This amounts to about 26% of the weight of the wood. If finely divided wood, as for instance sawdust, be heated, the charcoal will be in powder; but if a piece of wood be used, the charcoal will retain the form of the wood so perfectly that it will show distinctly the annual rings of growth of the wood.

Charcoal was once a very important fuel, but is now only used in a few minor metallurgical operations.

Properties of Charcoal.—Charcoal is dull black, soils the fingers slightly if of good quality, but very much if of poor quality. It should ring when struck, and should show the annual rings of growth very distinctly. It should ignite quite readily, and once ignited should continue burning till it is completely consumed. The temperature at which ignition takes place depends on the temperature at which the charcoal was prepared, the higher the temperature of charring the higher the temperature of ignition. It is worth noting that in the case of charcoal prepared at a low temperature, the ignition temperature is always higher than that of preparation, so that a hot-air pipe or other source of moderate heat, though it may char wood, is not likely to ignite the charcoal.

* Temperature of Preparation.		Temperature of Ignition.	
3000° F.	1650° C.	2500° F.	1371° C.
2500	1371	1300	705
2000	1093	1100	593
1500	815	900	482
1000	338	800	427
500	266	650	343

Charcoal absorbs gases very readily, and as a rule the lower the temperature at which it is prepared the greater is its absorbing power. Ammonia and hydrogen-sulphide are among the gases which are absorbed most readily. Charcoal saturated with a combustible gas may take fire on coming in contact with air or oxygen.

The density of charcoal varies with the nature of the wood from which it was prepared, the dense woods giving a dense charcoal, and the light woods a light charcoal. The specific gravity of charcoal varies from about ·203 to ·134, about ·2 being a fair average. The real density of carbon in the form of wood charcoal is about 2, so that the lightness of charcoal is due entirely to its porosity. Charcoal absorbs water on exposure to moist air, and may under ordinary conditions, though appearing quite dry, contain about 10%.

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* Thurston, *Materials of Engineering*, vol. i. p. 184.

Composition of Charcoal.—Charcoal is not pure carbon, as it is often considered to be, but always contains hydrogen, oxygen, nitrogen, and ash. The average composition may be taken as carbon 95, hydrogen ·5, oxygen 1·5, ash 3·0. Charcoal should not lose anything but water on ignition.[1] If combustible gases are given off it is evidence that the wood has not been perfectly charred.

Charcoal as a Fuel.—Charcoal is an excellent fuel for many purposes. When in small quantity at a low temperature it burns with a glow, the product being almost entirely carbon dioxide, though a small quantity of carbon monoxide is usually formed and frequently escapes combustion. At high temperatures large quantities of carbon monoxide are formed which burn with the characteristic pale-blue flame. Owing to the porosity of charcoal, air finds its way into the mass, and combustion takes place very readily. Its heating power is very high (about 13700 B.T.U.). Owing to the way in which it burns, and the absence of luminosity in the flame, it is better suited for blast-furnaces where it heats by contact, or open fires where it heats by direct radiation, than for reverberatory furnaces where radiation from the flame is the source of heat.

The ash contains only very small quantities of deleterious impurities. Hence charcoal has been used for the preparation of a very pure iron in blast-furnaces, iron so made being called charcoal-iron, and being highly valued. It can only be used in small blast-furnaces, as it is very friable and crushes easily if the superincumbent charge be too heavy; and for the same reason loss in transit is very considerable, often reaching 10% of the weight.

For domestic use charcoal is very objectionable, unless burned in a fireplace with a very good draught, on account of

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[1] According to Desmond, charcoal when heated to redness gives off 17 to 25 times its own volume of gas, having the composition—

Carbon dioxide,	9·14
Oxygen,	·26
Carbon monoxide,	18·08
Hydrogen,	49·11
Marsh-gas,	16·04
Nitrogen,	7·37

the poisonous carbon monoxide which is formed, and which, being odourless and colourless, is not easily detected.

Red Charcoal (Rothköhle).—This is merely wood which has been charred at a very low temperature; it has a brown colour, retains much oxygen and hydrogen, and is intermediate in composition between wood and charcoal.

Preparation of Charcoal in Circular Piles.—This method of charcoal burning has been in use from a very remote period. It is the method which was used in Great Britain when charcoal was largely used for smelting iron in the small blast-furnaces of the south of England, and it is still practised in the east of Europe where charcoal is used for smelting purposes.

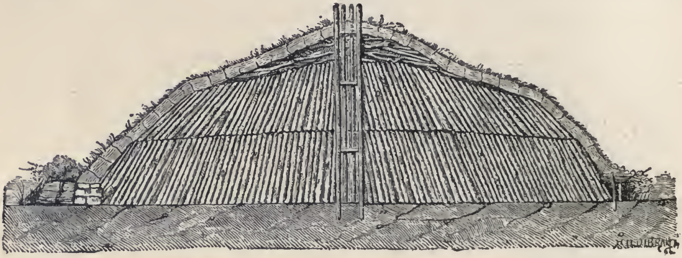

Fig. 4.—Charcoal Burning in Circular Piles.

A plot of dry level ground is selected, as sheltered as possible from the wind, and which should have a slight inclination downwards from the centre. In the centre three upright stakes, about 7 feet long, are driven into the ground at distances of about a foot apart so as to form in plan an equilateral triangle, and these are kept in position by short cross-pieces of wood placed at intervals.

Pieces of wood cut to a uniform length of about 2 ft. 6 ins. are stacked round this central triangular chimney in a series of concentric rings, till the heap is 5 or 6 feet in diameter. The pieces at the centre are nearly vertical, and the slope is made to increase slightly towards the circumference. On the top of this is stacked another similar series of pieces of about the same length, but placed a little more inclined, and on the top of this a layer of brushwood or other small wood, so as to give the heap a roughly semicircular section. Round the base of the heap is now driven a ring of **Y** sticks, so placed that the fork is about 6 inches above the ground, and resting on these forks are placed a series of bars of wood so as to form a ring encircling the heap. A cover is now made by putting sods, grass side inwards, over the heap, commencing at the ring resting on the forked sticks and terminating at the mouth of the chimney, and when this is finished the surface is plastered over with moistened charcoal dust so as to make it as air-tight as possible.

The space within the three central stakes is now filled with easily combustible wood, which is lighted, and as this burns away more is added, till the centre of the pile is well alight. Then the top of the chimney is closed with turf, the surface of the pile examined, and if it shows signs of sinking anywhere the cover is quickly removed at the spot, brushwood introduced, and the cover replaced, and the heap is left to itself for several days.

The heat of the combustion in the centre of the pile dries the wood. The moisture partly escapes as steam, and partly condensing on the inside of the cover runs down and escapes as water. This is therefore called the sweating stage. When this is complete the openings round the bottom are closed with turf. The cover is again carefully examined, and if it shows signs of cracking it is repaired with turf wherever necessary, and the heap is left for two or three days. At the end of that time a series of openings are made round the foot of the pile and another series at about the level of the top of the lower row of wood. Air enters the lower openings, and dense yellow smoke escapes from the upper ones. After a time the smoke becomes paler and less dense, and ultimately is replaced by a pale almost invisible haze. The upper row of holes is then closed, and another row is opened lower down, where the same phenomena take place, and so on till carbonization is complete. The openings are then all closed, and the heap is left at rest for two or three days, after which the cover is removed, the charcoal drawn, and at once quenched with sand or water and stacked for the market. The heap is usually drawn at night, as then it is much easier to see any unextinguished sparks. The whole operation takes about ten or fifteen days. These circular piles are called in German Meiler.

The form of heap and arrangement of the wood have been modified in different districts. The wood may be stacked horizontally instead of vertically, and the chimney may be replaced by a solid stake, the heap then being lighted by radial passages at the base.

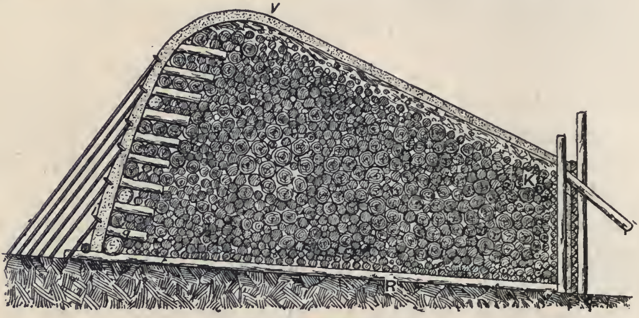

Fig. 5.—Rectangular Pile.

In Sweden large rectangular piles are used, the wood being placed horizontally and transversely, and resting on longitudinal beams R, so as to allow of the circulation of air underneath. The vertical sides are protected from the air by vertical screens of wood, the space between which and the ends of the pieces of wood is rammed with charcoal dust, and the top and the sloping end is made air-tight with a cover of turf or charcoal dust V, exactly as in the circular piles. The heap is lighted from a horizontal passage K left near the lower end, and when air is admitted it gets in through openings below the bottom of the pile.

Theory of the Process.—This is comparatively simple. During the early stages some of the wood in the centre of the pile burns, and the heat partially dries the rest. During the second stage carbonization goes on very slowly, and the whole heap becomes hot. At the expiration of this stage the wood in the centre is well charred, that at the circumference is only quite dried or slightly charred. When the openings are made at the bottom and round the pile a current is set up, air enters through the lower openings, travels by the path of least resistance, which is along the base of the pile, and then up through the partially charred wood, which will have shrunk very much, and thus left room for the passage of the air. Combustion at once becomes vigorous, the volatile matter is distilled from the wood, and dense yellow smoke escapes. As the charring is completed the evolution of smoke ceases and the charcoal itself burns, and an almost colourless vapour alone escapes. The upper holes are then stopped, and another row opened lower down. During this third stage there will be thus three zones: (1) a zone of charcoal, where the carbonization is complete; (2) a zone of charring wood near the opening; and (3) a zone of dry partially charred wood. The zone 2 moves downwards as the charring goes on. During charring there is a constant shrinking, and the cover not being rigid falls down and keeps in contact with the surface of the charcoal.

The gases which are evolved contain nitrogen, carbon monoxide, carbon dioxide, and hydrogen. A sample analysed by Ebelman gave—

Carbon monoxide, ...	9·33
Carbon dioxide, ...	25·89
Hydrogen, ...	9·28
Nitrogen, ...	55·56

From the composition of the gases Ebelman concludes that the heat of the pile is kept up by the combustion of the fixed carbon or charcoal. It seems, however, likely that a considerable portion at least of the heat may be derived from the burning of the combustible gases which are given off.

Yield of Charcoal.—The yield will naturally vary with the nature of the wood and its condition as to dryness, &c.,

and the method of conducting the operation. The yield by weight is about 20 per cent, but oftener less than more. Percy gives the limits as from 15 to 28 per cent, though it is doubtful if the latter figure is ever reached in an ordinary meiler. The yield by volume is about 67 to 68 per cent.

The rate and temperature of charring influence the result very much; the more rapid the charring the less is the yield. In one case given by Karsten, an experiment was made with young oak-wood, and it gave with rapid charring 15·64 per cent, and with slow charring 25·6 per cent.

Charring in Kilns.—Many forms of kiln have been suggested for charcoal burning. They are all similar in principle, though they vary very much in detail. One in use in America may be described as a type. The kiln is bee-hive in form, and is built of fire-brick. It is provided with two openings, one (A) at the bottom and the other (B) in the dome, which can be closed, when the kiln is in use, by iron doors. Near the bottom of the kiln are three rows of holes about 3 ins. by 4 ins., and 2 feet apart, the rows being about 1 foot apart. These holes are stopped with clay when not required. The wood used is pine; it is cut into lengths and stacked through the bottom door as far as possible, then the charging is continued through the upper door from the platform (C) till the kiln is full. The

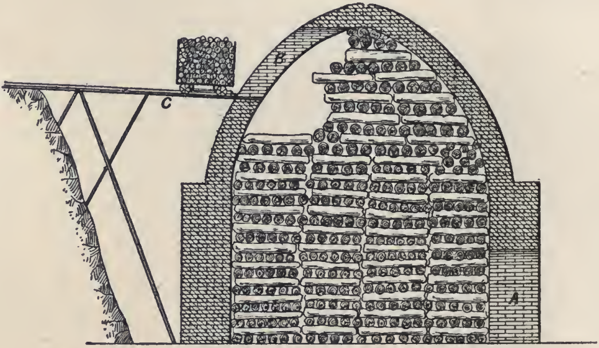

Fig. 6.—American Charcoal Kiln. From Eisler's *Argentiferous Lead.*

charge is lighted through the bottom door, the upper door being also left open, and as soon as combustion has fairly started both doors are closed and luted. The air then enters through the lower openings, and the products of combustion escape through the upper ones; and when combustion is complete all the holes are thoroughly stopped with clay, and the kiln is allowed to cool.

The charring takes about eight days and the cooling about four more. Each kiln holds about 3350 cubic feet of wood, and produces about 1300 bushels of charcoal.

The Pierce Process.—This process was devised in 1876 for the preparation of charcoal and the recovery of by-products. It is now largely used in the United States. Some of the kilns are made of large size, capable of treating as much as 60 tons of wood at one time.

The wood is heated in brick-kilns, which in the first works were 32 feet in diameter and 16 feet high in the centre, and held fifty-five cords of wood. The oven being charged with wood, gas from a previous operation, together with the requisite amount of air for its combustion, is sent in by means of steam jets. As the wood dries, steam is given off, which is allowed to escape into the air. After about eighteen hours the wood is quite dry and distillation begins. The top of the kiln is then closed, and the exit tubes are connected with the condensers. The products of distillation are drawn away by means of fans and passed to the condensing apparatus, and the uncondensed gases mixed with the proper proportion of air are returned to the kiln. The carbonizing occupies six or eight days, after which the kiln is allowed to cool and the charcoal is drawn. The whole operation—charging, carbonizing, cooling, and discharging—occupies about eight days. There is more gas than is required for charring, and the excess is used for raising steam. The kilns are set in batteries of sixteen, each set having its own fan and condensers.

The condensers are a series of copper pipes, set in wooden boxes about 4 feet square and 14 feet long, through which water circulates.

The charcoal is said to be excellent quality, and the yield is—

	Per Cent.	Per Cord of Wood.[1]
Charcoal,	25·30	50·6 bushels.
Methyl alcohol,	·75	4·4 gallons.
Acetic acid,	1·00	4·6 „
Tar,	4·00	16·5 „
Water,	45·95	220·7 „
Permanent gases,	23·00	11,000 c. ft.

The charcoal produced weighs about 20 lbs. per bushel, that made from the same wood by the ordinary processes weighing 16 pounds per bushel.

Comparison of Methods of Charcoal Burners.[2]

Method of Coking.	Wood.	Yield.	
		% Vol.	% Weight.
Retorts,	Dry pine,	81	27·7
Swedish meilers,	Fir and pine,	52·5	18·3
American kilns,	Yellow pine,	54·7	22·0
American meilers,	„	42	17·1

Distillation in Retorts.—In this country most of the charcoal used is produced as a by-product in the manufacture of pyroligneous (acetic) acid, by distillation in iron retorts. The charcoal thus obtained is of very inferior quality, not because the process cannot yield good charcoal, but because the wood is selected not because it will make a good charcoal, but because it will give a good yield of acid and the other products which are required. The yield of charcoal in retorts is much higher than that in heaps, often reaching 27 per cent.

Peat Charcoal.—Peat in its ordinary condition does not make a useful charcoal, as the residue which it leaves on distillation is very incoherent, and is quite incapable of supporting pressure. Many methods have been suggested for preparing a good charcoal from peat. They almost all consist in pulping the mass, separating the stones and roots, pressing into blocks,

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[1] A cord of wood is 128 cubic feet, equal to about 73 cubic feet of solid wood.

[2] *Journal of U.S. Association of Charcoal Ironworkers*, No. iv., 1883.

and then charring in retorts externally heated, or in superheated steam. By these means a fair charcoal can be obtained, but not one that can compete, either in quality or price, with other forms of fuel.

Coke.—When coal is heated without access of air, volatile, gaseous, and liquid products are given off, and a residue of coke is left, so that coke bears exactly the same relation to coal that charcoal does to wood. A coal which yields a coherent coke is said to be a coking or caking coal, but comparatively few coals yield a good coke. Coke is used in a large number of metallurgical operations, for which coal is not suited, especially for operations carried on in blast-furnaces and shallow hearths.

Coal may be distilled for either of the three products—the coke, the gas, or the tar and ammonia liquor,—and in each case the others are considered as by-products. In all cases special attention is paid to the substance which is the chief product and less to the by-products, so that these latter are often of inferior quality. Only those processes in which coke is the main product will be considered in this chapter.

Properties of Coke.—Coke varies enormously in properties according to (1) the nature of the coal from which it is made, and (2) the way in which the coking is carried out.

In general, two varieties of coke are made:—

(1) Soft coke, often called smithy char, used for smiths' forges and similar purposes; and (2) dense or furnace coke, suitable for use in the blast-furnace, and in many metallurgical operations.

Soft coke is black and porous. It kindles readily, is soft and brittle, and will not stand great pressure.

Furnace coke is hard, dense, and strong, bearing great pressure without crushing. It ignites with considerable difficulty, and has almost a metallic ring when struck. Coke made in the beehive oven has a dark-gray colour, with a metallic lustre, and breaks into columnar fragments. That made in Simon-Carvès and similar ovens is black and dull without lustre, and breaks into roughly rhombohedral lumps. The specific gravity of coke is about ·9, and as the carbon has a specific gravity of about 2, over 50 per cent of the mass must be spaces. Coke is not pure carbon, but in addition to the ash it always contains small quantities of hydrogen and oxygen, as is shown by the following analyses:—

	1.	2.	3.
Carbon, ...	85·84	93·15	84·92
Hydrogen, ...	·52	·72	4·53
Oxygen, ...	1·38	·90	6·66
Nitrogen, ...	·86	1·28	·65
Ash, ...	11·40	3·95	2·28

1, Dunkinfield (Percy). 2, Best Durham (Kubale). 3, Average Durham (Kubale).

On heating, it should lose nothing but water. Many cokes, however, if they are powdered and heated to redness, lose sensibly in weight, after all moisture is expelled, as is shown by the following examples:—

	1.	2.	3.	4.	5.	6.
Volatile matter, ...	—	—	—	·460	—	7·8
Fixed carbon, ...	92·59	87·57	90·31	89·576	87·05	86·25
Ash, ...	9·89	10·15	8·45	9·113	7·50	5·95
Sulphur, ...	·66	1·73	1·246	·821	1·95	·735
Moisture, ...	·30	·55	—	·21	3·50	—

1, Welsh (Jones). 2, Yorkshire (Jones). 3, Scotch. 4, Connellsville. 5, Gas coke (Pilkington). 6, Scotch, smithy char.

In practice, coke is usually assumed to contain 90 per cent carbon.

Strength of Coke.—The crushing strength of coke varies. A coke for blast-furnace use should be very strong. Good cokes have a crushing strength of from 500 to 1500 lbs. per square inch. It is, however, much less at high temperature; one sample gave 597 lbs. in the cold, but at a red heat only 398 lbs.

The density of coke varies very much, as is shown by the following:—

Coke.	Apparent density.	Real density.
Coppée,	1·01	1·81
„	·77	1·76
Beehive,	1·11	1·78

Coke as a Fuel.—Coke is an excellent fuel for many purposes, but especially for use under such conditions that it heats either by contact or by radiation, and where flame is not necessary. It has a greater calorific power, weight for weight, than coal. It is mainly used in blast and similar furnaces, and in these it is only the solid carbon which is burnt usefully, any volatile, combustible matters being expelled before combustion can take place, hence the necessity for a well-made coke.

In the blast-furnace, however, the reactions are complex. As the air is blown in, carbon monoxide and perhaps carbon dioxide are formed, and as the gas passes upwards any carbon dioxide is reduced to carbon monoxide; and unless there are other changes, such as the reduction of metallic oxides, practically the whole of the carbon will be carried off in this form. The heating value can only therefore be taken as that due to the formation of carbon monoxide.

Two fuels may have the same calorific power and yet not be equally efficient in the furnace. Charcoal, for instance, weight for weight, gives a higher temperature than coke.

Dr. W. Thourer says that charcoal consists of a large number of more or less regularly arranged cells, which are joined to one another longitudinally, and the walls of these cells are readily porous to gases, and are therefore very readily oxidized; whilst coke consists generally of separate unconnected cells, the walls of which are composed of a dense vitreous matter which does not admit of the passage of the air, and which is very difficult to oxidize; hence that the relatively smaller action in blast-furnace practice of coke as compared with charcoal would be increased if it were possible to cause the structure and character of coke to more closely resemble that of charcoal, either by the formation of a more porous, though sufficiently strong coke, or with greater certainty, by rendering the coke more easily oxidizable.

The question of the economical use of fuel in the blast-furnace is much more complex, however, than such differences would suggest, and will be fully discussed later.

Coke is admirably suited for domestic use, as its radiative power is very high, the chief objection to it being the difficulty of ignition. It is usually thought that coke contains more sulphur than coal, but this is not by any means always the case.

Sulphur in Coke.—All coals contain sulphur, part of which is eliminated during coking and part remains in the coke, and as a rule the coke contains a smaller percentage of sulphur than the coal from which it is made. The sulphur, as already mentioned, is present in three forms. That present as sulphates remains in the coke probably as calcium sulphide; that present in organic combination passes, at any rate to a large extent, into the gases; and that present in pyrites goes partly into the gas and part remains in the coke. The total amount of sulphur in the coal does not give any definite information as to the amount which will remain in the coke, as this depends on the form in which the sulphur was present. Even the quantity present in the coal as pyrites is not an absolutely safe guide, as changes other than the simple decomposition of the pyrites by heat may take place; and Dr. F. Muck asserts that in coke some of the sulphur is still present in organic combination, in which form it is not acted on by hydrochloric acid, which evolves all the sulphur from iron sulphide in the form of sulphuretted hydrogen. The only safe method is to determine the sulphur in the coal and in the coke derived from it on the small scale. As a rule the more iron the ash of a coal contains the more sulphur will be retained in the coke.

	Sulphur in Coal.	Sulphur in Coke.
1.	1·47	1·22
2.	1·93	1·60
3.	1·51	1·32
4.	1·26	·98
5.	·84	·797
6.	·74	·625

1 to 4, Hilgenstock.

In iron-works it is often assumed that one half of the total sulphur remains in the coke, the other half passing away with the gases.

Nitrogen in Coke.—When coal is coked, a very large proportion of the nitrogen, often as much as 75 per cent, remains in the coke in some form of combination. According to W. Foster, when coal is distilled the nitrogen is thus distributed:—

In gases as ammonia,	11	to 18	per cent.
,, ,, ,, cyanogen,	·2	,, 1·5	,, ,,
Remains in coke,	48	,, 66	,, ,,
Not accounted for,	21	,, 36	,, ,,

The amount not accounted for probably escapes as gaseous nitrogen.

Selection of a Coal for Coke-making.—In the selection of a coal for coking attention must be paid to various properties. The amount of coke which the coal will yield is of importance, but less so than its quality. For blast-furnace use the coke must be hard and dense, and capable of bearing great pressure without crushing, and the higher the furnace the stronger must be the coke. Some idea of the nature of the coke which a coal will yield can be obtained by coking a small quantity in a crucible; but this is never quite satisfactory, as the heating is not at all under the same conditions as in a coke-oven, so that an actual oven-test is the only safe method of ascertaining the coking power of a coal. Coals yielding more than 80 per cent or less than 60 per cent of coke in laboratory experiments never yield a coke hard or dense enough for furnace use. The coal should be as free as possible from sulphur and ash, and for coking should be in a coarse powder. Many coals are very much improved by washing.

Coke-burning in Heaps.—The earliest and simplest method of making coke was to char the coal in heaps, almost exactly in the same way as charcoal was made from wood. The heaps were either round or rectangular, and as a rule were larger in diameter but lower than the charcoal piles, and a brick chimney was used in place of the three wooden stakes above described. The coal was placed with the planes of bedding vertical, and as large lumps as possible were used. The heap was covered air-tight with breeze, and the burning conducted much as charcoal burning, except that, as coal contains but little water, there was no sweating stage.

This process was in use in a few localities till quite recently, even if it is now extinct. Some smelters prefer coke made in heaps to that made in ovens, and assert that it is freer from sulphur, though this does not seem to be likely.

Coke-making in Stalls.—This is a distinct improvement on the method of burning in heaps. It is carried out slightly differently in different places, and is fully described by Dr. Percy as it is used in Silesia.

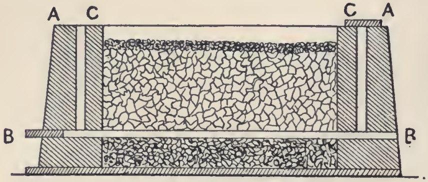

Fig. 7.—Silesian Coke Stall.

The kiln is a rectangular chamber, 60 feet long, 15 feet wide, and 6 feet deep. It is built of brick, and openings are left at each end for charging. In each of the side walls are a series of horizontal passages (B), which pass through the wall, and from the middle of each of these rises a vertical passage (C), which opens at the top of the wall. The openings are about two feet apart, and those in the two walls are exactly opposite.

To charge the kiln moistened coal-slack is spread over the floor in layers, each being well rammed down, till the level of the horizontal openings is reached. Long bars of wood, made slightly taper—so as to be easily drawn out—are put through the openings from side to side, and either they are surrounded by lumps of coal, so as to form a sort of tunnel, or coal is well pressed round them. The kiln is then filled up, each layer being stamped down as before, and the top is covered with a layer of ashes or loam, so as to exclude the air. The openings at the end are built up as the charge is put in. The long pieces of wood are then carefully withdrawn, leaving a series of transverse passages through the mass in which the coal is lighted by means of brushwood.

Before the fire is lighted, the top of the vertical passages on one side, and the end of corresponding horizontal passages on the other side, are closed with bricks and luted with clay. A current of air is thus set up through the passages, and the direction is reversed at intervals by opening the closed openings and closing the others. The horizontal passages are kept clear by means of iron rods. When the process is over, which is judged by the escape of white flame from the vertical passages, all the openings are closed, the charge is let cool and is then withdrawn. The whole process occupies about eight days; the yield is said to be large and the coke of excellent quality.

The theory of the process is very simple. The heat of the burning wood in the passages starts distillation of the coal in its immediate neighbourhood; the gases given off, coming into the passages, mix with air, and burn, thus producing more heat and so carrying the coking further and further into the mass, till at last, when coking is complete, no more hydrocarbon gases are given off, the coke itself begins to burn, and the operation is over.

Coking in Ovens.—Coke is now almost always made in ovens.

Classification of Coke Ovens.—The following classification includes all ordinary types of coke ovens, and the examples mentioned are those which are described in the text:—

A. Intermittent ovens.
    1. By-products are not recovered.
        a. Combustion takes place in the coking chamber.
            Beehive oven, Cox's oven.
        b. Combustion takes place outside the coking chamber. (Retort ovens.)
            Appolt oven, Coppée oven.

2. By-products are recovered.
    - *α*. Beehive type.
        - *a*. Combustion takes place in the coking chamber.
          Jameson oven.
        - *b*. Heated from below.
          Pernolet oven.
    - *β*. Retort type. Heated externally.
        - *a*. Without regenerators.
          Bauer oven.
        - *b*. With regenerators.
          Simon-Carvès oven, Otto-Hoffman oven, Semet-Solvay oven.

B. Continuous ovens.
    Lürmann oven.

Beehive Oven.—The oven in common use is the beehive—so called from its shape. The form of oven and method of conducting the process differ somewhat in different districts; the following description, which is that of the process as carried on in a large Scotch works, will serve as a type:—

The oven is built of fire-brick set in clay; it is 11 feet 6 inches in diameter at the bottom, and is cylindrical for a height of 2 feet 6 inches, and is then domed over, the dome being a little flat, so that the greatest height is 8 feet 6 inches. Each oven is provided with a working door in the front, an opening in the centre of the roof which can be closed with a damper, and an opening near the top for the escape of the products of combustion, which is so arranged that it can be put in connection either directly with the air or with a chimney. The ovens are usually built in blocks of twelve or twenty-four, so as to prevent, as far as possible, loss of heat by radiation. The working opening can be closed by a door made up of an iron frame, divided into two parts by a horizontal bar about six inches from the bottom. The upper space above this bar is filled up with slabs of brick luted with clay, a small hole being left near the top by which the interior of the oven can be seen, and which can be closed with a plug of clay when not in use. The narrow space below the cross-bar is filled up as required with fire-clay. The door is usually lifted into position and held firm by a cross-bar resting in catches in the door frame, but in some ovens it is attached to a chain running over a pulley, by which it can be readily lifted.

The charge having been drawn, and the oven being at a very dull, hardly visible, red-heat, the damper is closed and the charge of about seven tons of coal in a coarse powder is thrown in. While this is being done, an inner or false door of fire-brick set in clay is gradually built up so as to keep the coal from running out; this wall is four inches back from the main door, and is carried up to the top of the charge. As soon as the charge is in, the door is put up and luted, the slit along the bottom being also luted, and the damper is opened.

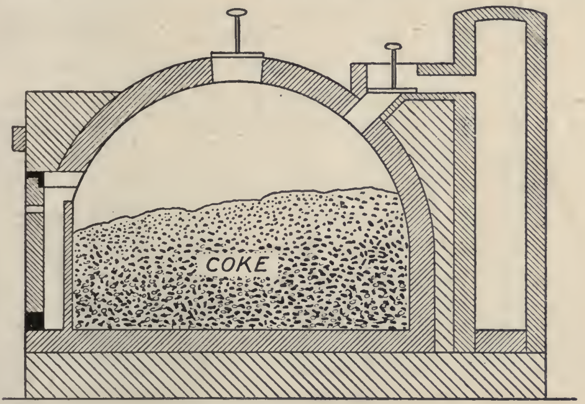

Fig. 8.—Beehive Coke Oven.

Combustion very soon begins, if the oven be sufficiently hot; if it be not, a coal fire is lighted on the top of the charge. Smoke soon begins to escape, and for about four hours dense white smoke is emitted from the top of the oven; then ignition takes place, the gas bursts into flame or the coal "strikes", and an opening is made at the bottom of the door so as to admit a good deal of air. For the next twelve hours the gases in the oven burn with a dull smoky flame above the surface of the charge. On the second day the flame gets redder, and the air supply is diminished by partially closing the opening at the bottom of the door with clay. On the third day the flame becomes very bright and the air supply is still further reduced. On the fourth day the flame becomes very red, and still less air is admitted, and by the end of this day no more flame is seen coming off from the coke, and the whole interior of the oven is red-hot, the bricks inside being distinctly visible through the sight-hole. All the gas now being off, the space below the door is thoroughly luted with clay, but the damper is left open for about six hours longer, when it too is closed and luted. The oven is thus closed air-tight and is left in this condition for about twenty-four hours, by which time the coke will have considerably cooled, and by the end of the fifth day (120 hours) from charging the oven will be ready for discharging. The outer and inner doors are taken down, and a few bucketfuls of water are thrown into the oven. This water is at once converted into steam and thus cools the coke so that it can be drawn. When the coal is cool enough a bar or "shackles" is hung across the top of the door, being suspended on pins in the masonry; on this hangs a pulley on two flanges. A long iron "cleek" or hoe with a heavy head is put through between the flanges, the handle resting on the pulley, and by its means the coke is drawn out into an iron barrow, in which it is wheeled away to the yard and is ready for riddling for sale. As the exposed surface of the coke is seen to be red-hot more water is thrown in, and so on till all the coke is drawn and the oven is ready for recharging.

Each charge of 7 tons of coal yields about 4 or 5 tons of coke, or about 61 per cent; the same coal yielding in the laboratory about 72 per cent of coke. Very frequently the coal is charged in through the charging-hole in the roof, and the coke is cooled by throwing in water from a hose for 40 minutes.

Theory of the Process.—This is very simple. The heat of the oven causes distillation to begin, and the air coming in contact with the gases they burn and thus more heat is evolved, the whole heating taking place from above downwards. This is undoubtedly the best method of heating coal for coke-making, for the dense hydrocarbons coming up from the distilling coal and coming in contact with the incandescent coke are decomposed, permanent gases are evolved, and carbon is separated. This has some effect on the yield, but still more on the quality of the coke, giving to beehive coke a peculiar tubular structure. The bubbles of gas as they ascend are often decomposed bubble by bubble, leaving thin shells of carbon joined together so as to form long hair-like tubes. The coke at the top, and also that at the bottom of the oven in contact with the floor, is softer and more porous than that in the body of the oven, and these portions are usually separated and sold for purposes for which dense coke is not necessary. As the coke cools it breaks up into more or less prismatic masses, and is of a steel-gray colour. This is said to be due to the thorough escape of the gas, obtained by leaving the damper

Fig. 9.—Discharging Coke Ovens.

open some time after all the gas seems to be off; if this be not done, but the damper closed at once, or if the coke be drawn immediately all gas appears to be off, the coke comes out black and lustreless.

Smithy Char.—This is made in similar ovens and of the same coal. The oven being hot, ten hundredweight of coal is thrown in, then at intervals two more charges of the same weight are added, and the whole operation is completed in twelve hours, the 48 cwts. of coal yielding about 38 cwts. of coke, or nearly 80 per cent.

Modifications of the Beehive Oven.—This process, modified in various details, but the same in principle, is used all over the world, and many coke makers and users contend that it gives a better coke than any other process.

The Welsh Oven.—"This consists of a rectangular chamber covered with a flat arch, and provided with a door at one end. The width of the oven is from 7 to 8 feet, the length 13 to 15 feet, and the height does not exceed 5 feet. The oven is provided on the top with one or two charging holes and in the front with a lifting door. One oven is separated from the next by a relatively narrow wall not exceeding 2 feet in thickness. The back wall of the oven is also provided with an opening through which the waste gases escape to reach the flue, leading the same to the chimney, and before doing so are in many cases utilized for heating boilers."[1]

The oven is charged from the top, and "strikes" from the heat of the oven itself. The heating is partially from above, partially from the sides. Owing to the thinness of the side walls the structure of the coke, except that from the centre of the oven, is not columnar as in the beehive oven, but has a conical, or, as it is often called, "cauliflower" structure. The average make is 6 tons 5 cwts. per week, and the yield 58 to 60%.

Connellsville Ovens.—At Connellsville, Pennsylvania, the great coke district of the United States, beehive ovens are

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[1] R. De Soldneoff, *J.I. and S.I.*, 1894, ii. p. 215.

used exclusively. They are about 12 feet in diameter and 7 feet high in the clear. They are charged through a hole in the roof, and each oven holds $4\frac{1}{2}$ to 6 tons of coal. The charge is levelled through the working opening, which is then walled up with brick. Coking is completed in about 72 hours. The door is taken down, water is thrown in with a hose to cool the charge, which is then drawn. The yield is about 67%.

The ovens are built of brick faced with sandstone, and are arranged either in single rows on the hillside (bank ovens) or in double rows (block ovens).

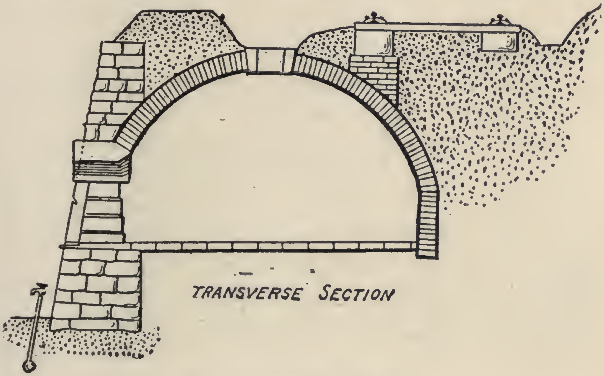

Fig. 10.—Connellsville Coke Oven.

Sources of Loss.—The beehive oven, though it yields an excellent coke, is not by any means an economical apparatus, as there is considerable loss both of matter and of energy.

The sources of loss of matter are—

1. Coke consumed.
2. The products of distillation, liquid and gaseous, are lost.

The sources of loss of energy are—

3. Heat lost by radiation, especially during charging and discharging, and in the interval between these.
4. Heat carried away by the products of combustion.
5. The potential energy of the combustible products of combustion.

The loss under the first head is very considerable, frequently amounting to 10 to 15%, and it can only be completely prevented by the use of an oven in which no air is admitted to the coking chamber. Many suggestions have been made for minimizing it in the ordinary oven. The inner door already described does something, but not much. A far more efficient arrangement is to construct a circular air-passage in the masonry of the oven above the level of the charge, with openings by which the air can enter the oven.

The loss under the second head is prevented by the use of suitable ovens and condensing plant.

The loss of heat by radiation is reduced by building the ovens in blocks of 12 or 24, so that the four end ovens have only two sides exposed to the air, and all the rest only one, and by covering the roof with a layer of non-conducting material such as sand. The loss during charging and discharging can be much reduced by performing these operations expeditiously by means of mechanical appliances.

The waste heat carried away by the products of combustion is almost always lost, though it is occasionally used for raising steam, and the heat due to the combustion of the products of combustion is at any rate partially used in promoting coking.

Cox's Oven.—This oven was patented in 1840, and is described by Dr. Percy. Though not now in use, it is of interest as marking a considerable improvement in some respects on the ordinary beehive type. The objects aimed at were as far as possible to avoid loss of coke by combustion and loss of heat by radiation. The circular form was abandoned, and the oven was made nearly rectangular, but slightly wider in the front than at the back, and with the floor sloping slightly towards the front. The roof was arched, and the side walls were carried to a considerable height above the roof, the space thus formed being filled up with sand. About eighteen inches below the arch was built a false arch, extending from the back to about a foot from the front. The open end of the oven was closed by a door which could be luted quite tight. The air was supplied by passages in the masonry, opening in front and running beside the space between the double arches, then passing to a descending passage and opening into the combustion chamber well above the surface of the coke. The coal was charged in through the front opening to a depth of 3 feet 6 inches, the door then closed as quickly as possible and luted with clay. The products of combustion passed away by the space between the two arches to the chimney.

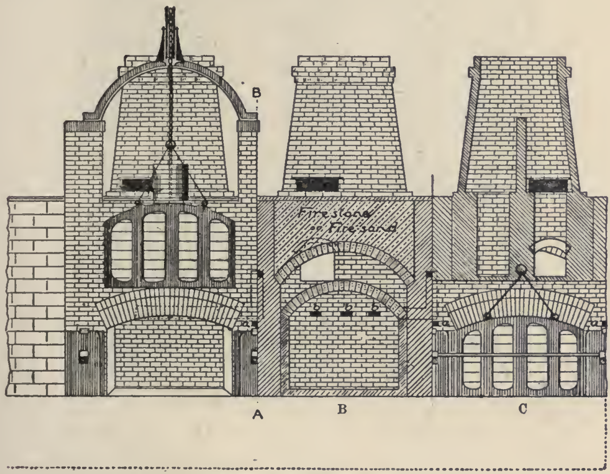

Fig. 11.—Cox's Coke Oven.

A, Front view with door raised. B, Section of oven showing the double and hollow arched roof. C, Front view with the door let down.

The discharging of such a long oven in the ordinary way would be inconvenient, so a drag was used. The drag consisted of a vertical piece of iron, fitting the lower part of the back of the oven, to which was attached a long iron rod, resting on the bottom of the oven. When the oven was to be drawn a chain was attached to this rod, and the mass of coke drawn bodily out. These ovens were said to be very successful, and to yield a good coke.

The Appolt Oven.—This oven, invented by the Brothers Appolt, is probably the most important of all the modern forms of oven in which the by-products are not recovered, and it is designed to prevent all chance of any of the coke being burned during the operation, and also to promote rapid and uniform coking. These objects are attained by coking in a separate chamber heated from outside by the combustion of the products of combustion. The coking chamber is in the form of a vertical fire-brick retort about 4 feet long, and 1 foot 6 inches wide at the base, and 3 feet 8 inches long, and 13 inches wide at the top, and about 16 feet high. Twelve to twenty-four retorts are built together into a block in such a way that an air space 8 or 9 inches wide is left round each of them, and the whole is inclosed in very thick walls. The retorts are held in position by cross bricks built in at intervals, tying them to the outer wall or to each other. The top of each retort is narrowed and provided with a charging hopper, and the bottom is closed by an iron door or pair of doors, opening outwards into a vault extending under the whole length of the retorts, and in which are rails, so that trucks

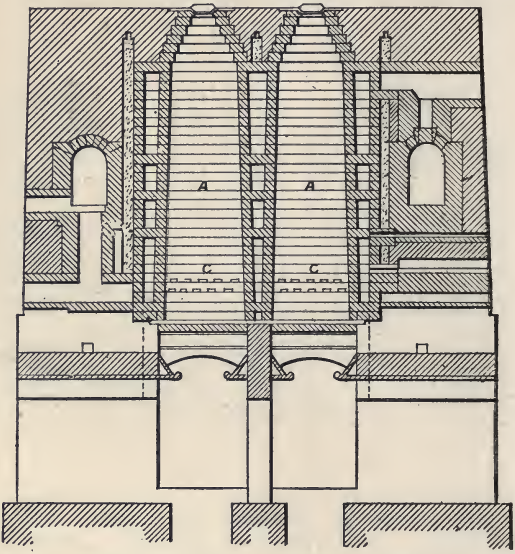

Fig. 12.—Appolt Coke Oven. A, Coking chambers. C, Lower tier of holes.

can be run under to receive the coke. The interior of each retort is connected with the outer space by two or three series of openings—one set near the bottom, another near the top, and sometimes a third about half-way up, and air is also admitted from outside.

The retort having only just been discharged, the bottom doors are closed, a charge of about 1¼ tons of finely-divided coal is let in, and the top is closed. The retort being very hot distillation commences at once, and the products pass through the openings into the outer space, where they burn; thus each retort is surrounded by a mass of flame, and since no air enters it, combustion of the coke is impossible. When coking is complete, the bottom doors are opened, and the charge falls out into an iron truck placed beneath, and is at once quenched with water

The retort being heated all round, coking is very rapid and uniform, and is completed in about 24 hours, and the work is so arranged that one retort is discharged and recharged every hour. When an oven is being newly lighted, temporary bars are put across the bottom of the retorts, and fires are kindled on these till the temperature is high enough for distillation, after which the ovens are charged in regular order.

The yield in these ovens is large, about 10% higher than that from the same coal in beehive ovens, and the coke is hard, dense, and of excellent quality. The first cost of the ovens is high.

The Coppée Oven.—These ovens, which have been also largely used on the Continent, are based on exactly the same principle as the Appolt oven, but the arrangement of the retorts and combustion chambers is quite different. The retorts are horizontal chambers about 30 feet long, 18 inches wide, and 4 feet high; they are built of fire-brick in stacks of 22, 24, or 50, side by side, and are worked in pairs, one being charged when the coal in its neighbour is half-coked. The oven tapers slightly from back to front, and is closed at each end by two well-fitting iron doors, the lower door being about 3 feet high, and the upper 1 foot. In the roof are a series of hoppers for charging, and each retort communicates by openings near the top with the combustion chambers outside.

The oven being hot, the lower doors at each end are closed and the coal is let in through the charging hoppers, and is quickly levelled by means of rakes through the upper doors, which are then closed. The products of distillation pass out of the retorts into the vertical flues between them, where they mix with air and burn. The products from the two contiguous retorts pass together into the horizontal flue under one of them, back under the other and to the main flue, and thence to the chimney, being often used on the way to raise steam.

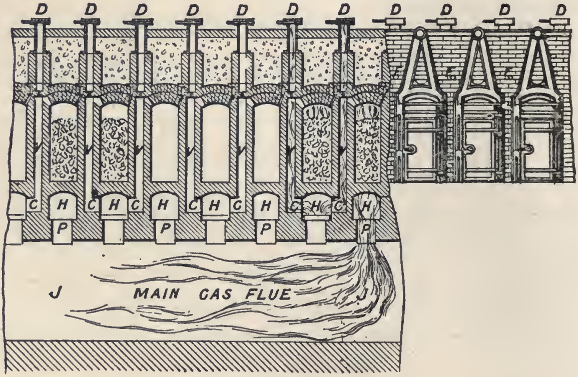

Fig 13,—Coppée Coke Oven.

V, Vertical flues between retorts. H, Horizontal flues. C, Flue connecting contiguous horizontal flues. P, Passage to main gas flue.

When coking is complete, the doors at both ends are opened and the coke is forced out at the wider end of the oven by a ram carried on a truck running on rails behind the ovens, and is instantly quenched with water.

The whole operation of charging occupies only about eight minutes. The coking occupies from twenty-four to forty-eight hours, and the coke yielded is hard and dense.

The Jameson Oven.—This is a modification of the beehive oven, arranged so as to allow of the recovery of the by-products with the smallest possible alteration of existing beehive ovens, and also without interfering with the heating from above. The bottom of the oven is provided with a series of passages covered with perforated tiles and uniting into a common discharge-pipe, by which a portion of the products of distillation are drawn away by suction. Air is admitted above the charge, and is drawn downwards. It is quite obvious that heat must be supplied by the combustion of the surface coke, and therefore that the yield must be low; but Mr. Jameson contends that this is more economical than burning the products of combustion in the usual way. Distillation takes place at a low temperature, the tar therefore is poor and the yield of ammonia is low, being only equivalent to about six pounds of ammonium sulphate per ton of coal. It will be seen that though heating from above is retained, the conditions are so changed that all the advantages of this method of heating are lost.

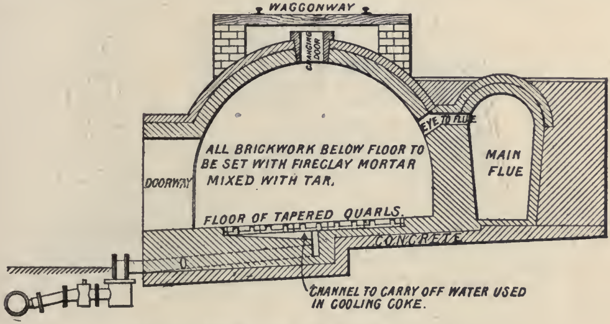

Fig. 14.—Jameson Coke Oven. From *J. I. and S. I.*

The Pernolet Oven.—This is another modification of the beehive oven to allow of recovery; it was one of the first introduced, and is also one of the simplest. The floor of the oven is raised about six inches or so, so as to leave a space beneath, at one end of which is arranged a small fireplace. The discharging door is so made that it can be securely luted; the charge is introduced through the roof by means of an opening (B), which can also be closed air-tight, and a pipe is fixed through the roof leading to the condensers. The products of distillation are passed through the condensers, and the permanent gases are returned and burnt under the oven, the fire in the fireplace serving to keep it alight and prevent any explosion by the accumulation of combustible gases.

The form of the beehive oven may be retained, or the oven may be made rectangular, but the whole principle of working is changed, and heating from below is substituted for heating from above. As no air gets into the oven the yield will be high, but the coke obtained is soft, porous, and black.

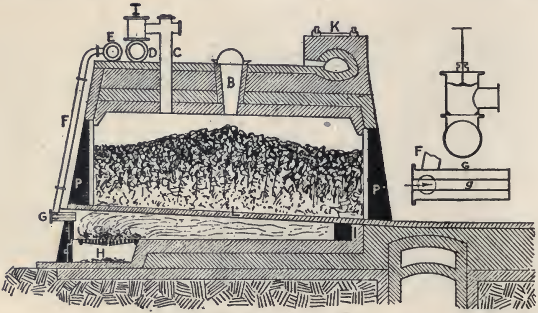

Fig. 15.—Pernolet Coke Oven.

B, Charging opening. C, Gas-pipe. D, Gas main. E, Return gas main. F, Gas-pipe. G, Gas burner. H, Hearth on which fire is kept burning. P, Doors.

The Bauer Oven.—This oven is a modification of the Appolt, or vertical retort type of oven, arranged so as to allow of the recovery of the by-products. Many such ovens have been devised, but this one may be taken as a type since it is probably more largely used than any other.

In the form of oven erected for Messrs. Baird & Co. at Dalry the stack is circular, the ovens being arranged in a series of forty round a central chimney, the retorts being therefore placed radially. Each retort is 10 feet high, 6 deep, and about 1 foot 4 four inches wide at the bottom, tapering to 1 foot at the top; the bottom of the retort is curved, so that when the iron door is opened the coke can slip out into a truck placed in front. The charge is introduced through a charging hopper at the top. The products are drawn off by a pipe, and after passing through the condensers the gases are returned to the oven. They pass into a combustion chamber, where they are mixed with air which has been admitted by a passage at the bottom, and heated by contact with the hot walls of the regenerative chamber. The burning gases pass down behind the retort, more air being admitted if necessary. The products of combustion circulate through heating chambers between the retorts, through the alternate passages of the regenerator and away to the chimney.

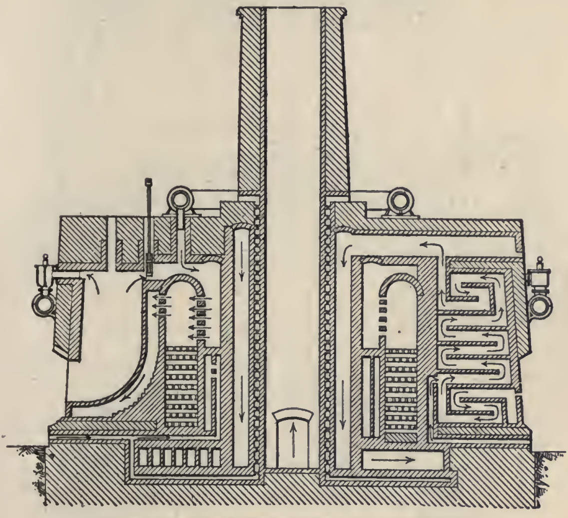

Fig. 16.—Bauer Coke Oven at Dalry. From *Engineering.*

Left-hand, section through coking chambers; right-hand, through heating flues.

If condensation is not required the gases may be passed at once from the retort to the combustion chamber.

Each retort holds two tons of coal, so that the whole charge is eighty tons, and the time occupied in coking is twenty-four hours.

It is claimed that this oven yields a good strong coke and large quantity of by-products.

The ovens are not necessarily arranged in circular form, but may be in rectangular blocks. A block of this form of 50 one-ton ovens at Creusot had up to 1886 worked 1800 charges; of these 100 were carefully weighed, and the yield was $80\frac{3}{4}\%$ of coke.

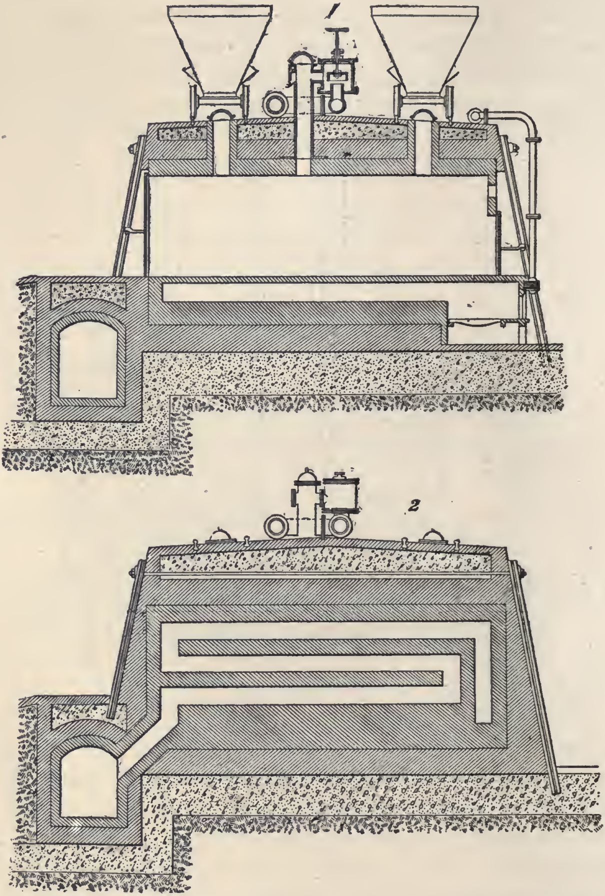

Fig. 17.—Simon-Carvès Coke Oven. Section through chamber and through flues.

The Simon-Carvès Oven.—Of all the forms of oven arranged for the recovery of the by-products this is the most used, at any rate in this country. It is a modification of the Coppée oven, or rather, perhaps it should be said, is of the Coppée type, with arrangements for the recovery of the by-products. The retorts are horizontal, 30 feet long, 2 feet wide, and 6 feet 6 inches high, and they are built in blocks of 20 to 60. The roof is covered with a layer of sand or non-conducting material, and is provided with three openings, the middle one connected with the condensing plant and the other two fitted with charging hoppers for the introduction of the charge. The ends are closed with iron doors, near the top of which are two openings also closed by iron shutters, through which tools can be introduced for levelling the charge. The oven being hot from the previous charge, the doors are closed, the fresh charge let in and levelled as quickly as possible, and the small openings then also closed. Distillation at once commences, and the products of distillation are passed through condensers, where the condensible products are separated and the permanent gases are returned to be burned under the oven. A small fire is kept burning to make sure that the gas shall not be extinguished, and the burning gas passes along under the whole length of the oven, back again, and then circulates through flues between the walls, by which means the retort is thoroughly heated. The products of combustion on their way to the chimney pass through alternate passages of

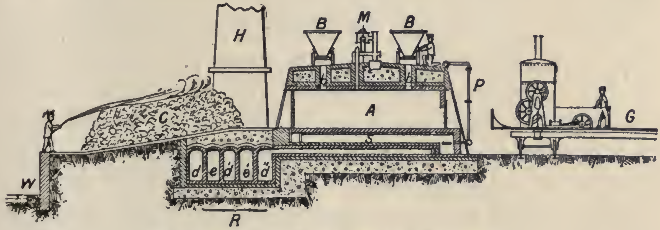

Fig. 18.—Simon-Carvès Coke Oven and Recuperator.

A, Coking chamber. B, Charging trucks. M, Gas main. P, Return gas main. S, Combustion chamber. R, Recuperator. *d*, *d'*, *d''*, Air-passages. *e*, *e'*, Chimney passages. G, Ram.

a fire-brick chamber or recuperator, through the other passages of which the air necessary for the combustion of the gas is passed, so as to become heated on its way. The coke is expelled from the oven by means of a ram carried on a truck which runs on rails behind the oven, and is at once quenched with water. The coking takes forty-eight hours. The coke is hard and compact, but is black instead of gray, and has no metallic lustre. As no air finds its way into the oven, no coke can burn, and the yield is high, over 10 per cent more than in beehive ovens, and the products of distillation are very perfectly recovered.

The Otto-Hoffman Oven.—This oven is of the Coppée type, *i.e.* it consists of horizontal retorts placed side by side. The arrangements for charging by openings in the roof, and discharging by means of a ram from one end of the retort, are almost exactly the same as in the Simon-Carvès oven. The difference is in the arrangement of the flues, and in the use of a regenerator to heat the air before the combustion of the gas. Two regenerators are used, which are alternately heated and used for heating the gas. They are long chambers, filled with a chequer-work of fire-brick, placed underground and extending the whole length of the set of ovens. At one end they communicate with the chimney, and with the source of air-supply—a fan or blower of any type—communication with either being opened and closed by means of a valve as required. A combustion chamber under each oven also communicates with the top of the regenerator by means of a valve. This combustion chamber is divided in two by a cross wall, so that there is no direct communication from one regenerator to the other. Each half of the combustion chamber communicates with a series of vertical flues in the wall of the oven by means of openings, and the flues from both combustion chambers enter a horizontal flue about the level of the top of the ovens. The coke having been withdrawn, the fresh charge is let down, levelled, and the doors are closed; distillation commences, the products pass through the condensers, and the gases are returned to one end of the combustion chamber under the retort, where they meet hot air from the regenerator, and combustion takes place. The products of combustion pass up the one set of vertical flues into the horizontal flue, down the other set into the other half of the combustion chamber, and away through the regenerator to the chimney. About every hour or so the direction of the air and gas is changed, so that the regenerator, which before was being heated by the products of combustion, now heats the air, whilst the other receives the hot products of combustion.

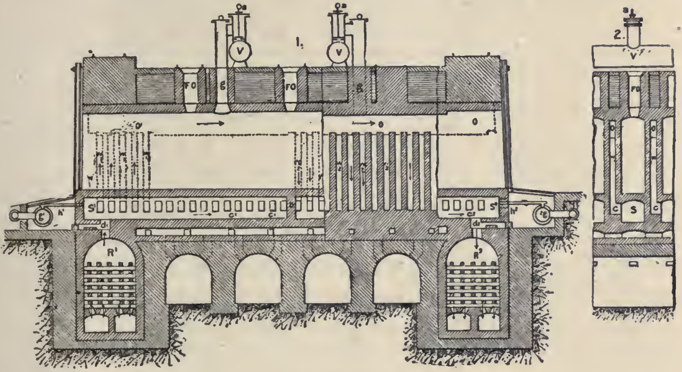

Fig. 19.—Otto-Hoffmann Coke Oven.

R^1, R^2, Regenerators. S, Combustion chamber. O, Upper flue. W, Vertical flues connecting O and S'. F O, Charging openings. V, Gas mains. C, Lateral openings from vertical flues. *d*, Hot-air passage from regenerator. *g*, Return gas main.

By use of these regenerators a very high temperature can be attained, the temperatures given by Dr. Otto being—

In the combustion chamber, ...	2200°–2550° F.
In the vertical flues, ...	2000°–2200° F.
In the regenerator, when air was first admitted, ...	1800° F.
One hour afterwards, ...	1330° F.
In the chimney, ...	800°–932° F.

The whole of the gas is not needed for coking. Dr. Otto says: "In one of our German coking works we produce, per coke oven per day, 24,700 cubic feet of gas, whereof we require for the coking process only 17,700, so that we have a surplus of 7000 cubic feet of gas per oven per day".[1]

Each retort holds from 5 to 6 tons of coal. The coking is complete in 48 hours. This oven is very largely used in Germany at the present time, there being 1759 in use up to the end of 1894.[2]

The Semet-Solvay Oven.—This oven, which is coming largely into use, is of the same type. The coking chambers or retorts are 10 metres long, 1·7 metres high, and from ·350 to ·500 metre wide, according to the nature of the coal being coked; the "rich coals with a high percentage of volatile matter should be treated in wider ovens, lean coal with a small percentage of volatile matter should be treated in narrow ovens".[3] The ovens are built in batteries, as in the case of others of the same type. The chambers consist of walls of brick covered with arches, well protected to prevent radiation. These chambers form the skeleton, and are "filled in on each side of each supporting wall by channel bricks containing the heating flues. These channel bricks are rebated one into another so as to break the joints, and as they have only their own weight to support, there is no fear of cracking or bulging when they are highly heated and when the process of coking is proceeding."[4]

The coal is charged in through hoppers in the roof, and is discharged by a ram through the end doors. The gases are drawn away through an opening in the roof, passed through the condensers, and delivered, together with heated air, into the top horizontal flue at the ram end of the oven, pass the whole length of the oven, and descend into the next flue, where they meet another supply of gas and heated air; then back along the third flue and into the common-flue under the oven, where the gases from the two sets of flues meet, and the hot gases may be used for steam-raising on their way to the chimney. The air is heated by passing through flues under the hot floor of the oven.

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[1] *Journal Iron and Steel Institute*, 1884, vol. ii. p. 520.

[2] *J.S.C.I.*, 1895, p. 339.

[3] Darby, *J.S.C.I.*, 1895, p. 337.

[4] Darby, *J.S.C.I.*, 1895, p. 337.

The yield of coke is very large, and it is hard and dense, "bright and silvery", when first drawn, but becoming black when cooled with water. The time of coking is about 22 hours, and each oven holds about 4 tons of coal.

Among the advantages claimed for this oven are the ready heating, owing to the thinner walls of the heating flues (these being able to be made thin as they have only their own weight to support) and the readiness with which the parts can be replaced.

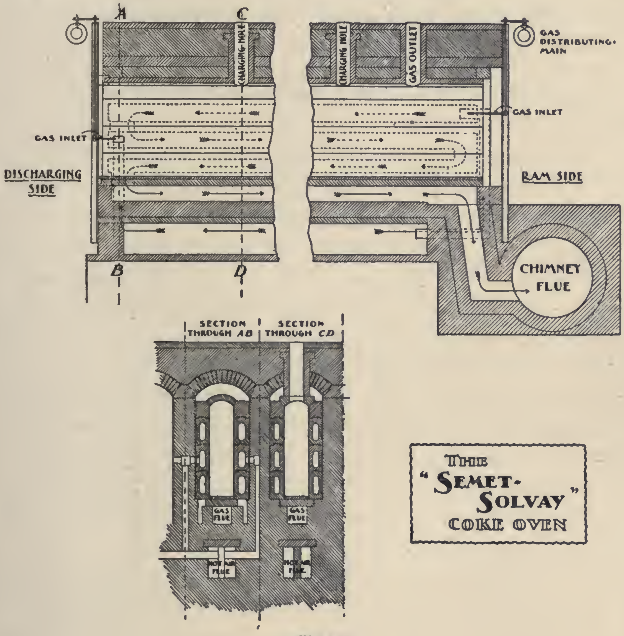

Fig. 20.

The Lürmann Oven.—This is a continuous oven, and therefore works without intermission. It consists of a number of separate coking chambers, into which coal is fed automatically. The gaseous products pass away to condensers, and are returned and burnt in flues surrounding the retorts. The coke falls into a large receiving chamber, whence it is drawn at intervals.

Coke from Non-caking Coal.—Coals which have but little caking power can sometimes be coked by using a very high temperature. It has been suggested to make coke from such coals by mixing them with slack of coking coal, pitch, tar, or other adhesive materials; but the cokes thus obtained are usually of very inferior quality.

Comparison of Coke Ovens.—It is not easy to compare the relative merits of coke ovens, so many points have to be taken into account, and the various types not having been tried side by side on the same quality of coal; and even if they were it would probably be impossible to select a best, for what would be best under one set of conditions would not be best under another. The beehive oven is excessively wasteful; not only are all the by-products lost, amounting, in Great Britain, according to Mr. Darby, to no less than 200,000 tons of ammonium sulphate per year, having a net value of about £1,625,000, in addition to enormous quantities of tar and other products, but there is a loss of 10 per cent or more of coke actually burned in the process. The annual production of coke in Great Britain is, according to Mr. Darby, about 10,000,000 tons, so that a loss of one-tenth of this would be no less than 1,000,000 tons.

All this might be saved by the use of the recovery ovens. There is a feeling among iron-masters that the coke made in recovery ovens is not as good for blast-furnace use as that made in beehive ovens, and some contend that that made in the more wasteful open heap is better still.

Sir I. Lowthian Bell states that he found that coke made in beehive ovens was more efficient than that made in Simon-Carvès ovens, and that the relative quantities required to produce one ton of pig-iron was as 100 : 91, whilst the actual carbon content was in the ratio 100 : 98·5. On the other hand, Mr. Darby states that Semet-Solvay coke is quite satisfactory for blast-furnace use, and that less coke is required than when beehive coke is used.[1] It will probably be found ultimately that coke can be made in the recovery ovens quite equal in all respects to that which can be made in beehive ovens, in which case great saving will result; but even if the quality of the coke should be slightly inferior, the by-products will still make it more economical in use.

In many cases ovens of the modern type have been put up, and abandoned without a fair trial; and in other cases failure has been due to faulty design, or to not adapting the ovens to the class of coal to be used. It is difficult to compare the various forms of recovery ovens, but the Semet-Solvay, Simon-Carvès, and Otto-Hoffman are among the best.

Recovery-oven coke is usually denser than beehive coke. It is strong, but is dull black in colour, and has not the metallic lustre and tubular structure of beehive coke.

Removal of Sulphur from Coke.—Sulphur is very objectionable in coke, and many attempts have been made to prepare a coke containing but little sulphur, but up to the present without success, except by purifying the coal by washing before coking.

When hot coke is quenched with water, hydrogen sulphide is evolved by the action of the water on the sulphides: $FeS + H_2O = FeO + H_2S$, $CaS + H_2O = CaO + H_2S$, and it has been suggested to make use of this reaction for the desulphurization of coke, by treating it with superheated steam. In some experiments Scheerer found that by treating a coke containing ·71 of sulphur about 60 per cent of this was removed, the residue only containing ·2 per cent; but such results have never been obtained on the large scale. It is impossible to make the steam reach every particle of the coke, and if the temperature is at all high the coke itself is acted on by water with evolution of hydrogen and carbon monoxide. Treatment with dilute acid has also been suggested, but the removal of the sulphur is very partial.

Mr. Calvert suggested mixing the coal before coking with common salt, a complex series of reactions being said to take

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[1] *American Manufacturer*, vol. lvi, p. 442.

place by which sulphur would be evolved. Many other methods have been suggested, but none have been successful.

Comparison of Coal and Coke.—Weight for weight, coke is a much more powerful heating agent than coal, but compared with the coal from which it is obtained the heating power of coke is much less, so that the loss of heating power by coking is very considerable. Even if the by-products are recovered, a considerable amount of heat will be used in distilling the coal. The whole of this heat, however, would not be recovered if the coal were burned in an ordinary fireplace, for the gas is there distilled out and then burned. When the flame is required, as in a reverberatory furnace, coal is best; but when the heating is to be by contact or by radiation, coke is preferable. In cases where the production of smoke is very objectionable, coke is used, though for boilers and similar furnaces it is quite unsuitable. It is often thought that coke contains more sulphur than coal, but that is not so, as has been already pointed out. The error has arisen from the fact that the other products of combustion being odourless, the sulphur dioxide produced by the combustion is more readily detected.

Briquettes.—Within the last few years fuel-blocks, or briquettes, have come largely into use. They are usually made of fine coal or other combustible material, cemented together by some cement. The combustible material is nearly always coal, but saw-dust, spent-tan, peat, and other materials have been suggested. The cementing material is usually pitch, but farina (starch), gelatinous matter obtained by boiling seaweed, dextrine, molasses, clay, Portland cement, lime, and plaster of Paris have all been patented for the purpose. The only materials in practical use are coal and pitch.

The variety of apparatus invented for making the blocks is probably even greater than that of the materials used.

The briquettes are usually made up into rectangular blocks weighing about 4½ to 9 lbs. The following analyses will indicate the nature of the commercial briquettes:—

	1.	2.	3.	4.
Volatile matter,	27·67	33·0	15·0	45·85
Coke,	68·18	59·4	84·0	39·27
Fixed carbon,	57·48	56·2	80·0	28·93
Ash,	10·7	3·2	4·0	10·34
Moisture,	4·15	7·60	1·0	...

1. Govan.
2. Coltness.
3. Welsh (average).
4. Russian, made from charcoal and pitch.

The blocks should be uniform in texture, and should be so strong that there is little loss by breakage in transport. Such loss should not exceed 5 per cent, though with most blocks at present made it is far higher. They should not contain more than 5 per cent of moisture and 5 per cent of ash. As many blocks absorb water very readily, attempts have been made to waterproof them by dipping in molten pitch, solution of silicate of soda, or other material; but none of the methods have come into general use. The blocks should not crumble when heated, though unfortunately many varieties do.

Briquettes have one great advantage over coal: being in uniform blocks, they pack easily and into small space. This is, however, only the case when they can be stacked by hand, and does not apply to cases in which they are thrown in in bulk, as when loaded into the hold of a ship. In this case it is very doubtful whether briquettes would occupy less bulk, weight for weight, than coal. The heating power of briquettes is about equal to that of the coal from which they are produced, the evaporative power being from 8 to 9 lbs., the calorific power about 14,000 B.T.U.

Manufacture of Briquettes.—The coal, preferably after washing, is either crushed in rolls or broken up by a disintegrator into a coarse powder. If very wet, as when sludge is used, it is then allowed to drain, and is dried in ovens preferably heated by steam, many forms of drying-oven having been designed to deal with the materials automatically and at the lowest possible cost. If the coal be not well dried a larger proportion of pitch is required to bind it. The pitch used is usually that obtained by the distillation of blast-furnace tars. It is quite hard at ordinary temperatures, but softens at about 170° F. The pitch is broken into small pieces and mixed with the coal before it is passed to the disintegrator, the pitch and coal being supplied in the required proportions by means of measuring apparatus or distributors of some kind. The finely-powdered mixture is transferred to a pug-mill, which consists of a vertical wrought-iron cylinder, 30 inches to 42 inches in diameter, and 6 or 8 feet high, containing a central shaft which makes from twenty to twenty-five revolutions per minute, and carries arms designed to turn over the paste and force it downwards. This is either steam-jacketed or arranged so that steam can be blown into it, the paste being in the latter case heated by mixing with the steam. The first is called the 'dry-heat', the second the 'wet-heat' process. In either case the steam may be superheated. "The weight of steam required to heat one ton of the mixture to 100° C. is theoretically only about 10 lbs., but in practice nearly 100 lbs. is used."[1] The presence of a small quantity of moisture (3 to 5 per cent) in the coal is essential, but the "wet-heat" process is apt to introduce too much, unless the steam be superheated before use; but it must not be heated to too high a temperature (above 200° C.) or pitch may be volatilized. The paste is passed from the pug-mill into the compressing moulds, where it is subjected to great pressure and thus solidified into blocks. Very many forms of compressing machines have been devised. In the simplest form a series of moulds are carried on a horizontal rotating table, above which is a hydraulic or steam ram. A mould is filled with paste, which should not be at a lower temperature than about 70° C., from the mixer, and the table is turned so as to bring it under the ram, which is then brought down and compresses the block; the ram is then raised, the table turned, the block removed from the mould, and the mould refilled. The table carries at least three moulds, so

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[1] Colquhoun, *Min. Proc. Inst. C.E.*, cxviii. p. 210.

that while one is being filled another is being pressed and the briquette is being removed from the third. In the type of machine made by Messrs. Yeadon of Leeds the moulds are cavities in a vertical rotating disc. Each disc has sixteen moulds, placed in pairs radially, so that two blocks are made at each stroke. The disc being in position, two moulds are filled from the mixer, two blocks are compressed, and two are expelled. A rotation of one-eighth of a circle brings two freshly-filled moulds opposite the compressing ram, two pressed blocks under the expelling ram, and two empty moulds under the spout from the mixer—the three operations being simultaneous. As the blocks are expelled they push the pair previously expelled on to the endless band by which they are carried away.

Such a machine will turn out about forty briquettes per minute.

In other forms each mould has its own ram, and in others the paste is forced out in a continuous prism, which is cut up into pieces of the required size by wires. The briquettes as they are removed from the press are soft and friable and will not bear handling. They are put on to an endless band and conveyed to the store, where they are carefully stacked, or they are delivered at once into trucks.

Cost of Briquette Making.—The cost of manufacturing at an English works, making 102½ tons per day of ten hours, with two presses, is given by Colquhoun[1] as 9*s*. 7·48*d*. per ton, made up as follows:—

	s.	*d.*
Labour, ...	1	0·85
Supplies, ...	0	5·50
Fuel (for boilers, &c.), ...	0	7·22
Materials for briquettes, ...	7	1·70
Interest and depreciation, ...		4·21
	9	7·48

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[1] *Min. Proc. Inst. C.E.*, cxviii.

CHAPTER V.

COAL-WASHING.

Object of Coal-washing.—When coal is raised from the pit it comes up in pieces of various sizes, the breaking of which necessarily produces a large amount of slack or smalls. For the market these must be removed either by hand-picking or sifting. The small coal is usually unmarketable, owing to the large quantity of dirt—shale and pyrites—which it contains.

For coke-making, and to a less extent for boiler-firing and producer-gas making, it is important that the coal should be as free as possible from ash and sulphur. For these purposes the coal may be used in a fine state of division, and as the sulphur is mostly present in the form of pyrites, which is much heavier than coal, it may be separated by methods of washing analogous to those used for the dressing of metalliferous ores.

These methods have now come largely into use, and much dross, which would otherwise be quite valueless, has been rendered available for coke or briquette making and other purposes, while at the same time the larger "coals" have been improved by the removal of the smalls and earthy or pyritous matter which otherwise would have remained with them.

Principle.—Many forms of apparatus have been devised for coal-washing, but they are all based on the same principle, viz. that if particles of the same size, but of different weights, be allowed to fall through water the heaviest particles will fall most quickly. The rate of fall has been investigated by Rittinger, who gives the following formula as expressing the rate at which a body will fall in still water:—

$$V = 1{\cdot}28 \sqrt{D(d-1)}.$$

where V = velocity in feet per second, D = diameter of holes in riddle through which the substance has passed, d = density of the substance, and 1·28 a constant deduced from experimental results.

If the particles be all of the same density the falling through water will sort them according to their sizes; and if they be all the same size, but of different densities, it will separate them according to their density; whilst if they vary both in size and density, they will be separated in a way depending on the ratio of the two; hence for the complete separation according to density, good sizing is absolutely essential. If the water be in motion instead of at rest, the same law will hold good. If the water be flowing, the lighter particles, taking longer to fall, will be carried further forward. If the water be moving upward, the rate of fall will be diminished, and if the upward flow be rightly adjusted the lighter particles may be carried upwards whilst the heavier fall downwards.

There are two varieties of coal-washing machines in use—those in which the coal is washed by running water; and those in which the water is kept in agitation by a piston moving up and down, in a compartment of the washer, as in the ordinary Cornish jig, these being therefore called jig machines.

Either type of machine may be applied to the washing of coal in lumps, where the larger lumps are to be used for domestic or other furnace consumption, or for washing crushed coal for coke-making and similar purposes.

Trough Machines.—These usually consist of a series of inclined troughs, each terminating in a grating, through which the water and finer materials can pass into another trough below, the larger pieces passing over the grating into a receptacle.

The coal is supplied to the first trough, and is washed down by the stream. As it passes along an attendant picks out any lumps of shale and throws them on one side. The coal passes over the end of the grating into a receiver, and the finer particles pass through into the next trough. This trough is provided with riffle bars which retain the heavier particles of pyrites, whilst the lighter coal is carried away into settlers.

The separation is usually completed in jig machines.

Robinson Washer.—This consists of a truncated inverted cone, 8 feet diameter at the top, 1 foot 10 inches at the bottom, and 6 feet 6 inches deep. A strong shaft is fixed in the centre which carries a cross-head, to which are bolted wooden arms. To each of these arms are attached three vertical iron rods which nearly touch the side of the washer. The dross is delivered into the washer in a stream. Water is sent in at the bottom and rises upwards through a perforated movable bottom plate. The arms are kept in rotation, the coal is carried over the top of the washer, and the brasses, shale, and other heavy materials sink to the bottom and are removed at intervals.

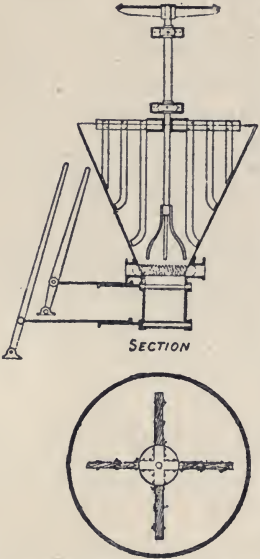

Fig. 21.—Robinson Coal-washer. From Lock's *Mining Machinery*.

Jig Machines.—These are much more efficacious than simple trough machines. The jigger is a vessel divided into two unequal parts by a vertical division reaching nearly to the bottom. Across the larger part is a horizontal screen perforated with holes. In the smaller part a piston is fitted air-tight. As the piston goes down the water is forced up through the screen in the other division, and as it rises the water returns. The coal is fed into the larger division on the top of the screen, and as the water is kept pulsating by the motion of the piston the coal is carried away through an opening near the top, whilst the heavier material escapes through an opening just above the level of the screen.

For washing fine coal the jigger is a little different in form. The screen is provided with openings large enough to allow the dirt, brasses, shale, &c., to pass through, and on this rests a layer of felspar or other similar material, just too large to pass through the holes. As the piston descends the water carries the felspar up with it, the lighter coal flows away as before by an opening near the top of the chamber, whilst the heavier dirt mixing with the felspar settles down; the dirt therefore works gradually downward and ultimately escapes through the screen into the space below, from which it is removed at intervals.

The Lührig Process.—Of all the complete systems of coal-washing which have been suggested the one which is most

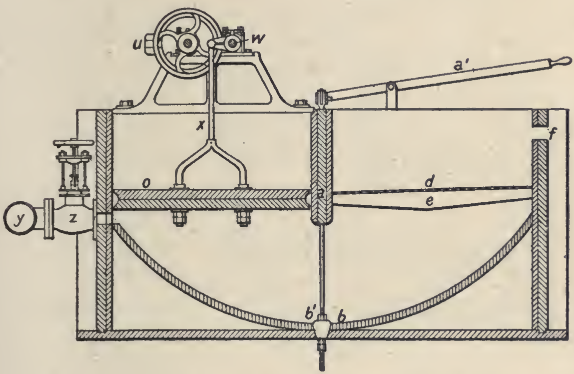

Fig. 22.—Lührig's Coal-washing Jig. From Lock's *Mining Machinery*.

***z*, Pipe for supply of water. *o*, Piston. *d*, Screen. *e*, Bars to carry screen. *f*, Opening for escape of coal. *b*, Valve for removal of sludge, worked by lever *a′*.**

largely used is that devised by Mr. Lührig, and it will be sufficient to describe it.

Assuming that the coal is to be treated as it comes to bank, *i.e.* it is not first crushed, the coal is brought up in tubs, which are automatically emptied over screens perforated with 2-inch holes, so that all coal smaller than that passes through.

The larger coal falls on to endless belts made of steel bars with spaces between, so that any small coal formed by breakage will pass through, on to another belt below. The large coal is picked by hand in the usual way, and at the end of the belt is a charging shoot, by which the coal is delivered into trucks; the lower end of this can be lowered so that the coal may fall into the truck without being broken.

Any pieces of shale which are picked out and which seem to contain coal are thrown into a hopper, whence they pass to a stone-breaker, and thence to the small-coal screens, and the refuse which does not contain coal is sent to the waste heap. The small-coal which passes through the screens falls into a hopper of 100 tons capacity, and thence is lifted by an elevator to the sizing drum. This is an inclined drum the surface of which is perforated with holes so as to sort the coal into four sizes: Treble nuts, 2 inches to $1\frac{1}{4}$ inches in diameter; double nuts, $1\frac{1}{4}$ inches to $\frac{7}{8}$ inch in diameter; single nuts, $\frac{7}{8}$ inch to $\frac{5}{16}$ inch in diameter; peas and small below $\frac{5}{16}$ inch; though of course other sizes may be substituted if required.

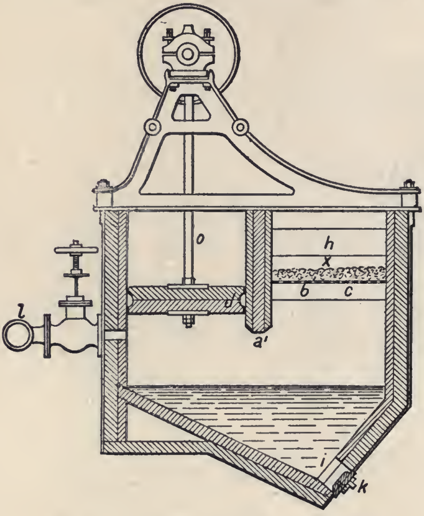

Fig. 23.—Lührig's Fine Coal Jig. From Lock's *Mining Machinery.*

l, Water pipe. *d*, Piston. *o*, Piston-rod. *b*, *c*, Screen and its supporting bars. *x*, Layer of felspar pebbles. *k*, Trap for removal of sludge. *h*, Overflow for coal.

Each size is conveyed by a shoot to its own washer. The washers are jigs as already described (Fig. 22), the stroke of the piston being regulated according to the size of the coal being washed. The screen is not provided with felspar pebbles, and the holes are smaller than the holes of the sorting screen, so that only the fine dust passes through. The coal is carried away by the water over the top of the jigger, and the dirt which accumulates on the screen is drawn off from an opening just above its surface.

The washed nuts pass over draining shoots, to which a shaking motion is given, to remove water, then to the loading hopper and to the trucks. As the coal passes down the shoots it is sprayed with water to remove any adhering dust.

The small-coal, as it comes from the sizing drum, meets the overflow water from the nut-washers, and is carried to a grading box consisting of a series of inverted pyramids, in which the small-coal is deposited in constantly decreasing sizes, the largest settling first and the finer in the later boxes.

The mixture of dirt and shale from the nut-washers is carried by a spiral conveyer to an elevator, and thence to rolls, by which it is crushed, and delivered to a shoot by which it descends and mixes with the small-coal.

The small-coal from the conical settlers passes to a series of small jigs (Fig. 23), the screens of which are provided with a layer of felspar. The washed coal flows away with the washing water to a revolving drum perforated with holes $\frac{1}{64}$ inch in diameter; the water and sludge escapes, and the coal passes to a hopper for loading. The sludge passes to a long trough or tank of brickwork or cement running underneath the building; as the sludge settles it is removed by scrapers on endless chains and delivered to a hopper, from which it may pass to felspar washers or may be simply dried and used. The water is kept in constant circulation and is used over and over again.

The plant is made to treat from 1000 to 3000 tons of coal per day.

Results of the Washing.—When this process is used coal can be utilized containing so much shale that it would otherwise be quite useless, and all the coal is very much improved. Less time need be spent in picking in the mine, and this alone would lead to considerable saving. At one colliery about 5400 tons of coal per year were thrown on one side as containing too much shale for use. By the Lührig process this was treated and yielded 4428 tons of marketable coal; and in addition to other saving, about 700 tons of pyrites, containing 40 per cent of sulphur, was obtained and sold.

The percentage of ash is enormously reduced, thus greatly increasing the value of the coal, as the following examples will show:—

Colliery.	Capacity of Plant per day.	Ash.	
		Unwashed.	Washed.
Aston Hall Colliery,............	1000	21	$4\frac{1}{4}$
Rosehall,..........................	800	20	$4\frac{1}{4}$
Bardykes,..........................	800	22	$4\frac{1}{2}$
Motherwell,.......................	1500	$21\frac{1}{2}$	$4\frac{1}{4}$

For coke and briquette making, washing is almost essential, if a good fuel is to be obtained.

The following tests, made at Ellenborough Colliery, near Maryport, will give some idea of the results obtainable:—

	Slack before Washing.	Pearl Coal, Air-dried $\frac{3}{16}$-$\frac{1}{16}$.	Sludge, $\frac{1}{16}$-0.	Coke from Pearl Coal.	Clean Pieces of Coal Picked.	
					Sp. Gr.	Ash.
Water,................	5·24	4·92			1·292	3·44
Coke,..................	65·27				1·255	1·60
Fixed carbon	42·86				1·256	1·80
Volatile,............	29·49					
Ash,..................	22·41	4·48	11·90	8·92		
Sulphur,............	1·69	1·11		1·28		

	1. Small-coal before Washing.	2. Mixture of Pearl Coal and Sludge.	Pearl Coal.	Sludge.	Coke from Mixture 2.
Sulphur,.................	1·35	·85			·99
Ash,......................	13·78	4·14	2·78	11·60	6·59

Coal in final dirt, 2·835 per cent.

CHAPTER VI.

LIQUID FUELS.

Natural Oils.—Natural oils or petroleums have been found in many parts of the world, but it is only lately that they have been worked in large quantities, and at present only two countries, the United States and Russia, yield them in sufficient quantity to be of commercial importance, and both of these yield large supplies of the oil.

The natural oils vary very much in colour, consistency, smell, and other properties; some are thin, limpid, and of pale colour, others are dark-coloured, and of nearly the consistency of treacle.

The petroleum from the oil-wells of America is mainly composed of saturated hydrocarbons of the paraffin series (C_nH_{2n+2}), sometimes containing oxidized bodies, the higher solid paraffins being dissolved in the lighter liquid members of the series. The oils always contain members of the olefine (C_nH_{2n}) and the benzene (C_nH_{2n-6}) series, and in some cases also sulphur, whilst the Russian petroleum consists much more largely of olefines. The following analyses by M. Goulishambaroff may be taken as examples:—

	Sp. Gr.	Composition.			C. P. British Units.	Evaporative Power.
		C.	H.	O.		
Russian crude petroleum, Light	·884	86·3	13·6	·1	22628	17·4
Russian crude petroleum, Heavy	·938	86·6	12·3	1·1	19440	16·4
Pennsylvanian crude heavy oil,	·886	84·9	13·7	1·4	19210	

These figures must only be regarded as examples, as the actual composition of the oils varies very much.

Occurrence of Petroleum.—Petroleum usually occurs impregnating porous sandstone or limestone rocks, these rocks sometimes holding as much as one-eighth their bulk of oil. "This means 1½ inches of oil to the vertical foot of rock, equal to 1000 barrels per acre. Carll states that the oil rock of the Venango[1] is from 30 to 50 feet thick in the third sand, and 15 to 30 feet in the other sands; assuming only 15 feet of good rock, this means 15,000 barrels per acre, or nearly 10,000,000 barrels per square mile."

The oil is obtained by means of wells sunk down to the oil-bearing strata, the oil being raised by pumping or otherwise. In many cases the oil flows from the bore-hole without the need for pumping, it having been confined in a synclinal trough or by a fault, so that the pressure of the mass of oil alone is sufficient to force it out of the opening, and thus to produce an oil spring or flowing well.

"Many facts support the theory that the oil-producing sands lie in pockets or patches surrounded by impervious rock, so that each pool forms a separate, and to a very large extent independent reservoir of oil."

Petroleum is not confined to rocks of any particular age, nor does it occur on any special geological horizon. The Pennsylvanian deposits are mainly in Devonian and to a less extent in carboniferous rocks. Part of those of Ohio and those of Kentucky are in Silurian limestone. The oil of the Florence field (Colorado) is in the cretaceous, the oil fields of California and also those of Eastern Europe are in tertiary rocks. Oil has even been found in volcanic rocks, though probably as an infiltration from saturated rock masses.

Origin of Petroleum.—Several theories have been advanced as to the origin of mineral oils, but up to the present the matter cannot be regarded as settled. It has been suggested that they might be due to the action of water on certain carbides, such for instance as calcium carbide, which under ordinary pressures yields acetylene, and which therefore under other conditions it is thought might yield other hydrocarbons.

The general view is that it is of organic origin, and derived either from plant or animal remains. Several eminent geologists have held that the oils have resulted from the distillation by heat of beds of coal or similar materials; but against this

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[1] Venango County in Pennsylvania.

may be put the fact that the beds in which the oil occurs show no sign of the action of heat. Another view, first propounded by Dr. T. Sterry Hunt, is that the oils have been formed from vegetable remains, but by a process different to that which produced coal. He held that vegetable matter may decay in two ways: (1) in presence of air and water, when the hydrogen and carbon will be partially eliminated, and a solid residue or coal will be left; or (2) in the absence of air and moisture, when the tendency would be to form saturated hydrocarbons.

More recently it has been urged that mineral oils are probably derived from animal remains, and C. Engler asserts that any animal fat can be converted into petroleum by distillation under pressure.

Crude petroleum is usually subjected to fractional distillation before use, and only the heavier portions are used for fuel.

Prepared Oils.—The prepared oils used for fuel are obtained by the distillation of—

1. Crude mineral oil.
2. Oil shales.
3. Blast-furnace tar and similar materials.

Distilled Petroleums.—The crude Pennsylvanian petroleum is distilled in iron retorts heated by a fire, and the products of distillation are passed through condensers which usually consist of straight lengths of pipe connected by return bends and contained in a large vessel of water. The distillate is turned into separate vessels as the temperature rises, so that four distinct distillates are usually obtained—light and heavy naphthas, and light and heavy oils—the division between the four varying in different works.

The yield is: naphtha 8% to 20%, oils 76% to 78%, residue 5% to 9%, and loss, *i.e.* permanent gases, about 5%.

The heavy oil may be used as fuel direct, or it may be subject to further fractional distillation so as to prepare different grades of burning and lubricating oils.

The custom at most of the Baku works is to distil off about 30% of the crude oil, and to use the residue, known as petroleum refuse, as fuel. The results obtained being: light petroleum 5 to 6%, burning oil (1), (kerosene) 27 to 33%, burning oil (2), (solar oil) 5 to 6%, residues 50 to 60%.

Shale Oils.—These oils are largely obtained by the distillation of bituminous shales. The nature of the shales can be seen from the following figures:—

	1.	2.
Volatile matter,	34·96	13·5
Coke,	65·04	86·5
Fixed carbon,	7·44	2·5
Ash,	57·50	84·0

1, Broxburn. 2, West Wemyss (Fife).

The shale is distilled in vertical retorts, into which steam is blown. The products of distillation are passed through condensers, which consist of several series of vertical tubes exposed to the air. The products, separated according to their condensibility, consist of crude oil, sp. gr. ·890–·896; light oil, ·790–·805; naphtha, ·730, and large quantities of permanent gases which escape. The oils are further refined by fractional distillation and treatment with acids and alkalies, and separated into the various grades of illuminating and lubricating oils and petroleum naphthas.

Oil from Blast-furnace Tar.—The tar obtained from the waste gases of blast-furnaces fed with coal is the source of a considerable quantity of oil suitable for use as a fuel. Each ton of coal consumed yields about 40 gallons of tar; this is distilled in wagon-boiler retorts, and each 100 parts yields about 50 parts of water, 20 parts of oil, and 30 parts of pitch. The oils obtained are divided into two portions—heavy or creosote oils, which have a specific gravity of ·960 to ·980, and light oils or spirit, having a specific gravity of ·900 to ·901. The heavy oils are those which are used as fuels.

Oils as Fuels.—Oil fuels have many advantages over solids, among which the following may be noted:—

1. Reduction of weight by about 40 per cent.
2. Reduction of bulk by about 35 per cent.
3. Reduction of number of stokers required in about the ratio 4 : 1.
4. Very small proportion of ash in the fuel.
5. Prompt kindling of fires and consequent early attainment of the maximum temperature of the furnaces.
6. The fire can be extinguished at any moment.
7. Uniformity of combustion and therefore of heating power.

Against these advantages may be set the disadvantages of:—

1. Danger of explosion.
2. Loss of fuel by evaporation.
3. Unpleasant odours.

These are, however, of little importance, and no doubt will be effectively guarded against as oil comes to be better known and more largely used as a fuel.

Cost of Oil.—Whether or no oil will ever be largely used as a fuel will depend almost entirely on its price, and on the economy with which it can be used. The following case, worked out in America, will show the lines on which a comparison must be made, though it is, of course, of no other value:—

"The coal used in the experiments evaporated 8 pounds of water per pound of fuel, which was equal to 7729 units; as the calorific power of the fuel was 14000 units, the useful effect was 55·2 per cent, and one ton (2000 lbs.) of coal would evaporate 16,000 pounds of water at a cost of 3 dollars.

"The oil had a calorific power of 20479 units, and if the efficiency were the same as that of the coal, would evaporate 11·7 pounds of water. A gallon of the oil (sp. gr. ·87) would weigh 7·27 pounds, and costs ·016 dollar, so that 187·5 gallons would cost the same as one ton of coal, and would evaporate 15,938 pounds of water, almost exactly the same as the coal." But all incidental expenses would be much in favour of the oil.

Future of Oil Fuel.—There can be little doubt that in the future oil fuel will be more largely used as its advantages come to be recognized. That it will supersede coal, either used directly or through the form of gas, is not at all likely, but there are very many purposes for which its use will be very advantageous.

The following table will show the relative heating values of petroleum and coal:—

Fuel.	Sp. Gr.	Composition.				C. P.	E. P.
	32° F.	C.	H.	O.	S.	B.T.U.	Water at 212°.
Pennsylvania heavy crude oil, …………	·886	84·9	13·7	1·4	—	20736	21·48
Caucasian light crude oil, …………………	·884	86·3	13·6	·1	—	22027	22·79
Caucasian heavy crude oil, …………………	·938	86·6	12·3	1·1	—	2085	17·3
Petroleum refuse,. ….	·928	87·1	11·7	1·2	—	19832	17·1
Good English coal, mean of 98 samples,	1·380	80·0	5·0	8·0	1·25	14112	12·16

CHAPTER VII.

GASEOUS FUEL.

Natural Gas.—In certain localities considerable quantities of combustible gases are given off from the earth, and in Pennsylvania these have been largely used as fuel. In many cases in boring for oil vast reservoirs of gas, evidently under great pressure, were struck, which therefore escaped with great force. It was, however, some years before anyone thought of utilizing this gas for fuel, though its heating power was well known. The first attempt was made in 1879, when pipes were laid to carry the gas from one of the vents to an iron-works near Pittsburg, where it was used for puddling.

The amount of gas escaping is very large. It was estimated that in 1885 there were 50 gas wells at work, yielding in the aggregate about 100,000,000 cubic feet of gas per day. The pressure at which the gas escapes varies much, and at Pittsburg is from 100 to 200 lbs. on the square inch. The gas region covers a very large area, and is very intimately connected with the oil-bearing region, the two indeed being geologically identical, though the gas-field seems to cover a larger area. Gas very generally accompanies natural oils, but occurs also in coal districts.

Composition of Natural Gas.—Natural gas consists almost entirely of marsh-gas (CH_4) and hydrogen, and has a very high calorific power. The following analyses (Ford, quoted in Mills and Rowan's *Fuel*) will give an idea of the composition of the gas:—

	1.	2.	3.	4.
Carbonic acid, CO_2,	·8	·6	—	—
Carbonic oxide, CO,	1·0	·8	·58	1·0
Oxygen,	1·1	·8	·78	2·10
Ethylene (olefiant gas),	·7	·98	·98	·8
Ethane,	3·6	5·5	7·92	5·20
Marsh-gas,	72·18	65·25	60·70	57·85
Hydrogen,	20·62	26·12	29·03	9·64
Nitrogen,	—	—	—	23·41

To calculate the calorific power of the gas, Mr. Ford assumes the following average composition:—

Carbon dioxide,	·6	·6 litres =	1·2275 grms.
Carbon monoxide,	·6	·6 ,,	·7526 ,,
Oxygen,	·8	·8 ,,	1·1468 ,,
Ethylene,	1·0	1·0 ,,	1·2534 ,,
Ethane,	5·0	5·0 ,,	6·7200 ,,
Methane,	67·0	67·0 ,,	48·0256 ,,
Hydrogen,	22·0	22·0 ,,	1·9712 ,,
Nitrogen,	3·0	3·0 ,,	3·7632 ,,
	100	100 ,,	64·8585 ,,

Calculating to heat units (gramme Centigrade):—

Carbon monoxide,	·7526 grms.	1808 units.
Ethylene,	1·2534 ,,	14910 ,,
Ethane,	6·7200 ,,	77679 ,,
Methane,	48·0256 ,,	627358 ,,
Hydrogen,	1·9712 ,,	67929 ,,
		789694 ,,

So that 100 litres of the gas would give 789694 units of heat, which, divided by 64·8585, the weight in grammes of the 100 litres, would give 12177 units as the calorific power; it therefore has a much greater heating power than coal or coke.

12177 C. units is equal to 21919 B.T.U., and 1000 cubic feet of the gas weigh almost exactly 38 pounds; the heat value per 1000 cubic feet is therefore 832922 units.

The gas, as will be seen from the above analysis, is quite free from sulphur. On strong heating it is said to split up and deposit a hard glassy coke, so that it cannot be used with regenerators in the Siemens furnace.

Artificial Gas.—Many forms of gas have been made at various times for lighting and heating purposes. Those which are at present in use are—

1. Coal-gas.
2. Producer-gas.
3. Water-gas.
4. Oil-gas.

Coal-gas.—This is the gas obtained by distilling coal in closed retorts, and which is generally used for lighting purposes, and to a small extent for domestic heating. It has a very high calorific power, and is an excellent fuel. It is too expensive for furnace use, but is used with success in many minor operations where only a small quantity is used, and therefore where its cost is only of secondary importance. The amount of gas yielded by coal varies from 8000 to 12,000 cubic feet per ton. The gas to be used for lighting purposes is carefully purified from carbon dioxide and sulphur compounds. This of course adds to the cost, and would not be necessary if it were to be used only for fuel purposes. The cost of gas varies in this country, say, from 2*s.* 6*d.* to 8*s.* per 1000 cubic feet, the usual cost being probably about 2*s.* 6*d.* to 2*s.* 9*d.* The luminosity of the flame of coal-gas gives it an advantage for many purposes over those gases which burn with a non-luminous flame. The following analyses will give an idea as to the composition of coal-gas:—

	1.	2.	3.	4.
Hydrogen,...........................	51·8	48·32	36·1	4·8
Carbon monoxide, ...	9·1	4·63	6·8	·2
Marsh-gas, ...	31·8	39·55	37·8	53·7
Olefines, ...	5·2	5·18	16·4	41·2
Nitrogen, ...	2·1	2·32	2·9	·1

1 and 2, London gas (Wright). 3, Cannel-gas. 4, Oil-gas (American pretoleum).

It will be seen that nearly the whole of the gas is combustible, only about 2 per cent being non-combustible.

As an average the following figures (*J. S. C. I.*, 1888, p. 20) may be taken:—

Hydrogen, ...	... 48 litres =	4·291 grs.	× 34180 =	146666
Carbon monoxide, ...	8 „	9·947 „	× 2427 =	24141
Methane, ...	... 36 „	25·804 „	× 13062 =	103815
Ethylene, ...	... 3·8 „	4·762 „	× 11857 =	56463
	95·8 litres.			
Non-combustible ...	4·2 „			
	100·0 litres.	50·082 grs.		331085

So that 100 litres will evolve 331085 units, and its calorific power will be $\frac{331085}{50{\cdot}082} = 6411$ (C. units), or 11540 B. T. U. 1000 cubic feet would weigh 31 lbs.; so that 1000 cubic feet would evolve on combustion 347740 B. T. U.

At 2*s.* 9*d.* per 1000 cubic feet the cost per 1000 B. T. U. would be ·095*d.*, whilst a coal of 7000 B. T. U., C. P. at 10*s.* a ton would cost only about ·008*d.* per 1000 B. T. U.

It is easy to imagine cases, however, in which even this great difference might be more than compensated for by the greater convenience of the gas.

Producer-gas.—When air is blown through red-hot charcoal or coke, combination takes place, and since the temperature is high and the carbon is in large excess, carbon monoxide is produced, which makes the resulting gas combustible, $C + O = CO$. Since air contains by volume 21 per cent of oxygen and 79 per cent of nitrogen, and since the carbon monoxide produced occupies twice the volume of the oxygen which is consumed, the gas thus obtained would contain about 34·7 per cent of carbon monoxide. Such a gas, though combustible, has naturally a very low calorific power, and whilst many attempts were made to utilize it, they were unsuccessful until the introduction of the Siemens regenerative furnace. Gas from blast-furnaces, which, as will be seen later, is of much the same character, had been utilized for various purposes as far back as 1840.

The calorific power of the gas can be easily calculated:—

Carbon monoxide, ...	34·7 litres	= 43·53 grs.	= 105168
Nitrogen, ...	65·3 ,,	= 82·91 ,,	= —
	100 litres.	126·44 grs.	105168

and the calorific power would be $\frac{105168}{126{\cdot}44} = 832$ C. units, or 1498 B.T.U., or 1000 cubic feet would weigh 78·9 lbs., and would evolve on combustion 118192 B.T.U.

This gas may be called simple producer-gas to distinguish it from other forms of gas which are produced by similar means but enriched in various ways, and which may therefore be called enriched producer-gas. The principal methods of enriching are by blowing in steam or water, which undergoes decomposition, the liberated hydrogen and carbon monoxide enriching the gas, $C + H_2O = CO + 2H$; and by using coal instead of coke, in which case the volatile products of distillation mix with the gas.

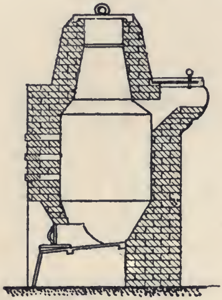

Fig. 24.—Bischof Gas Producer.

The Bischof Producer.—The first attempt to manufacture producer-gas for furnace use was made by Bischof in 1839. The producer consisted of a cylindrical brick chamber having a capacity of about 150 cubic feet; at the bottom of which was a grate, on which rested the column of fuel. The fuel used was peat, which was charged at the top, and air was admitted beneath the grate. Round the body of the producer were arranged holes through which the working could be observed, and the gas was drawn off at the side near the top. No blast was used, but the air current was kept up by chimney draught.

Since that time an enormous number of gas producers have been invented.

Classification of Gas Producers.—To arrange a classification which will suit all the forms that have been suggested is almost impossible. The following, however, includes all the more important types:—

1. Producers worked mainly by natural draught, *i.e.* with open hearths.
   - *a.* With fire-bars.
   - *b.* With solid bottom.
2. Producers worked by blast, usually produced by a steam jet.
   - *a.* With fire-bars.
   - *b.* With solid bottom.
     - (1) Bottom worked dry.
     - (2) With water bottom.

The Bischof producer, already described, always falls under class 1, division *a.*

The Siemens Producer.—This is the first form of producer that was a commercial success. In the early days of the Siemens or open-hearth steel process it was almost universally used, and it is still in use, usually with some modification, in many steel works. The Siemens regenerative furnace was invented in 1861, and it is from that time that the practical use of producer-gas must be dated.

One form of this producer suitable for burning non-coking slack is thus described by Siemens: "In form it is a rectangular fire-brick chamber, one side of which, B, is inclined at an angle of from 45° to 60°, and is provided with a grate C at its foot. The fuel is filled in at the top of the incline A, and falls in a thick bed upon the grate. Air is admitted at the grate, and as it rises through the ignited mass the carbonic acid first formed by the combustion of oxygen with the carbon of the fuel takes up an additional equivalent of carbon, forming carbonic oxide, which is diluted by the inert nitrogen of the air and by a little unreduced carbonic acid, and mixed with the gases and vapours distilled from the raw fuel during its gradual descent towards the grate, and is led off by the gas flue to the furnace. The ashes and clinkers that accumulate on the grate are removed at intervals of one or two days.

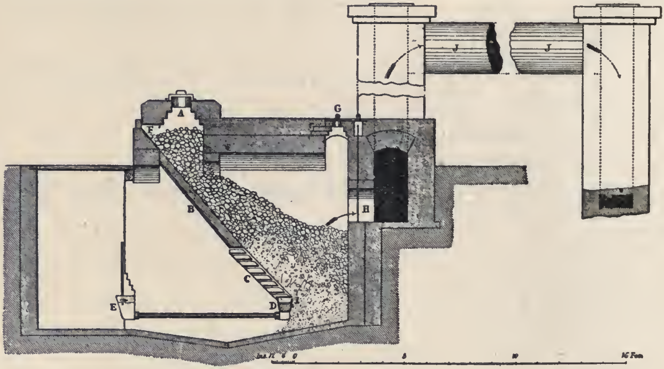

Fig. 25.—Siemens Gas Producer.

"The composition of the gas varies with the nature of the fuel and the management of the gas producer. That of the gas from the producers at the plate-glass works, St. Gobain, France, burning a mixture of ¾ caking coal and ¼ non-caking coal, is as follows by an analysis dated July, 1865 (by volume):—

Carbonic oxide	23·7	24·2	34·6
Hydrogen, ...	8·0	8·2	
Carburetted hydrogen, ...	2·2	2·2	
Carbonic acid, ...	4·1	4·2	65·4
Nitrogen, ...	61·5	61·2	
Oxygen, ...	·4		
	99·9		

"The trace of oxygen present is no doubt due to carelessness in collecting the gas or to leakage of air into the flue. The figures in the second column give the composition of the gas, allowance being made for the accidental oxygen."[1]

In all the producers of this type in use now water is supplied; either a steam jet is fixed under the bars or a water-spray is projected on to the bars or into the fire. Fig. 26 shows a form of this producer at present in use.

As the air supply depends entirely on the draught produced by the ascending current of hot gas, the pressure is very small and the combustion is slow, the amount of coal consumed being only about 12–13 lbs. of coal per square foot of grate area per hour.

The gases leave the producer at a temperature of about 500° or 600° C. (1000° F.), and being therefore very light they tend to rise, thus producing the draught. "It is necessary to maintain this pressure through the whole length of the gas flue, in order to ensure a free supply of gas to the furnaces, and to prevent its deterioration in the flue through in-draught of air at crevices in the brickwork. The slight loss of gas by leakage, which results from a pressure in the flue, is of no moment, as it ceases entirely in the course of a day or two, when the crevices become filled with tar and soot.

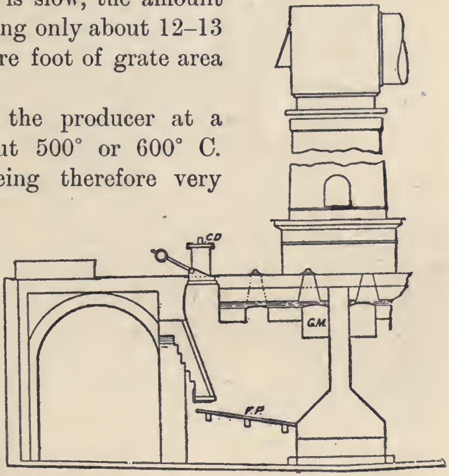

Fig. 26.—Siemens Gas Producer.

"Where the furnace stands so much higher than the gas producer that the flue may be made to rise considerably, the required plenum of pressure is at once obtained; but more frequently the furnaces and gas producers are placed nearly on the same level, and some special arrangement is necessary

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[1] Siemens, *Collected Works*, vol. i. p. 219.

to maintain the pressure in the flue. The most simple contrivance for this purpose is the 'elevated cooling-tube'. The hot gas is carried up by a brick stack to a height of eight or ten feet above the top of the gas producer, and is led through a horizontal sheet-iron cooling-tube of not less than 60 square feet of surface per gas producer, from which it passes down either directly to the furnace or into an underground flue.

"The gas rising from the producer at a temperature of about 1100° F. is cooled as it passes along the overhead tube, and the descending column is consequently denser and heavier than the ascending column of the same length, and continually overbalances it. The system forms, in fact, a syphon, in which the two limbs are of equal length, but one is filled with a heavier liquid than the other. The height of cooling-tube required to produce as great a pressure in the flue as would be obtained by placing the gas producers say *ten feet* deeper in the ground, may be readily calculated. The temperature of the gas as it rises from the producers has been taken as 1100° F., and we may assume that it is cooled in the overhead tube to 100° F., an extent of cooling very easily attained. The calculated specific gravity, referred to hydrogen, of the gas of which I have quoted the analysis being 13·4, we obtain the following data:—

Weight of gas per cube foot at 1100° F. = ·022 lb.
" " " " 100° F. = ·061 "
Weight of atmosphere per cube foot at 60° F. = ·076 "

and from these we have on the one hand the increase of pressure per foot of height in a flue rising directly from the gas producer = ·076 – ·022 = ·054 lb. per square foot, and on the other hand the excess of pressure at the foot of the down-take from the cooling-tube, over that at the same level in the flue, leading up from the gas producer (per each foot of height of the cooling-tube) = ·061 – ·022 = ·039 lb. per square foot. The height of the cooling-tube above the level of the flue that will be sufficient to produce the required pressure equal to 10 feet of heated gas column, is therefore $\frac{\cdot 054}{\cdot 039} \cdot 10$ feet $= 13$ feet 10 inches, or say 14 feet."[1]

Siemens further points out that objection has been taken to the use of cooling-tubes on the ground of the loss of heat entailed, but he contends that this objection does not hold, because there is no advantage in supplying the gas hot to the regenerators, and further, that cooling condenses a large quantity of moisture which would otherwise be carried into the furnace.

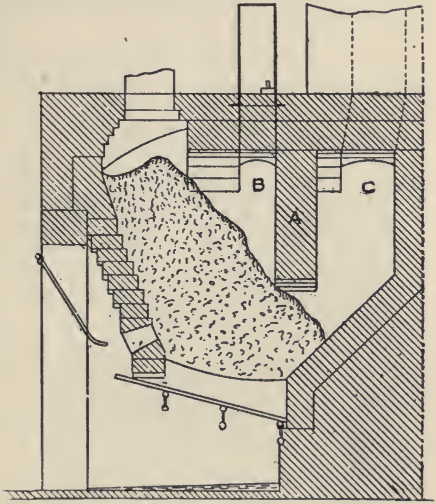

Fig. 27.—Siemens Producer, arranged for the Destruction of Tar.

A, Descending wall. C, Gas main. B, Cleaning door.

Improvements on the Siemens Producer. — The Siemens may be taken as the type from which all modern producers have been derived. The development in the more recent producers has been mainly in the direction of greater economy of heat and greater speed of working. To attain these objects more steam is used, and the producers are worked closed, so that a blast pressure can be used instead of allowing the air supply to depend entirely on chimney draught.

One difficulty with the ordinary form of producer as described was the collection of a large amount of tar in the cooling-tubes, which not only tended to block the tubes, but also leaked out and kept the place in a mess. To prevent this, and to convert the tar into carbon which can be consumed

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[1] Siemens, *Collected Works*, vol. i. p. 222.

in the producer, and permanent gases which will pass away, it is is only necessary to heat the tarry vapours to a high temperature. This is best done by compelling them to pass through incandescent coke. This was first done in the Wilson producer, but can equally well be arranged in almost any type. Fig. 27 shows a Siemens producer arranged for the destruction of tarry matters.

Siemens Circular Producer.—This is a solid bottom open producer. The body consists of a circular shell of brickwork cased in iron, and carried on an inverted portion of a cone, the smaller end of which rests on a series of short columns, from between which the ashes and clinker can be withdrawn. The coal is charged by a hopper at the top, and the products of distillation are made to descend through the incandescent coke on their way to the gas-flue. Round the top of the producer runs a flat metal pipe through which air passes, and is thus heated by the hot gas, being then carried down by a pipe and into the centre of the mass by means of a steam jet. It will be seen that in this producer part of the air is supplied by a steam jet into the mass of burning fuel, and part finds its way in by natural draught round the bottom. It was found, however, very difficult to work a producer by means of a steam jet, and at the same time use an open bottom, and this form of producer has never come largely into use.

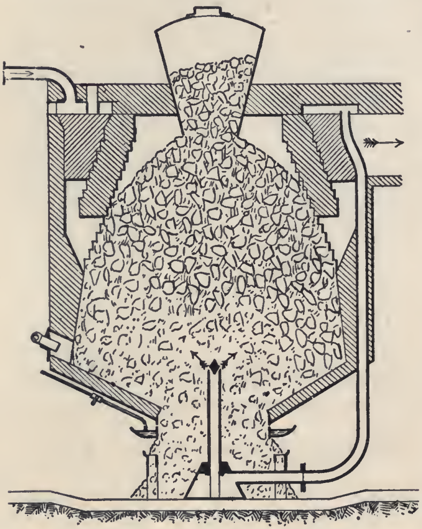

Fig. 28.—Siemens Gas Producer, circular form.

Closed-bottom Producers.

Siemens Type.—It is quite easy to modify the Siemens type of producer so as to work with a closed hearth and a steam jet, all that is necessary being to close up the hearth and introduce the steam below the bars. An arrangement for doing this was described by Siemens, and it consisted simply in closing the ash-pit by air-tight doors and introducing a jet of steam. This form of producer has been used to some extent, but has not been very successful, the grate area being too small, and the layer of fuel too thin to allow of the rapid combustion usually associated with closed-hearth producers. In another form used in some steel works the sloping wall is done away with, and the bars are placed horizontally so as to give a large grate area. The ash-pit is divided into two by a transverse wall, through which passes a steam-pipe, from which the steam and air are discharged on both sides under the bars.

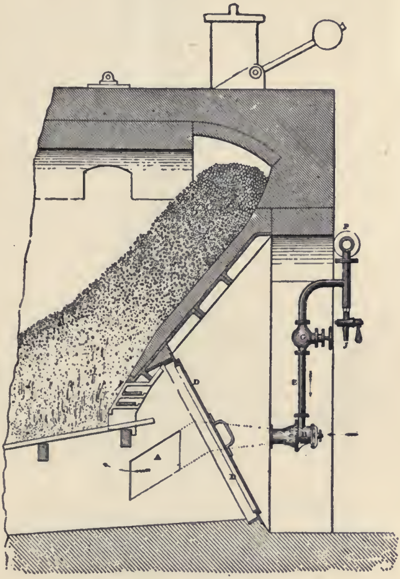

Fig. 29.—Siemens Closed-hearth Producer.

The Steam Jet.—In all closed-bottom producers the air must be supplied under slight pressure, and as a supply of steam is also necessary, a steam jet is always used to supply both. The steam jet seems to have been first suggested for this purpose by Siemens, and he has investigated the nature of the action which takes place. The form of steam jet suggested by Siemens is shown in fig. 30.

"A very thin annular jet of steam is employed in the form of a hollow cylindrical column discharged from the annular orifice between the two conical nozzles A B, the steam being supplied by the pipe C into the space between the two nozzles. The inner nozzle A can be adjusted up and down by the handscrew D, so as to diminish or increase the area of the annular orifice between the two nozzles for regulating the quantity of steam issuing. The air to be propelled by the steam jet is admitted from the pipe E through an exterior annular orifice surrounding the steam jet, and also through the centre of the hollow jet. The tube G, into which the steam jet issues, is made of a conical shape at the bottom, so as to form with the annular nozzle B a rapidly converging annular passage for the entrance of the air, and the width of this air-passage is regulated by adjusting the nozzle B by means of the nut H at the bottom. The tube G continues to converge very gradually for some distance above the jet orifice, the length of the convergent portion increasing with the width of the annular orifice, the object being to ensure the complete commingling of the steam and air within the length of the mixing chamber G, beyond which the tube

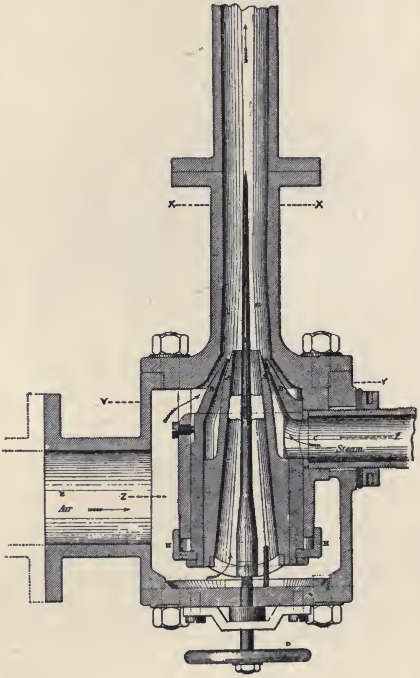

Fig. 30.—Siemens Steam Jet.

gradually increases in diameter in a parabolic curve to the upper end.

"The rationale of this arrangement is as follows:—First, by gradually contracting the area of the air passages on approaching the jet the velocity of motion of the entering air is so much accelerated that before it is brought into contact with the steam the difference in the velocity of the two currents, at the point where they come together, is much reduced, and in consequence the eddies which previously impaired the efficiency of the steam jet are to a great extent obviated, and a higher useful result is realized. Secondly, by the annular form of the steam jet the extent of surface contact between the air and steam is greatly increased, and the quantity of air delivered is by this means very much augmented in proportion to the quantity of steam employed; also, the great extent of surface tends to diminish eddies. Thirdly, by discharging the combined current of steam and air through the expanding parabolic delivery funnel of considerable length, in which its velocity is gradually reduced and its momentum accordingly utilized by being converted into pressure, the degree of exhaustion or compression produced by the steam jet is very materially increased under otherwise similar circumstances. The results of a long series of experiments with this form of steam jet, both for exhausting and compressing air, have led to the following conclusions:—First, that the quantity of air delivered per minute by a steam jet depends upon the extent of surface contact between the air and the steam irrespective of the steam pressure, up to the limit of exhaustion or compression that the jet

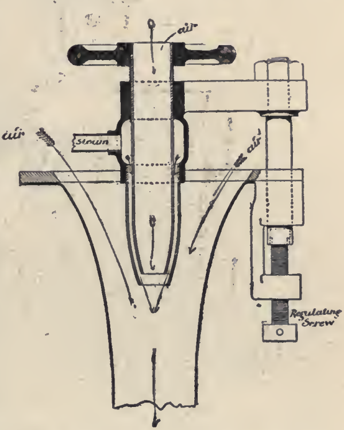

Fig. 31.—The Thwaite Annular Steam Jet.
Details of head and adjustable nozzle.

is capable of producing. Second, that the maximum degree of vacuum or pressure attainable increases in direct proportion to the steam pressure employed, other circumstances being similar. Third, that the quantity of air delivered per minute, within the limits of effective action of the apparatus, is in inverse relation to the amount of air acted upon; and that a better result is therefore realized in exhausting air than in compressing it. Fourth, that the limits of air pressure attainable with a given pressure of steam are the same in compressing and exhausting within the limit of a perfect vacuum in the latter case."[1]

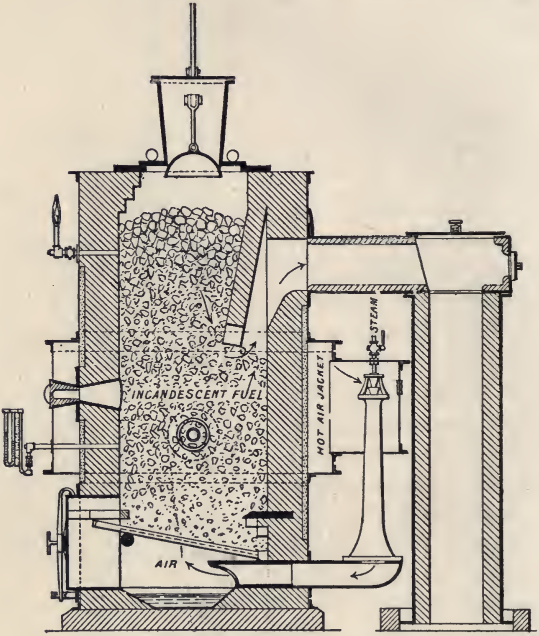

Fig. 32.—Thwaite Simplex Producer.

Thwaite Steam Jet.—This is a somewhat simpler form of jet, now largely used. As will be seen the area of the an-

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[1] Siemens, *Collected Works*, vol. i. p. 142.

nular steam jet can be easily reduced or enlarged by lowering or raising the inner tube by means of the regulating screw.

The Thwaite Simplex Producer.—This is a very good example of a bar-bottom closed-hearth producer. It consists of a circular iron shell lined with fire-brick, with a grate at the bottom, the bars of which are placed slightly sloping; the ash-pit is closed air-tight, and steam and air are blown in from a steam jet. The gas is drawn off at the side beneath a curtain wall, so that it passes through the hot coke, and tarry matters are broken up. The air before being used is heated by circulating in a jacket surrounding the casing. This is probably the most efficient producer of this type that has been designed.

The Thwaite Twin Producer.—This is a larger producer of the same type, and is specially so arranged that the gases pass through a thick layer of incandescent fuel, and therefore that it is almost impossible for any tarry matter to escape decomposition. The shell is circular, and is provided with a set of horizontal fire-bars, beneath which the jet of steam is blown, the ash-pit being closed. The fuel chamber is divided into two by double walls reaching nearly to the bottom, and between which the gas escapes to the gas main, and the charge is introduced by two hoppers, one on each side of the double wall. To clean out the producer, false or clinker bars are put across, through holes left for the purpose above the ordinary fire-bars, which are then withdrawn and the ashes allowed to fall; the bars are then replaced, the clinker bars withdrawn, and the charge settles down.

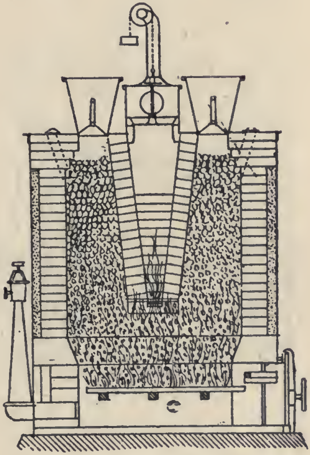

Fig. 33.—Thwaite Twin Gas Producer.

The Dowson Producer.—This producer is also a circular iron shell, lined with fire-brick, and provided with fire-bars and a closed ash-pit, into which steam and air are blown.

This producer is usually provided with an apparatus for raising the steam required, which consists of a coil of pipe heated by the combustion of some of the gas, one end of the coil being connected with a water supply and the other end with an injector. Coal may be used as fuel, but as this producer is chiefly used for making gas for gas-engines and similar purposes, coke is almost always preferred.

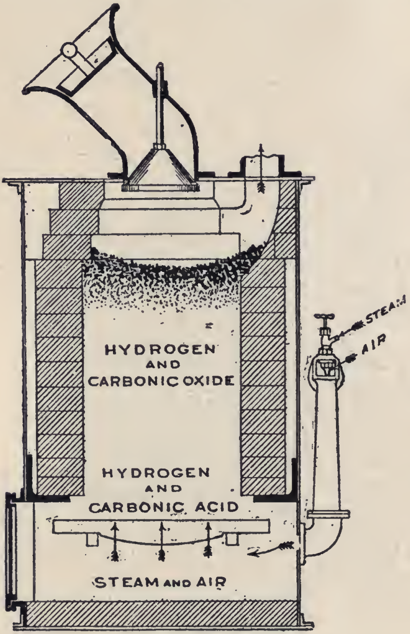

Fig. 34.—Dowson Producer.

Wishaw Producer.—Another example of this type of producer is one which is now in use at the Wishaw Steel Works of the Glasgow Iron and Steel Company.[1] These producers are circular in form—10 feet 6 inches external and 8 feet 6 inches internal diameter, and 14 feet high—and are built of fire-brick cased with iron. The ash-pit is only 3 feet square, and the top of this is provided with horizontal fire-bars on which the charge of fuel rests, and under which the mixture of air and steam is supplied from a jet of the usual type. Above the fire-bars are the necessary cleaning doors. These producers are said to be very satisfactory.

The Shiel Producer.—"This producer consists of a

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[1] *Engineering*, 1895, vol. i. p. 536.

wrought-iron casing lined with brickwork, into which near the bottom is built an annular cast-iron twyer or blast-box, furnished with a loose grate which can be withdrawn by means of a hand-wheel and screw, and clear, or partially so, of the bottom opening. The ashes and clinkers fall into a water trough beneath. The producer is charged about every half-hour by means of a bell and hopper, and the interior is kept about two-thirds full of fuel. The air to promote combustion is forced in by means of a steam jet blowing down a taper pipe at the side and then into an annular twyer, which is thus kept sufficiently cool by the air and steam to protect it from being burnt, and from whence it escapes into the fuel through holes in the circumference into the centre of the blast-box, and up through the fuel to support combustion. To prevent the escape of the blast, a lute is made at the bottom of the casing by adding plates to the wrought-iron shell and allowing them to dip into the water trough. The gas is drawn off under a slight pressure from the top."

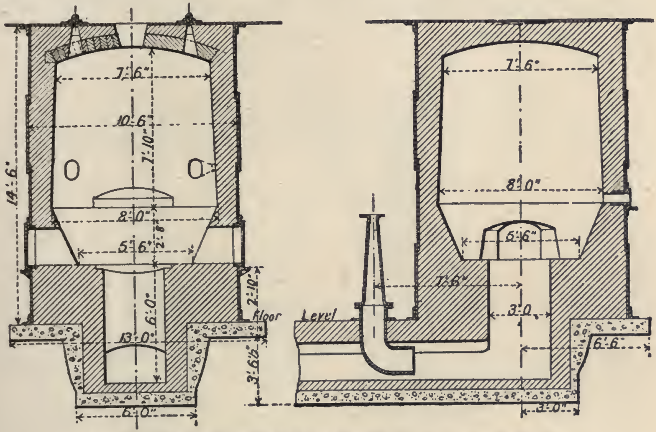

Fig. 35.—Gas Producer used at Wishaw Steel Works (from *Engineering*).

Solid-bottom Producers.—In this type of producer there are no fire-bars, but the fuel being gasified rests on the solid bottom of the producer, the air and steam being supplied at some distance above the bottom. They may be divided into two groups: those in which the bottom is kept dry, and those in which it is supplied with water; and the first group may be again subdivided into those in which the height is small relatively to the diameter, and the ashes and clinker are drawn solid; and those in which the height being greater, the ashes are fused and tapped out in the liquid condition.

The Wilson Producer.—The producer which was patented by Messrs. Brooke & Wilson in 1877 was one of the first, and is still one of the best of this type, and is very largely used.

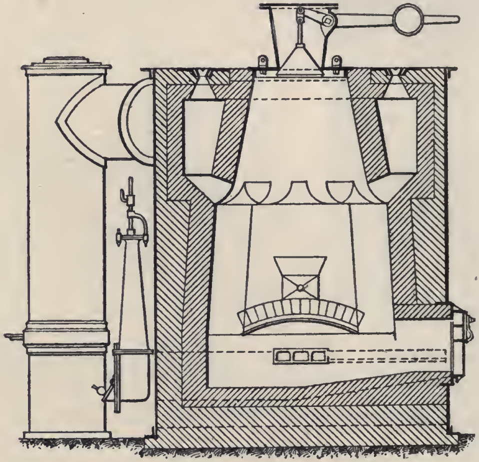
Fig. 36.—Wilson Producer.

The producer is a cylindrical shell of iron lined with fire-brick. The upper part of the interior is made conical, and is surrounded by a gas passage, into which the products of distillation enter by openings some distance from the top, so that they traverse the hot coke and tarry matters are completely broken up. The fuel is charged by a hopper at the top, and the gases are drawn off from the annular gas ring. The arrangement for the supply of steam and air is peculiar but very efficient. Across the bottom of the producer is a hollow ridge of brickwork, which communicates with the interior of the producer by a series of openings on each side. The mixture of steam and air is blown into the interior of this, and escapes into the fuel by the openings. As the steam and air are thus blown into the middle of the producer, the diameter must not be so great that the air cannot reach the circumference. The usual diameter is about 8 feet, but they can be made up to 12 feet.

The ridge from which the mixed air and steam are supplied divides the bottom of the producer into two halves, each of which is provided with a cleaning door. When it is required to clean out the ashes—about once each 12 hours—the steam supply is turned off, and iron bars are put in through small side doors, so that the ends rest on the brick ridge, the cleaning doors are opened and the ashes are raked out; the doors are then closed, the bars removed, so that the fuel settles down, and the steam is turned on—the whole operation only occupying a very short time. The fuel consumed is about 26 pounds per square foot of bottom in ordinary cases, but with a good steam supply it may be brought up to 40 pounds.

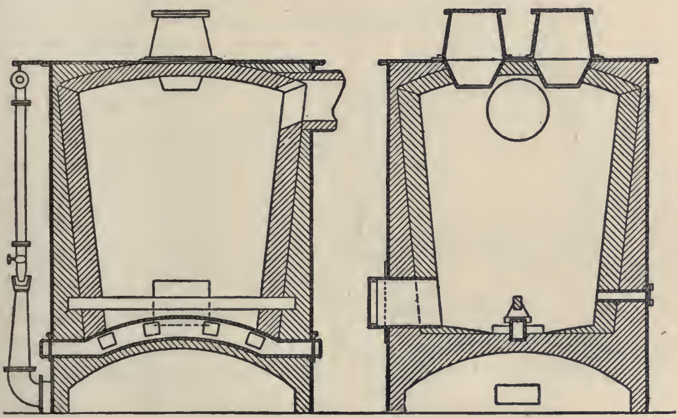

Fig. 37.—Modified Type—Wilson Producer.

In some producers, wrongly called Wilson, the conical upper portion of the interior is abolished, so that the tarry matters are not destroyed. The air is supplied through an iron channel connected with an underground air chamber, and a strong iron bar is fixed across the producer to carry the ends of the cleaning bars.

The Wilson Automatic Producer.—This is a modification of the ordinary Wilson type, designed by Mr. Wilson to avoid the necessity for the periodical stops for cleaning. The producer is much of the same form, but is somewhat taller, and the air and steam are delivered at a much higher level. The two halves of the bottom are made conical instead of flat, and in each of these works an archimedean screw, by which the ashes are continuously carried outwards and discharged. The bottom is filled with water, which keeps the screw cool and at the same time acts as a seal to prevent the escape of gas. This form of producer is said to be very convenient. Though of the Wilson type it rather belongs to the water-bottom class.

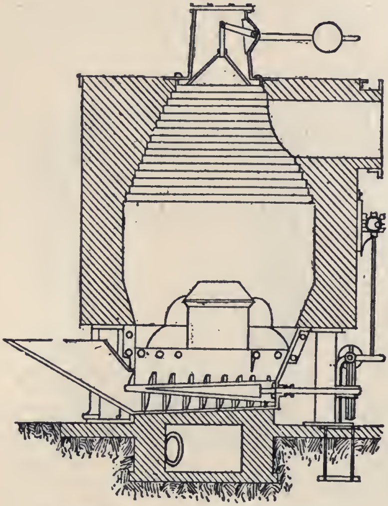

Fig. 38.—Wilson Automatic Gas Producer.

The Ingham Producer.—This producer consists of a wrought-iron casing lined with fire-brick, the interior being made conical. Air is supplied by a flue, over which is a cast-iron arch (B) covered with fire-brick. There are also two cleaning doors in such a position that they do not get very hot and are therefore not likely to warp.

One producer, 7 feet in diameter and 8 feet 6 inches high, gasifies 4 cwts. of coal per hour, producing 30,000 cubic feet of gas

The Taylor Revolving-bottom Producer.—This is a modern American form of producer, which has given excellent results in practice. As in most other solid-bottom producers the shell is cylindrical, and is of fire-brick cased with iron. The lower portion is made in the form of an inverted cone, and in the centre is an air-pipe by which the mixture of steam and air is supplied high up into the mass of fuel. The fuel is supplied by a hopper, and the gas is drawn off at the top in the usual way. The bottom is a flat revolving plate, a little larger than the opening at the bottom of the chamber, and

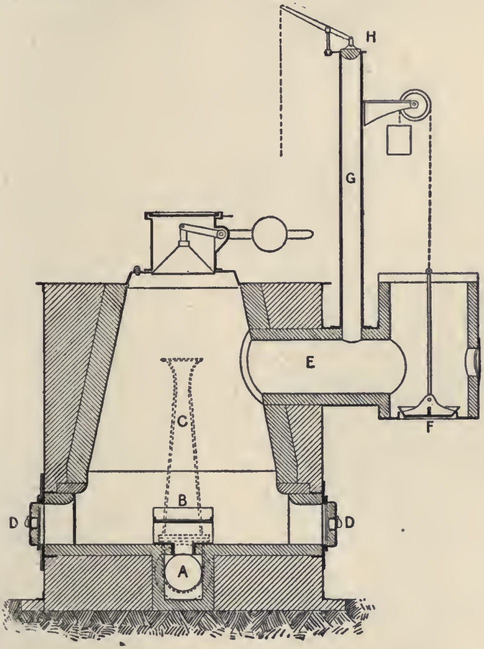

Fig. 39.—Ingham Producer.

A, Air and steam delivery-tube. B, Brick curb. C, Blower. D, Cleaning doors. E, Gas main. F, Valve to main flue. G, Tube for escape of gas when valve F is closed. H, Valve.

working in a closed ash-pit. The space between this plate and the bottom of the producer chamber is such as to allow the ashes to take their natural angle of slope. The level of the ashes or clinker is kept about 6 inches above the level of steam and air inlet, or about 3 feet 6 inches above the revolving bottom. As the ash accumulates the bottom is set in rotation for a time until it is reduced to the proper level, this being necessary once every six hours or so. The rotation "causes a grinding, and closes up any passages that may have been formed by the action of the blast"; "a few turns of the bottom at frequent intervals will keep the fuel-bed always in a solid condition". The clinker is removed from the ash-pit every twenty-four hours.

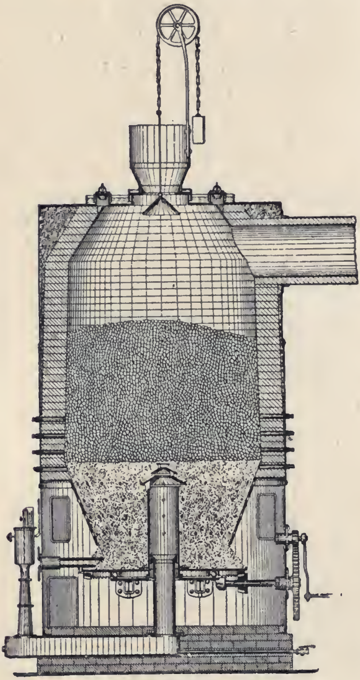

Fig. 40.—The Taylor Revolving-bottom Gas Producer. 6 feet inside diameter.

Round the lower part of the chamber are a series of openings by which bars can be introduced to break up the clinker if necessary.

The Howson Producer.—In appearance this producer is much like the Wilson, but in principle it is quite different, being worked in the reverse direction. Air and steam are admitted at the top, and blown downwards through the fuel—the gases being drawn off at the bottom. The dense hydrocarbons are completely broken up. It is difficult to see how in such a producer combustion can be complete, so as to allow of the withdrawal of the ashes, unless the air be supplied in great excess, in which case the gas would contain much carbon dioxide.

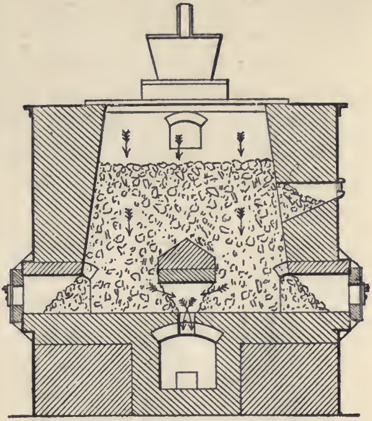

Fig. 41.—Howson Producer.

The Thwaite Duplex Producer. — This is a solid-bottom producer, so designed as to ensure the complete breaking-up of all tarry matters and the conversion of all carbon dioxide into carbon monoxide. It consists of two separate chambers or producers united by cross pipes at top and bottom, the lower one being provided with a valve, and it communicates with the gas main. Air and steam are introduced at the bottom

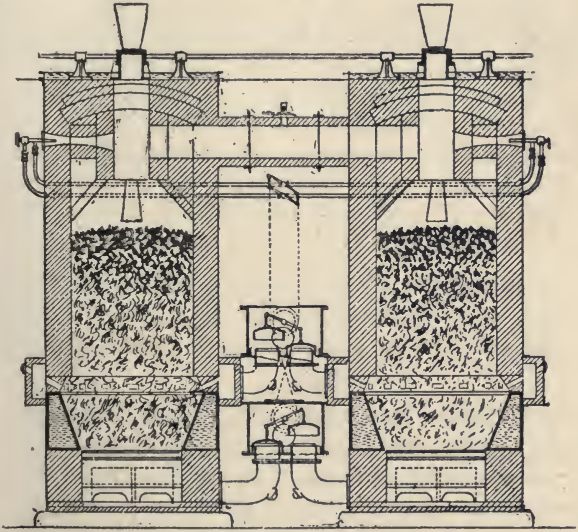

Fig. 42.—Thwaite Duplex Producer.

of one chamber, and the gas is drawn off at the bottom of the other. Suppose the producer to be at work, a charge of coal is let down into, say, the left-hand chamber, and the steam and air are blown into the bottom of the same chamber. The products of distillation pass into the second chamber, down through the hot coke which it contains, and away to the gas main. When the coal is completely carbonized, a charge is let down into the right-hand chamber, and the valves are reversed. The direction of the current is usually reversed every ten minutes, either automatically or by hand. The gas is quite free from tar and carbon monoxide, and is therefore well suited for use in gas-engines.

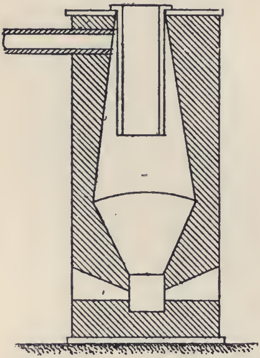
Fig. 43.—Ebelmann's Gas Producer.

Blast-furnace Type of Producers.—These have not at present been largely used. The first, Bischof's, was almost of this type, though it was provided with fire-bars and the clinker was not fused. That of Ebelmann, which was the next one invented, was much more blast-furnace-like in type. It resembled a small blast-furnace, about 10 feet high and 3 feet 4 inches diameter at its widest part, the air being forced in through twyers in the usual way. The clinker was fused and tapped out, iron slag being added to increase its fusibility.

Water-bottom Producers.—In this type of producer the ashes or clinker are received in a vessel of water, so arranged as to act as a seal and thus prevent the escape of gas.

The Dawson Producer.—This form, designed by Mr. Bernard Dawson, was one of the first of its type. "In this producer advantage is taken of an old idea in the shape of a water bottom. A water trough forms the base of the whole structure, and into this the ash and clinkers fall, the water forming at the same time a seal which prevents the blast escaping. The ash is raked out by hand from time to time, and no arduous labour is required to get away the clinkers. The steam from the water trough probably assists in breaking up the clinkers, as it falls into the trough by natural gravitation. The producer itself is very similar to the 'Wilson' in external appearance, but the fuel rests on a cast-iron hopper—an inverted cone—in the centre of which is an opening for the passage of the ash downwards and the blast upwards. Below this hopper is an open space showing connection with the injector, and kept tight by means of saddles dipping into the water trough. The top of the producer is dome-shaped, and all the internal structure is so arranged that no special lumps are required in the building. A man-hole is placed at any convenient part, the only door in the apparatus, and is used only when repairs are going on inside. This is a great advantage of itself over the old system, where doors had to be opened, screwed up, and luted tight. Producers of this kind have worked for months at a time without being stopped at all—a near approach to the case of the blast-furnace."[1]

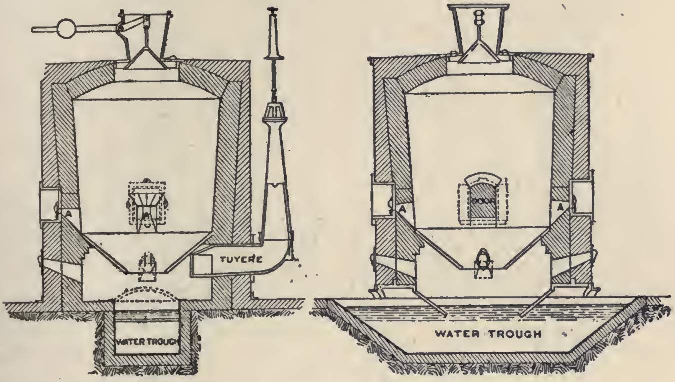

Fig. 44.—Dawson Gas Producer.

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[1] *Gas Producers*, by R. Booth, M.I.M.E. Read before the Civil and Mechanical Engineers' Society, 17th February, 1892

The Dick Producer.—This is a combination of the two types. The casing dips down into the water trough so as to form a water seal; across the centre chamber pass three bars, on which rest two sets of inclined fire-bars forming two inclined grates. The steam and air are blown in beneath the grates and pass up through the fuel, whilst the ashes and clinker fall into the water and are easily removed, the fall being aided when necessary by poking with iron rods introduced through holes left for the purpose in the casing.

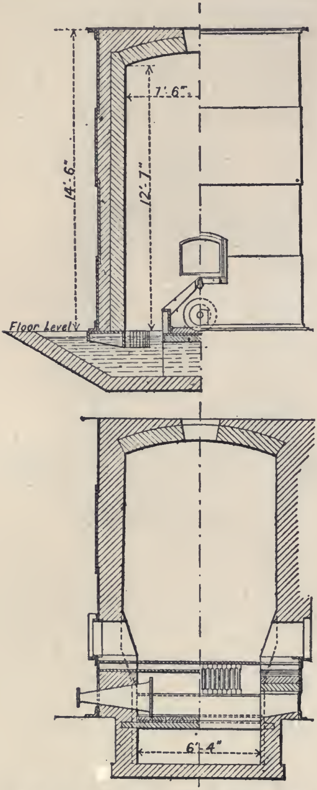

Fig. 45.—Dick Producer. From *Engineering.*

The Thwaite Small-power Gas Generator.—In this generator the fire-grate is formed of a girdle of suspended fire-bars that hang from a truncated cone casting, supported from the outside casing. The fuel at the base thus takes a cone-shaped form. The ashes descend into water, and the heat of the clinkers evaporates part of the water, the vapour, ascending through the fuel, adding hydrogen to the gas produced.

The clinkers and incombustible matters can easily be removed, and without arresting the progress of gas-making, by inserting a rake or bar below the surface of the water, and below the seal formed by the side plates of the gas generator. In this girdle form of grate the ash does not reduce the grate efficiency, and the vertical grate does not offer a suitable surface for the repose of either coke or clinker. It is self-clearing, and the passages for the air are continuously uninterrupted.

As shown by the direction of the arrows, the air-blast supply passes round the air belt encircling the gas generator, and is consequently heated by contact with the heated plates.

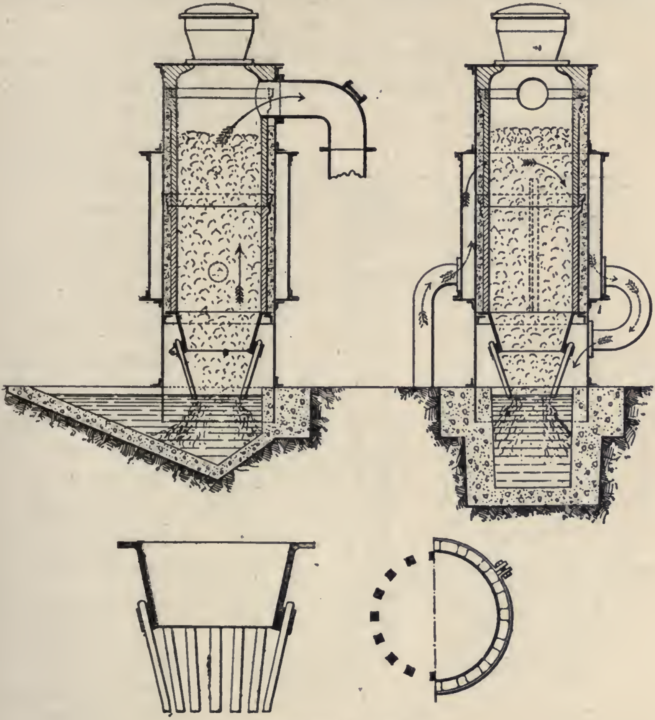

Fig. 46.—Thwaite Small-power Producer.

The Thwaite Duplex Non-reversal Gas Generator.—In this, one of the latest types of gas generator, the method of utilizing the hydrocarbon constituents of the coal is as follows:—

There are two generators, which are connected together at the top by a conduit. The air is supplied at the base of the fuel in left-hand generator, and a secondary air supply is introduced above the fuel level in sufficient volume to ensure the oxidation of the hydrocarbons, and to provide sufficient heat to raise the coal in second chamber to a condition of incandescence.

The flame due to the oxidation of the gases raises the temperature of the fuel in the second generator to bright redness, and in the descent of the gases through this incandescent carbonaceous column the carbon dioxide is converted into carbon monoxide, and the water forms carbon monoxide and hydrogen.

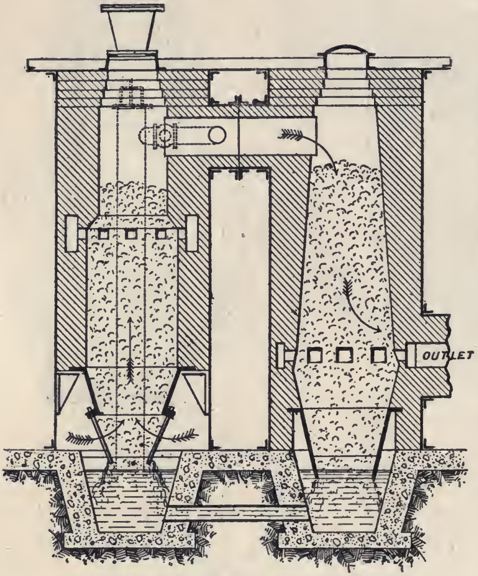

Fig. 47.—The Thwaite Non-reversal Gas Producer.

The coal is fed in at the top of the fuel in both generators, and the escape of the gases is below the upper surface of such fuel, consequently any dust or dirt introduced cannot be carried forward into the flues; only pure uncondensable gases can escape from this generator.

The clinker and incombustible matters gradually fall to the base of the fuel, where they give up their sensible heat to the water, from which they can be withdrawn without stopping the production of gas.

"This generator permits bituminous slack coal to be employed for gas-engines and gas stoves and furnaces, and removes the difficulties of flue deposits of carbon and tar, the common associates of every single-vessel gas generator."[1]

Use of Steam in Gas Producers.—The use of steam as a means of enriching producer-gas has already been briefly mentioned, and, as will be seen from the descriptions of the different forms of producer, its use is now universal.

The reaction $C + O$, by which the gas is obtained, is exothermic, and is accompanied by the evolution of a large quantity of heat.

The heat value of the reaction $C + O = CO$ is 29000 + C. units, or 52000 B.T.U., whilst the heat value of the reaction $C + 2O = CO_2$ is 96960 C. units, or 174528 B.T.U., so that about one-third of the heat which the coke could evolve by combustion is given out in the producer, and is therefore lost for practical purposes. It is usually stated that about one-third of the available heat of the fuel is used in converting the coke into gas, but this statement is not correct; it should be, that one-third of the available heat is evolved in converting the coke into gas, which is quite a different matter.

In the case of the conversion of water into steam there is an absorption of heat in doing work, and this can only be recovered when the work is undone, *i.e.* when the steam is converted back into water; but in the case of the formation of carbon monoxide from carbon and air, heat is evolved, only it is evolved in the wrong place—in the producer, where it is not required, instead of in the furnace, where it is. The action of the steam is to absorb some of this heat and transfer it to the furnace, so that though the actual calorific power of the fuel is not altered, its available heating power is much increased.

When steam is blown over hot charcoal or coke it is decomposed thus, $H_2O + C = CO + 2H$, so that each pound of carbon gives the same amount of carbon monoxide that it would have done had it been burnt with oxygen, and in addition an equal volume of hydrogen. This reaction is endothermic, that is, it absorbs a large quantity of heat. It may be regarded as made

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[1] Mr. Thwaite.

up of two reactions, and the actual thermal value will be the algebraic sum of these.

The decomposition of water absorbs heat, the amount of heat absorbed being the same as that evolved in the formation of the water. The heat value of the reaction $2H+O=H_2O$ is 123050 + B.T.U., so that the value of the decomposition will be 123050 − B.T.U.

∴ Decomposition of water, ...	123050 −
Formation of carbon monoxide, ...	52000 +
Heat of the double reaction, ...	71050 −

Every pound of carbon, therefore, which is burnt by means of steam absorbs 5920 British units of heat.

It is quite obvious, therefore, that the quantity of steam which can be used is limited, for unless enough heat be supplied in some other way to make up for this absorption of heat, and also to make up for all losses in the producer, the temperature will fall and the action will cease altogether.

Assuming that there were absolutely no loss of heat, and that the temperature were high enough to start the reaction, about 1·4 lbs. of carbon must be burnt by air to supply the heat necessary for the combustion of one pound of carbon by steam.

In this case the heat evolved by the combustion of the gas would be identically the same as that which would be evolved by the combustion of the solid carbon. This may be seen from the following figures:—

$$C+2O=CO_2=174528+\text{B.T.U.}$$

$C+H_2O=CO+2H=$		71050 −
$CO+O=CO_2=$	122428 +	
$2H+O=$	123050 +	
		245478 +
Difference, ...		174528 +

There is therefore no loss of heat. The steam only effects the transference of some of the heat from the producer to the furnace.

It need hardly be said that these conditions can never be even approached in practice, and that therefore the quantity of steam used is always very much less than the maximum shown above.

The proportions of steam and air used are usually given by volume. In round numbers, 1 volume of steam contains as much oxygen, and is therefore as efficient for burning carbon, as 5 volumes of air. For combustion of carbon in the theoretical ratio 1 part by steam to 1·4 parts by air would require the steam and air to be in the ratio of about 1:7, or the mixture would contain about 12·5 per cent steam and 77·5 per cent air. The maximum proportion of steam used in practice is about one-third of this, or perhaps in rare cases a little more. The amount of steam used does not depend entirely on the amount supplied, since, if it be used in excess, some may escape undecomposed.

Calculation of Composition of Gas.—Assuming that coke or charcoal is the fuel fed into the producer, and knowing the composition of the mixture of air and steam supplied, it is possible to calculate the composition of the gas, and also the amount of heat lost in its preparation. Assume that the mixture of air and steam supplied contains 5% of steam and 95% of air—*i.e.* in 100 litres, 5 litres of steam and 95 litres of air—5 litres of steam will contain oxygen which in the free condition would occupy 2·5 litres, and the 95 litres of air will contain (assuming 21% of oxygen) 19·95 litres of oxygen, and of course 75·05 litres of nitrogen. Since water vapour contains its own volume of hydrogen which will be liberated, the resulting gas will contain 5 litres of hydrogen. Since oxygen gives twice its own volume of carbon monoxide, the composition of the gas will be—

Hydrogen, ...	5 litres =	4·00%
Carbon monoxide from steam, ...	5 „ =	4·00
Carbon monoxide from air, ...	39·9 „ =	31·90
Nitrogen, ...	75·05 „ =	60·10
	124·95 „	100·00

It is possible to calculate also the amount of heat saved by the use of the steam; the amount of carbon burnt by steam compared with that burnt by air is in this case as nearly as possible 1 : 8; so that

1 lb. of carbon burnt by steam ... ... = 5920 – B.T.U.
8 lbs. of carbon burnt by oxygen = 4333 × 8 ... ... = 34664 +

Heat evolved in producer ... ... = 28744 +
Or for one pound of carbon, ... = 3194 +
Total heat which could be evolved by the combustion of one pound of carbon to carbon dioxide, ... = 14544 +
Loss % = 22 as against 33 when no steam was used.

In the calculations, it has been assumed for simplicity that coke is the fuel used. In practice coal is always used. This is coked at the top of the producer, the products of distillation mixing with the gas which rises from below, so that the gas actually obtained is a mixture of the gas produced by the action of air and steam on the coke with that resulting from the distillation of the coal. The gas is, therefore, richer in hydrogen and hydrocarbons, and has a higher calorific power than that which would be obtained from coke.

Sources of Loss of Heat in Gas Producers.—There are many sources of loss of heat in the gas producer, and the aggregate of them determines the maximum amount of steam which can be used, since all losses must be made up by the combustion of the coke by air. Some of these sources of heat are peculiar to the producer, and therefore militate against the efficiency of gaseous fuel; others are common to all classes of fuel. The sources of loss are—

1. Heat carried away by gases.
2. Heat lost by radiation.
3. Heat absorbed by dissociation of the solid fuel.
4. Heat carried out with clinker, &c.
5. Carbon dioxide in the gases.
6. Water in the gases.

1. *Heat carried away in gases.*—This is a very large item in all ordinary forms of producer, as the gases escape at

a very high temperature. In the open-hearth types of producer it is necessary to allow the gases to escape hot, in order to produce a draught, but with the closed-hearth producers there is no need for this, and the cooler the gases are the better, as there seems to be no advantage in sending the gas hot to the regenerators.

Taking for simplicity a producer fed with coke; for each pound of carbon consumed there will be about 6·8 lbs. of gas, and assuming this to escape at a temperature of 600° F. the amount of heat carried away by it will be $6{\cdot}8 \times 600 \times {\cdot}25 = 1070$ units, or about $\frac{1}{3}$ of the heat evolved in the producer when 5% by volume of steam is used. If the temperature were 1000°, 1700 units of heat would be thus lost.

2. *Heat lost by radiation.*—This is probably very considerable in all cases, but no sound estimate can be made as to its amount. In some forms of producer it is utilized in heating the air.

3. *Heat due to dissociation.*—Undoubtedly, the dissociation of the coal into coke and gaseous products absorbs some heat; the amount is, however, probably small and has not been determined. It is of little practical importance, as the same loss takes place when solid fuel is burnt in an ordinary fire.

4. *Heat carried away in solid products.*—The heat due to the high temperature of the solid products is of little moment, as it is usually small in amount. In water-bottom producers there is little loss from this source, as any heat is utilized in volatilizing some of the water. In bar-bottom producers there is often considerable loss from unburnt carbon falling through the bars.

5. *Carbon dioxide in the gases.*—Most producer-gas contains some carbon dioxide, and the presence of a considerable quantity is not infrequent. This is probably the most serious source of loss in most forms of gas producer. The presence of carbon dioxide is always due to the column of fuel either not being deep enough or not hot enough to decompose all the carbon dioxide which may be formed. When it is remembered that the conversion of a pound of carbon into carbon dioxide evolves

about three times as much heat as the conversion into carbon monoxide, it will be seen that a very large amount of heat may thus be lost, and the efficiency of the gas very seriously diminished. No producer can be considered as being satisfactory which allows any sensible quantity of carbon dioxide to pass into the gas.

6. *Excess of steam.*—This is also very objectionable, and is due to the supply of more steam than the coke can decompose under the conditions of working. Steam has a high specific heat and a high latent heat, so that it may carry away a considerable quantity of heat.

The actual loss from all sources has been variously estimated. It should not exceed 15 to 20 per cent of the available heat of the fuel, but it is often very much more. Siemens gives 12%, but this is certainly too low.

Working the Producer.—With the introduction of the closed-hearth producers the need for a draught, and therefore for the overhead cooling-tubes, disappeared, and in all modern plants they have been dispensed with, underground flues being substituted. It is still a moot point whether any advantage is to be gained by sending the gas to the regenerators hot, but no attempt is made now to cool the gases, and where the old overhead flues are still used, they are very frequently thickly lined with fire-brick so as to prevent cooling. Unless the tar be destroyed by passing the gas through hot fuel—as is done in many of the producers already described—the gases on cooling will deposit tar and sooty matters, which are troublesome. If, however, the gases be kept hot there is comparatively little deposition, most of the tarry materials being carried over to the furnace and burned. In some cases an excess of steam is intentionally used, it being contended that the steam coming in contact with the tarry matters in the regenerators will convert them into carbon monoxide and hydrogen, which are thus added to the gas.

The cleaning of the flues is often a matter of considerable trouble, and in most cases the tarry matters are burned out.

Mond Gas.—M. Mond obtains a gas somewhat different from ordinary producer-gas by using a very large excess of steam. The producer used is of the water-bottom type, and the products of distillation of the coal are made to pass through the incandescent fuel so as to destroy the tar in the usual way. About $2\frac{1}{2}$ tons of steam is blown in for each ton of coal consumed, the greater portion of it passing through undecomposed. Each ton of coal yields about 160,000 cubic feet of gas, which has the composition—

	By Volume.		By Weight.
Carbon dioxide, ...	17·1	......	32·0
Carbon monoxide, ...	11·0	......	13·1
Olefines, ...	·4	......	·5
Marsh-gas, ...	1·8	......	1·2
Hydrogen, ...	27·2	......	2·2
Nitrogen, ...	42·5	......	51·0
	100·0	......	100·0
Combustible gas, per cent,	40·4	......	17·0

The calorific power of the gas is—

Carbon monoxide, ...	$\cdot131 \times 4418 =$	679 B.T.U.
Olefines (C_2H_4), ...	$\cdot005 \times 21343 =$	107
Marsh-gas, ...	$\cdot018 \times 24021 =$	432
Hydrogen, ...	$\cdot022 \times 61524 =$	1354
Calorific power, ...	=	2572

And, as 1000 cubic feet would weigh about 65·68 pounds, this would give 168929 B.T.U.

The amount of heat lost in the producer is said to be not more than 20 per cent of that obtainable from the coal. The large amount of steam carried through must be condensed, and as the amount of ammonia in the gases is large (up to 90 lbs. of sulphate per ton of coal), it is passed through scrubbers before use. It contains very little tar. The washed gas has been found to be efficient for heating a steel furnace.

The cost of raising the steam is considerable, but this is far more than paid for by the large amount of ammonium sulphate obtained.

The Blast-furnace as a Gas Producer.—The iron-smelting blast-furnaces are the largest gas producers in the world. The gas is merely a by-product, and though it has been used for heating the blast for working the furnaces, and for other purposes, it is only recently that much attention has been given to it. The gases from blast-furnaces are of two kinds, depending on whether coke or coal is used as the fuel.

If no changes other than those produced by the action of the air on the coke took place the gas would be exactly of the nature of producer-gas; but the furnace is used for smelting, and this modifies the result. The air blown in at the twyers at once attacks the carbon, forming carbon monoxide, which rises up through the charge. Coming in contact with oxide of iron it reduces it, at the same time being converted partially into carbon dioxide, $Fe_2O_3 + 3\,CO = 2\,Fe + 3\,CO_2$, which thus mixes with the gas, and as this change takes place at a temperature below that at which carbon can act on carbon dioxide this gas is not decomposed. Limestone is also added as part of the charge, and this is split up at high temperature into lime and carbon dioxide, $CaCO_3 = CaO + CO_2$; as, however, the temperature at which this reaction takes place is high the resulting carbon dioxide is wholly or partially converted into carbon monoxide.

The following analyses (by volume) of gas from coke-fed blast-furnaces will indicate its nature:—

	1.	2.	3.	4.
Carbon dioxide, ...	11·39	12·01	·9	5·9
Carbon monoxide, ...	28·61	24·65	34·6	29·6
Nitrogen, ...	57·06	57·22	64·4	63·4
Hydrogen, ...	2·74	5·19	—	·1
Hydrocarbons, ...	·20	·93	1	—

1, Coke, Ebelmann. 2, Charcoal, Ebelmann. 3, Coke, Thwaite. 4, Charcoal, Thwaite.

Owing to the quantity of carbon dioxide present the calorific power of the gas is low. Taking No. 1 as a type the calorific power can be calculated.

Carbon dioxide,	11·39 litres	=22·45 gms.	—
Carbon monoxide,	28·61 ,,	35·85 ,,	=86613 units.
Nitrogen,	57·06 ,,	71·51 ,,	—
Hydrogen,	2·74 ,,	·25 ,,	= 8545 ,,
Methane,	·20 ,,	·14 ,,	= 116 ,,
	100·00 litres.	130·20 gms.	95274 units.

Or the C.P. in Centigrade units is 732. In B.T.U. this is 1317. 1000 cubic feet will weigh 81·6 pounds, and will therefore evolve on combustion 107467·2 B.T.U.

In Scotland, and in some parts of England, the furnaces are fed with splint-coal, raw, *i.e.* uncoked. The gases are therefore enriched by the admixture of the products of distillation of the coal.

The following analyses will show the nature of these gases:—

	1.	2.	3.	4.
Carbon dioxide,	8·57	8·61	5·4	6·79
Carbon monoxide,	27·15	28·06	30·1	26·40
Hydrogen,	5·48	5·45	6·2	12·23
Marsh-gas,	4·29	4·37	3·2	1·71
Nitrogen,	54·29	53·38	55·1	58·81
Ammonia,	not est.	·13	—	—

Again taking No. 1 as a type—

Carbon monoxide,	27·15 litres	=16·91 gms.	=82458 units.
Carbon dioxide,	8·57 ,,	34·13 ,,	—
Hydrogen,	5·48 ,,	·49 ,,	=16748 ,,
Methane,	4·29 ,,	3·07 ,,	= 2557 ,,
Nitrogen,	54·29 ,,	68·05 ,,	—
	100·00 litres.	122·65 gms.	101763 units.

Or the calorific power in Centigrade units is 838. In B.T.U. the C.P. is 1508.

1000 cubic feet weigh 76·5 pounds, and would evolve on combustion 115362 B.T.U.

It will thus be seen that the gases are quite comparable with those of a gas producer and are as good as some, for there are many cases in which producer-gas contains as much carbon dioxide as blast-furnace gas (see table of analyses, p. 182). In iron-works the gas obtained is usually far more than enough to drive all the plant of the works, and in some cases has been utilized in addition for steel-making and other purposes.

WASHED AND UNWASHED BLAST-FURNACE GAS.

	1. Green or Unwashed.	2. Washed.	
Carbon dioxide, ...	6·23	7·92	In each case Average of three Samples taken at same time.
Carbon monoxide, ...	28·19	28·06	
Hydrogen, ...	10·24	7·11	
Marsh-gas, ...	1·78	2·77	
Nitrogen, ...	53·56	54·14	
Moisture, ...	·6116 grm. per c.ft.	·2084	
Tar, ...	·4276 „	trace	
Per cent combustibles,	40·21	37·94	
Calories per 100 litres,	126·128	125·784	
B.T.U. per 1000 c. ft.,	—	—	
Flame temperature,...	1978° C.	1933° C.	

The blast-furnace is probably the most perfect gas-producing plant, and this for several reasons.

1. Owing to the high column of material the gases can be effectively cooled. This cannot be so well done, however, owing to the chemical reactions, in a blast-furnace used for smelting as it could in one used only for gas producing.

2. Owing to the depth of the column of material and its high temperature, the gas as it passes up is quite free from carbon dioxide, that gas being subsequently added by chemical reactions which would not take place in a blast-furnace used only for gas-making.

3. Owing to the slag being tapped out in the liquid condition there is no loss by the escape of unconsumed carbon.

Comparison of Gas Producer and Blast-furnace.—Gas producers are usually worked at a very low pressure, 2 to 10 inches of water, and the amount of coal gasified is usually about 25 lbs. per square foot of grate area or bottom per hour, reaching a maximum of 40 or 50 lbs. in very quick driving.

A blast-furnace is worked at a much higher pressure, $2\frac{1}{2}$ to 7 lbs. per square inch. An ordinary furnace with a hearth, say 8 feet in diameter, will consume, *i.e.* gasify, about 70 tons of coal in the 24 hours, which is equal to about 130 pounds of coal per hour per square foot of bottom, and with larger furnaces the consumption is very much greater. It is a wonder that the blast-furnace type of producer has not been more largely used, for it offers advantages that are not possessed by any other form. Steam could readily be used, and a rate of production reached in excess of that at present given by any producer in use, whilst the sources of loss due to the escape of hot gas and the production of carbon dioxide would be effectually diminished if not stopped.

Water-gas.—When steam is passed over red-hot coke, as already explained, a mixture of carbon monoxide and hydrogen is produced which is called, very improperly, water-gas. As this reaction is powerfully endothermic, heat must be supplied either by working the apparatus intermittently, or by heating the retort in which the action takes place by separate fires.

The Strong Producer.—This producer is one of those most largely used in America, though it has never come into use to any extent in this country. It consists of three fire-brick chambers, the one a producer, the other two regenerators filled with a chequer-work of fire-brick. The producer is filled with coke in the usual way, and air is blown through, thus producing ordinary producer-gas. At the surface of the charge this meets more air and is thus burned, and the products of combustion pass down the one regenerator and up the other, thus heating the brickwork to whiteness. When the regenerators are sufficiently hot, the air current is stopped and steam is blown in to the top of the first regenerator. By the time the steam reaches the producer it has become intensely hot and partially decomposed. As it enters the producer it meets a stream of coal-dust fed in from a hopper; this is distilled by the heat, and the products of distillation pass with the steam through the hot coke, where decomposition is completed, and the gas passes away either to a gas-holder or to the furnace. When the coke in the producer is cooled the steam is turned off, and air is passed through again until the temperature is brought up to the required point.

The Lowe Producer.—This form of producer is also largely used in America, mainly for the production of illuminating gas. The gas, therefore, is washed by being passed through a scrubber before passing to the gas-holder. The apparatus consists of two parts, a producer and a regenerator, both of which are circular chambers lined with fire-brick; the former is provided with fire-bars on which the fuel rests, and the latter is filled with a chequer-work of fire-brick. The producer is charged with anthracite and blown in the usual way; the producer-gas thus obtained is passed into the regenerator and burned so as to heat the brickwork to a very high temperature, the products of combustion being allowed to escape into the air. When the regenerator is hot enough the chimney-valve is closed, and that leading to the scrubber and gas-holder is opened, the air supply is stopped, and steam, preferably superheated, is blown into the producer; it is of course decomposed, a mixture of carbon monoxide and hydrogen being produced. At the top of the producer this meets a spray of petroleum, which is at once volatilized, and passing with the water-gas over the hot brickwork in the regenerator, becomes converted into permanent gases which pass through the scrubber to the gas-holder. When the coke is too cool to decompose all the steam, the steam is turned off, and air is again sent through it.

Plant at the Leeds Forge.—Most of the water-gas plants erected in this country have been on the principle of that erected at the Leeds Forge. This consists simply of a producer without any regenerative chamber. It is circular in form, lined with fire-brick, and provided with a charging hopper at the top. The fuel used is usually coke. Air is blown in at the bottom, and thus the coke is consumed and the temperature rapidly rises, the producer-gas obtained either being allowed to burn at the chimney, or being conducted to steel or other furnaces for use. When the coke is sufficiently hot the air and producer-gas valves are closed, and steam is blown in at the top of the producer, the water-gas escaping at the bottom and passing to a gas-holder. When the coke is sufficiently cool, the currents are reversed and air is sent

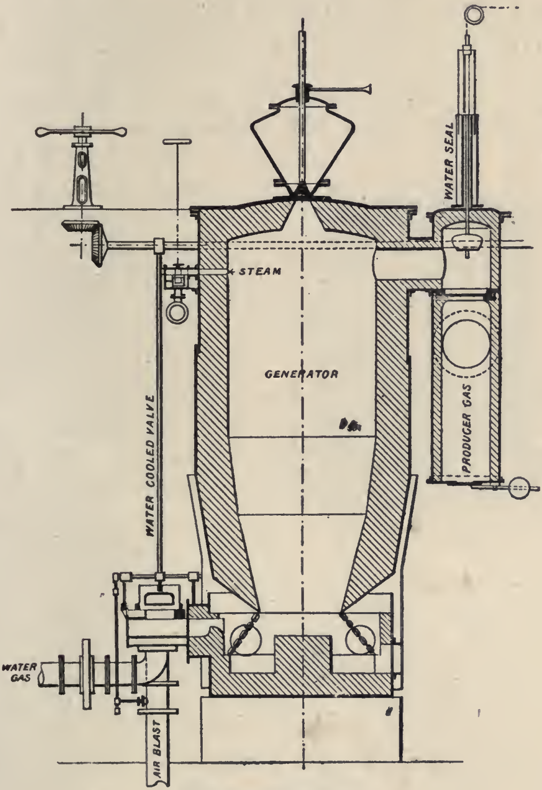

Fig. 48.—Water-gas Plant.

through till it is again hot enough to produce water-gas. The times at the Leeds forge being about 4 minutes gas making and 10 minutes heating up. The coke yields about 34,000 cubic feet of water-gas per ton.

The Loomis Producer.—This is one of the most recent and successful forms of water-gas plant. It consists of a cylindrical casing about 12 feet × 9 feet, lined with fire-brick. At the top is a charging door, and at the bottom a fire-brick grate over an ash-pit, across which are placed slabs of fire-brick. The ash-pit is provided with a door, and also a brick-lined tube leading to a boiler, and thence to an exhauster. The producer is provided with a cleaning door, and also with a series of ports leading to the gas main.

Coal or coke may be used as fuel. The producer being charged the charging door is left open, the exhauster set in action, and air is drawn downward through the charge; the producer-gas thus obtained, passing through the ash-pit, heats the superheating slabs to a very high temperature, and passing to a boiler its sensible heat is used for steam raising. It is then passed to a gas-holder. As soon as the charge is sufficiently hot the charging door is closed, steam is blown into the ash-pit; passing over the hot superheating slabs it becomes strongly superheated, and then passing up through the hot coke water-gas is formed which passes away by the ports to the water-gas holder.

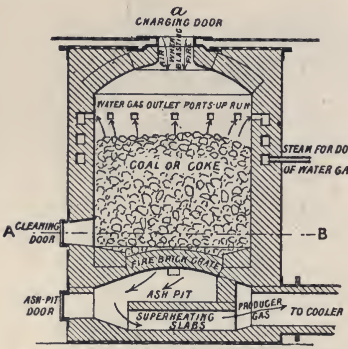

Fig. 49.—Loomis Gas Producer. From *J. I. and S. I.*

Mr. Loomis gives the following estimate as the cost per 1,000,000 cubic feet of gas with coal at $3 per ton:[1]—

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[1] *J. I.* and *S. I.*, 1890, vol. ii. p. 280.

Coal, 25 tons at $3·00, ...	$75·00
Coal for steam, 3 tons, ...	9·00
Labour, ...	22·00
Supplies and repairs, ...	4·00
Purifying	5·00
	115·00
Received for producer-gas, ...	44·00
	75·00
Interest and depreciation, ...	25·00
	100·00

Or cost per 1000 cubic feet, $0·10 = say 5*d.*, or if the producer-gas be lost, $0·14, say 7*d.*

Nature of Water-gas.—Water-gas has a much higher calorific power than producer-gas, as will be seen from the following figures:—

Hydrogen, ...	49·17 litres	4·40 grammes =	159192 units.
Methane, ...	·31 „	·22 „	183 „
Carbon monoxide,	43·75 „	54·89 „	133062 „
Carbon dioxide,	2·71 „	5·34 „	—
Nitrogen, ...	4·00 „	5·09 „	—
	100·00 litres.	69·94 grammes.	292254 units.

Or the calorific power would be 4180 in C. units, or 7524 in B.T.U.

1000 cubic feet weigh about 43 pounds, and would therefore evolve 323532 B.T.U. on combustion.

1000 cubic feet of water-gas will therefore evolve on combustion about twice as much heat as enriched producer-gas and three times as much as simple producer-gas.

Water-gas therefore is well suited for use where a high temperature is required to be attained quickly. It burns with a non-luminous flame, but it may be used for lighting by making it heat a comb or mantle of magnesia, zirconia, or other infusible earth, or it may be made luminous by making it take up some volatile hydrocarbon. If acetylene can be produced at a cheap rate, it should be easy to make a good luminous gas by mixing water-gas with it.

Water-gas is very poisonous and is odourless, and several accidents have happened by the non-detection of escapes; to obviate this danger the gas is frequently mixed with some strong-smelling volatile body such as carbon disulphide.

The great objections to water-gas are the necessity for making it intermittently, so that gas-holders are necessary, and that such a large quantity of producer-gas is obtained at the same time—this usually being about four times the amount of the water-gas.

Oil-gas.—This gas is made by the destructive distillation of oil at a high temperature, with or without the use of steam. It is almost entirely used for lighting purposes, but has been tried for furnace use. In the Archer process "steam superheated to about 1000° F. is made to pass through an injector and draw with it a quantity of oil which becomes mixed with the steam. The mixture is further heated to about 1300° F., when it receives an additional quantity of oil; and finally the mixture is heated to 2400° F., whereby it is converted into permanent gas." Gas made by this process is called water-oil-gas. In the Pintsch, and some other processes, the oil is gasified by being allowed to drop into red-hot retorts.

The yield of gas varies very much, but it may be taken as being from 80 to 150 cubic feet per gallon of oil, or about 22,000 to 42,000 cubic feet per ton—the higher quantities only when steam is used with the oil; and at the same time there is a considerable quantity of liquid residue.

The gas has a heating power of about 21000 B.T.U. per pound, or 550 units per cubic foot.

Composition of Various Gases.—The analyses on p. 182 will give a good idea of the nature of the gases used as fuels.[1]

The composition of the various gases is graphically shown in Fig. 50.

Advantages of Gaseous Fuel:—

1. The supply of both air and gas is under control, so that any required temperature can be maintained with perfect regularity

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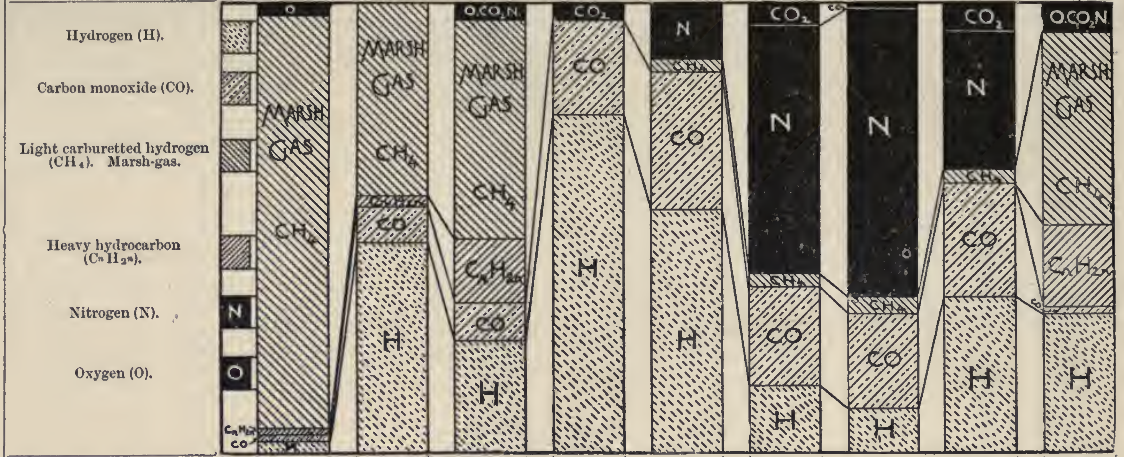
[1] Nos. 1 to 21 are from a paper by Mr. G. Ritchie, read before the West of Scotland Iron and Steel Institute. Author is Mr. Ritchie.

Fig. 50.—*Diagram and Tables, showing various Constituents of Combustible Gases.*—Prepared by B. H. THWAITE.



Reference Indications.	Natural Gas.	Ordinary Towns Gas.		En-riched Water-gas.	Water-gas.	Steam-jet Producer or Carbonic Oxide Gas.	Natural-draught Producer-gas.	Thwaite's Semi-water-gas.	Oil-gas.
		Common Coal.	Cannel Coal.						
Carbon dioxide and oxygen } Incombustible.	1·30	0·00	2·07	2·29	12·00	4·00	0·00	8·00	0·00
Nitrogen, N.,……………	0·00	0·00	0·00	0·00	0·00	56·78	63·40	28·40	5·06
Light carburetted hydrogen (CH_4),…	95·20	41·53	51·20	0·00	1·62	2·22	2·20	1·92	17·02
Heavy hydrocarbon (C_nH_{2n}),………	0·50	3·05	13·06	0·00	0·00	0·00	0·00	0·00	46·17
Carbon monoxide (CO),……………	1·00	7·82	7·85	20·04	31·86	23·00	24·20	27·42	0·14
Hydrogen (H),………………………	2·00	47·60	25·82	77·03	54·52	14·00	10·20	34·26	31·61
	100·00	100·00	100·00	99·36	100·00	100·00	100·00	100·00	100·00

PRODUCER.	Source of Analysis.	Per Cent Total Combustibles.	Per Cent of Hydrogen.	Per Cent of Methane, &c.	Per Cent of Carbonic Oxide.	Per Cent of Carbonic Acid.	Per Cent of Nitrogen.
1. Ebelmann's,	Ebelmann.	41·20	14·00	—	27·20	5·50	53·30
2. Do.,	Do.	35·01	1·48	—	33·53	·85	64·10
3. Do.,	Do.	29·47	7·64	—	21·83	9·06	61·47
4. Siemens Open-hearth,	Snelus.	30·00	—	4·40	25·60	4·30	65·70
5. Do. Closed-hearth (Steam-blown),	Do.	35·40	8·60	2·40	24·40	5·20	59·40
6. Do. do. do.,	Author.	38·24	19·43	2·66	16·15	11·53	50·23
7. Do. do. do.,	Do.	40·53	12·13	2·00	26·40	9·16	50·31
8. Wilson,	Do.	39·06	14·81	1·14	23·11	4·84	56·10
9. Do.,	P. & S.	37·20	10·55	3·05	23·66	5·25	57·55
10. Do.,	Do.	39·45	13·82	2·22	23·41	4·69	55·86
11. Do.,	Do.	39·89	11·55	1·45	26·89	4·00	56·11
12. Ingham,	Author.	39·18	10·90	1·28	27·00	4·50	56·32
13. Do.,	Do.	38·63	13·00	2·22	23·41	4·69	56·68
14. Do.,	Do.	36·00	12·60	3·50	20·40	5·50	58·00
15. Dowson,	Thorpe.	44·42	18·73	·62	25·07	6·57	49·01
16. Essen Water-gas from Coke,	Do.	93·23	49·17	·31	43·75	2·71	4·06
17. "Lowe" Water-gas from Anthracite,	Do.	86·60	44·50	—	42·10	3·60	9·80
18. Gas from Peat,	R. Akerman.	31·20	·90	3·10	27·20	12·10	56·70
19. "Thwaite" Oil-gas,	Thwaite.	95·20	31·61	63·19	·40	—	5·06
20. Natural Gas,	Thorpe.	96·40	22·00	73·00	1·40	·60	3·00
21. Do., Ohio,	Höfer.	95·75	1·64	93·70	·41	·25	3·41
22. Strong Water-gas,	Moore.	92·75	52·76	4·11	35·88	2·05	4·43
23. Siemens Closed-hearth,			9·60	3·60	21·60	5·00	58·60
24. Do. do.,			1·90	·71	26·00	4·20	66·59
25. With large excess of steam for NH_3 (average),			23·00	3	10	15	49
26. Blast-furnace Coal-fed,	Archibald.		3·68	3·62	27·50	6·15	59·27
27. Gas from Charcoal Generator,	Thwaite.		·2	—	34·1	·8	64·9
28. Gas from Coke Generator,			·1		33·8	1·3	64·8

for any time; and also the nature of the flame can be regulated, so that it can be made oxidizing, reducing, or neutral, as required.

2. Perfect combustion can be maintained with a very slight excess of air over that theoretically required, and no smoke need be produced.

3. Much higher temperatures can be attained than is possible with solid fuel, as both air and gases can be heated to a high temperature by means of regenerators before combustion.

4. Changes of temperature being less, the furnaces, &c., will last longer.

5. A commoner quality of fuel can be used.

6. The great ease with which the gas can be conveyed in pipes to any part of the works required, all the solid fuel being delivered at the producers placed conveniently for the purpose.

7. The gas can be used directly for the production of energy in a gas-engine.

The disadvantages are—

1. Danger of explosion. This is of no importance, as accidents are easily prevented.

2. The flame of many of the gases being only slightly luminous, its radiative power is not very high.

CHAPTER VIII.

RECOVERY OF BY-PRODUCTS.

Nature of By-products.—When coal is subjected to destructive distillation, whether for the coke or for the gas, other products are produced. These are mainly tarry matters and ammonia, and as these are valuable, many attempts have been made to recover them.

Coal contains about 1 to 1·5 per cent of nitrogen, and when the coal is distilled under ordinary conditions about 15 per cent of this goes off in the form of ammonia, and can be collected and converted into ammonium sulphate, the yield being, under ordinary circumstances, about 25 lbs. of ammonium sulphate per ton.

Method of Collecting the By-products.—This is almost always done in the same way. The gases are passed through cooling-tubes or "atmospheric condensers", and then through scrubbers or washers, where they are brought into contact with water, and all the condensable and soluble constituents are removed, the permanent gases only escaping.

Recovery from Coke Ovens.—It is only recently that attempts have been made to recover the by-products from coke ovens, it having been the general opinion that they were all needed to effect the coking. The gases alone, however, are quite sufficient, and, if regenerators are used, only a portion of these is required.

In the case of coke-making the total quantity of gas to be dealt with is small, as it is only the gas distilled from the coal unmixed with air or steam, and the coals used for coking will probably not yield a very large quantity of gas.

The gas from the ovens passes into a main, that from all the ovens flowing to one set of condensers. The condensers consist of a series of vertical wrought-iron pipes standing on an iron box, with partitions between each pair of pipes, those separated at the bottom being connected at the top by a cross pipe, so that the gas has to travel up and down through the whole series. The cooling surface of the pipes should amount to about 7 or 8 square feet for each 1000 cubic feet of gas per 24 hours, and assuming that the coal used gives, say, 10,000 cubic feet of gas per ton, this will be about 70 or 80 square feet of surface for each ton of coal coked per 24 hours.

From the atmospheric condenser the gases pass to the scrubber. The scrubber is usually a circular iron vessel about 20 feet high, and 8 to 10 feet in diameter. The arrangement inside the scrubber varies very much. In the common form it is provided with a series of perforated shelves, on each of which is placed a thick layer of coke, or the whole tower is loosely packed with coke, and a spray or rain of water is kept constantly falling. The ascending gas meets the descending water, and, being brought into contact with it and the wet coke, all the ammonia is dissolved out.

In the Livesey scrubber, which is very largely used, the tower is filled with a series of boards, 9 to 11 inches wide and 3 inches thick, set on edge at a distance of 1 inch apart, the layers being arranged one above the other so as to break joint, and water is allowed to trickle down, exactly as in the coke scrubber. The amount of water used is about 10 gallons per ton of coal or coke.

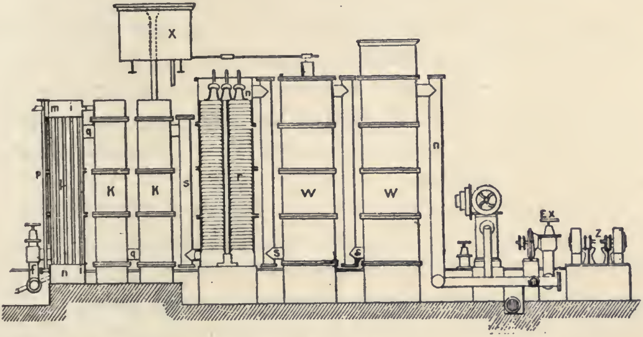


Fig. 51.—Apparatus for Recovery of Tar and Ammonia from Coke Oven Gases.

f, Gas main. m, Water reservoir. K K, Coolers, the first with casing removed. W W W, Scrubbers, the first with casing removed. p, Distributing plates.

The passage through the condensers and scrubbers cools the gas, and at the same time its passage is hindered, and it is necessary to use an exhaust of some kind to draw it through and produce a vacuum of about 2 inches of water, the gas being returned to the ovens under a pressure of about the same amount.

Root's blowers or fans are usually used. Steam-jet blowers have been tried, but the steam carried forward with the gas is objectionable.

One form of plant used in a German work is shown in fig. 51. The gases pass into the coolers, K. These consist of iron cylinders, through which pass a large number of vertical iron tubes, through which water descends, while the gases ascend around them. Thence the gases pass to the scrubbers, W. These are large iron cylinders, fitted with a large number of perforated plates. Water is kept falling down the towers, and this meeting the ascending gas washes it thoroughly. The gas is drawn through by means of an exhauster.

Products of Distillation.—The products recovered are tar and ammonia.

Tar, however, is not a substance of definite composition, but varies much in composition and value, according to the nature of the coal and the temperature at which distillation takes place—tars produced at a low temperature consisting mainly of paraffins and other members of the fatty series, whilst those produced at a high temperature are rich in benzene and other aromatic hydrocarbons.

Ammonia.—The ammonia liquor separated from the tar is boiled with lime, the liberated ammonia is received in sulphuric acid so as to form ammonium sulphate; this solution is crystallized, and the crystals are fished out and dried.

In the Simon-Carvès oven the amount of ammoniacal liquor obtained is about 27·70 gallons per ton of coal, equal to 26 pounds of sulphate of ammonia.

Tar.—Taking the Simon-Carvès oven as a type, the amount of tar obtained is about 6·12 gallons per ton of coal, equal to about 3·3 per cent. It is black and thick, and has a specific gravity of 1·2. It contains only small quantities of paraffins, and is rich in naphthalene and anthracene, but contains less benzene, toluene, and carbolic acid than some gas tars, but as much as others. On the whole, it very closely resembles ordinary gas tars, and may be used for the same purposes. The figures on p. 187 are given by Mr. Watson Smith as being the result of a fractional distillation of 2400 c.c. of the tar.

The value of the by-products from Simon-Carvès oven is said to be 4*s.* 6*d.* per ton.

Ovens of other types, in which the heating is not so quick or the temperature so high, yield a tar of quite a different nature. Taking, for example, the tar from the Jameson oven,

Temp. Cent.	Vol. c.c.	P.c. by Vol.	Remarks.
Below 120°	Water, ...149	6·2	
	Naphtha, 39	1·6	
,, 210	,, 70	2·9	
,, 220	,, 30	1·3	Nearly all solid naphthalene.
230	,, 13	·5	
,, 300	,, 446	18·6	Mixture of naphthalene and anthracene, with but little intermediate oils.
Above 300	,, 820	34·2	Nearly all solid crude anthracene; comparatively little red oil.
	1567		
Half-coked pitch, 807 grms., ...	807		
	2374		
Loss, ...	26		
	2400		

as described by Watson Smith, the specific gravity was ·949. It was subjected to fractional distillation, and the fractions were examined. No naphthalene or anthracene could be detected. Many of the distillates had a distinct fluorescence, and a considerable quantity of paraffin wax was obtained. The coke residue left in the retort from one litre of the tar was 97 grammes.

Where it is intended to recover the by-products, the coal should be coked at as high a temperature as possible.

By-products from Gas Producers.—The recovery of by-products from ordinary gas producers has only been attempted in a few cases, and at present there is not sufficient evidence to form a reliable opinion as to the advisability or not of this. The conditions of distillation are quite different to those in the coke oven, and the amount of gas to be dealt with is very much larger, amounting to about 130,000 cubic feet for each ton of coal consumed, and therefore the condensing plant must be on a much larger scale.

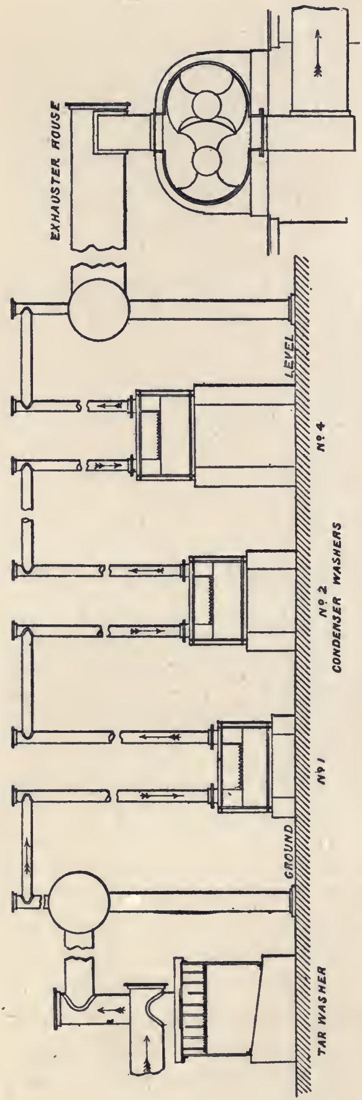


Fig. 52.—Gillespie Plant for the Recovery of By-products from Gas Producers. The 3rd Washer is omitted.

Fig. 52 shows an apparatus designed by Mr. A. Gillespie, of Glasgow, for dealing with the gases from a system of six producers, each using ten tons of coal per day, the products to be recovered being about $11\frac{3}{4}$ cwts. of ammonium sulphate and about 9600 lbs. of tar, which will be distributed through about 7,800,000 cubic feet of gas.

The gas from the producers enters the first or "tar washer, which also acts as a collecting main, at about 400° F. The gas from each producer enters the washer by a separate branch, so that each of the six may be isolated for any purpose. The gas is there broken up into thin streams by a serpentine diaphragm with serrated edges. The lower or serrated edge of the diaphragm is sealed in water, which is immediately displaced by the tar as it is deposited from the gas. It has been found preferable to feed the washer with tar got further on in the process, with the double object of, so far as possible, drying the tar by exposure to the hot gas, and at the same time entangling the tar particles from the gas as it passes through the serrations."[1]

The gas reduced in temperature in the tar-washer to 200° F. passes to a collecting main, then to the condensers. These consist of four boxes made in sections, each box having 27 pairs of 8-inch steel pipes 30 feet high; the boxes are fitted with serpentine plates with serrated edges, sealed with liquor, through which the gas has to pass. The four boxes are arranged at different levels, so that fresh water is supplied to the fourth and runs down to the first, whence it passes to the store-tank. The gas is drawn through by an exhauster.

The tar and ammonia liquors are drawn off and treated in the usual way.

The question whether it is advisable to wash producer-gas cannot be said to be definitely settled. The tar and ammonia can be recovered, but what effect will it have on the gases?

The washed gas, being freed from dense hydrocarbons, burns with a less luminous flame, and is therefore not suited for heating by radiation, a serious defect for some purposes; and there is no doubt but that the heating power of the gases is diminished to some extent, but by how much it is at present impossible to say. It has been stated to be as much as 20%. Analysis gives very little difference between the washed and unwashed gas, as is shown by the following analysis of blast-furnace gas:—

	Unwashed.		Washed.	
	1.	2.	3.	4.
Carbon dioxide,	7·00	6·60	6·60	6·00
Carbon monoxide,	28·00	27·40	27·20	28·20
Marsh-gas,	2·73	2·64	2·68	2·76
Olefiant gas,	—	—	—	—
Hydrogen,	6·77	6·86	7·66	7·44
Nitrogen,	55·50	56·50	55·86	55·60

Samples 1 and 3 and 2 and 4 were taken at the same time.[2]

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[1] *Journal West of Scotland Iron and Steel Institute*, vol. ii. p. 51.

[2] Ritchie, *Journal West of Scotland Iron and Steel Institute*, vol. i. p. 140.

In one case, whilst unwashed blast-furnace gas was quite satisfactory for working a steel furnace, it was found impossible to maintain the necessary temperature with the washed gas.

On the other hand, the gas is much drier after washing.

Treatment of Blast-furnace Gases.—Coke contains a small quantity of nitrogen, but the amount of ammonia it would yield would be so minute as not to pay for recovery, so that there is nothing to recover from the gases from coke-fed blast-furnaces. In Scotland, and in parts of England, the furnaces are fed with coal, and the gases then contain tar and ammonia in sufficient quantity to pay for treatment.

The coals used in Scotland are splint coals, yielding about 60 per cent of coke and say 40 per cent of volatile matter, all of which of course goes into the gases. They also contain about 1·4% of nitrogen, about 15 per cent of which escapes as ammonia, and can be obtained as sulphate.

An ordinary blast-furnace of the size used in Scotland will consume 400 tons or more of coal per week, and as each ton of coal gives about 125,000–130,000 cubic feet of gas, each furnace will give about 72,000,000 cubic feet of gas per week, or 10,000,000 cubic feet per day. Plant for dealing with the gases from six or eight furnaces must therefore be on a very large scale.

Several forms of plant have been designed, most of them depending on cooling and washing.

1. Cooling and washing.
    (1) Alexander & M'Cosh process.
    (2) Dempster process.
    (3) Gillespie process.
2. Gas washed with sulphuric acid.
    (4) Neilson process.
3. Gas mixed with sulphur dioxide, and the resulting ammonium sulphite washed out.
    (5) Addie process.

The Alexander & M'Cosh Process.—This was the first process brought into use, and the first plant was erected by Messrs. Baird & Co. at their Gartsherrie iron-works in 1880. The gases were collected from eight furnaces, each consuming about 60 tons of coal in the 24 hours, so that the amount of gas to be dealt with was about 7,800,000 cubic feet per day.

The gas is collected in a gas-main 7 feet in diameter, provided with dust-boxes, and thence passes to the atmospheric condenser. This is much like the condenser described for coke-oven gases, but is of much larger size, consisting of 200 pipes $2\frac{1}{2}$ feet in diameter and 40 feet high. They are arranged in 20 rows of 10 pipes each connected alternately at the top by cross pipes, and at the bottom of the box on which they stand, diaphragms being placed so as to compel the gas to pass up the tubes, these diaphragms having a 7-inch water-seal. Each particle of gas therefore traverses 20 tubes. The gas enters this condenser at 400° F. and leaves at 120° F., and in order to ensure sufficient cooling in hot weather a spraying apparatus is arranged. The gas next passes to the water-condenser; this is a large iron chamber 45 feet long, 45 feet high, and 18 feet wide, divided into seven chambers by diaphragms, with openings alternately at the bottom and top, so that the gas passes up one, down the next, and so on. These chambers are crossed by 2700 3-inch iron pipes, connected outside into series by bends, through which a current of cold water is kept circulating, and the gas leaves this at about 60°–70° F. The total cooling surface in the two condensers is about $2\frac{1}{4}$ square feet per 1000 cubic feet of gas passing each 24 hours. From the water-condenser the gas passes to the scrubber, a square iron

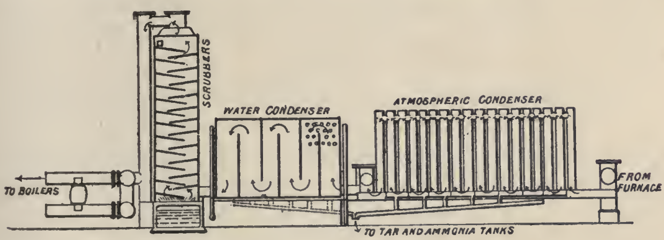

Fig. 53.—Alexander & M'Cosh Plant.

tower 80 feet high and 25 feet square, crossed by a number of perforated sloping diaphragms, each of which stops 20 inches short of one side, so as to allow passage for the gas even though the holes should become stopped with tar, and down which a shower of water is kept constantly falling. From the scrubber the gas passes to the exhausters, in this case a series of Root's blowers, giving an exhaust of 3 inches of water and a pressure of 2 inches, and is distributed for use to the stoves and boilers.

The gas is free from tar, and only contains ammonia about equal to 2 ounces of sulphate per ton of coal consumed.

The tar and liquor are run into a tank of about 70,000 cubic feet capacity and allowed to separate.

The ammonia liquor is boiled off in large boilers, the gas is passed into iron lead-lined saturators containing sulphuric acid, the saturated liquor is run into lead-lined iron boxes evaporated by steam, and the crystals are fished and dried. The yield is about 23 pounds of sulphate per ton of coal.

The tar is distilled; each 100 gallons of "green" tar yields about 60 gallons water, 20 gallons of oil, the remainder forming pitch which is run out of the stills. The make of tar is about 40 gallons, equal to 16 gallons of boiled tar per ton of coal.

In a similar plant erected at another works by the same firm the atmospheric condensers are dispensed with, the apparatus being in all other respects identical.

The Dempster Process.—This process is on the same principle as that of Messrs. Alexander & M'Cosh, and gives almost exactly the same results. It is modified in detail, and is a little cheaper to erect. The gas passes through large dust-boxes and then into the primary washers. These are large iron boxes divided into four compartments filled with water, so that the gas has to pass four times under water in its passage. The bottom of the washer is made to slope so that the separated tar all runs to one end. The gas then enters the atmospheric condenser, which is exactly similar to that already described. The box on which the pipes rest also slopes to one end, so as to allow the separated tar to collect, and valves are arranged so that any row of pipes can be shut off for cleaning. The gas next passes to the exhausters, which are sometimes Root's blowers and sometimes ordinary horizontal-cylinder blowing engines, and is forced on through another set of washers, and then to the scrubbers. Four scrubbers are used 100 feet high and 12 feet in diameter, the gas being brought from the top of the one to the bottom of the next by a pipe, so as to ascend the four in order before passing to the stoves. The scrubbers are filled with boards set on edge. Fresh water is supplied to the fourth, this is again pumped up for the third, and so on; so that a fairly strong liquor is obtained at the first scrubber. Between the scrubbers and the stoves a water-valve is placed, so as to prevent risk of explosion.

"Mr. Dempster puts down the cost of his apparatus at £6000 per furnace."

The Gillespie Plant.—This is the most recent of the cooling and washing type of plant. It differs from the others in several important points, and is probably the most efficient. The huge scrubbers used in the other forms are dispensed with, Mr. Gillespie contending that washing, if properly carried out, is quite as efficient as scrubbing. The principle on which Mr. Gillespie's washers are based is that of breaking up the gas current into a large number of small streams, which are therefore brought into very intimate contact with the water.

The washer (Fig. 54), which is an important part of this plant, is a long iron box, divided into two by a horizontal floor, the space above this being again divided into two by a longitudinal vertical division, the gases being delivered on the one side and escaping from the other.

Beneath the horizontal division are arranged a series of transverse plates with finely serrated edges, which dip beneath the water in the lower part of the vessel. The two chambers above the horizontal division communicate by means of openings with opposite sides of these transverse divisions. The gas from the furnace enters the left-hand upper chamber and passes through the opening into one of the lower divisions.

This being of large area the rate of flow slackens and the gas bubbles up slowly under the division plate, and is broken up by the serrated edges of the plate into numberless minute streams. It then passes up into the right-hand division and away. It will be seen that the right and left upper divisions of the washer communicate with opposite sides of the transverse divisions.

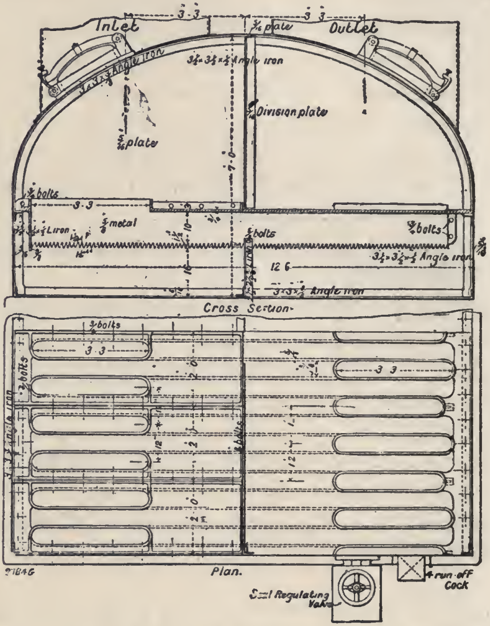

Fig. 54.—Gillespie's Washers at Wishaw Steel Works. From *Engineering*.

A plant on this system has recently been erected at the Wishaw works of the Glasgow Steel & Iron Company.[1] The gas from the four furnaces passes through an 8-foot brick-lined main to the primary washer, which it enters at 250° F., and after being washed either with tar or water, leaves at about 130° F. Thence it passes to the atmospheric condenser, and

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[1] See *Engineering*, vol. lix., 1895, p. 427, *et seq.*

up and down through eighteen pairs of tubes, each tube being 54 feet high and 20 inches in diameter. These cooling-tubes are arranged in sets on separate tanks, so that any set can be cut out for cleaning or repairs without interfering with the rest, and a spraying arrangement is fixed for use when necessary. The gas leaves these condensers at about 70° F., passes through a washer, then through the exhausters (in this case Root's blowers), through another washer, and into the return main. Valves are fitted at various parts of the apparatus so as to prevent danger of explosion. The tar and ammonia liquor are separated as usual. The ammonia is boiled from the latter and converted into sulphate, and the tar is distilled for oil and pitch. The water which comes over at the commencement of the tar distilling contains a little ammonia, and is sent back to the washers.

In a plant of this type 119 lbs. of pitch, 10 gallons of oil, and 23·3 lbs. of ammonium sulphate were obtained for each ton of coal consumed.

The by-products stated to be obtainable per week at Wishaw are given as—

Coal consumed, ...	2000 tons.
Pitch recovered, ...	100 tons = £120.
Oil recovered, ...	20,000 gals. = £125.
Sulphate of ammonia, ...	20½ tons = £225.

The cost of the plant for four furnaces is about £28,500. The cost of running the plant, wages, and superintendence are put at £30 a week, and the sulphuric acid costs about 20*s.* per ton of sulphate.[1]

The Neilson Process.—In this process the gases are first passed downwards through a water scrubber, then upwards through a second scrubber, in which they are washed with a descending stream of sulphuric acid. The whole of the ammonia is recovered, but the sulphate is apt to be contaminated with tarry matters, and the recovery of tar is small.

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[1] *Engineering, loc. cit.*

The Addie Process.—This process was carried on at the Langloan Works. The gases were collected into a main mixed with sulphur dioxide, obtained by burning pyrites in small blast-furnaces, and the mixed gases were passed through two scrubbers, passing up one and down the other. Almost the whole of the ammonia was recovered, but only about 40 per cent of the tar. The ammonia was present in the solution as acid sulphite, sulphate, and hyposulphite. It was treated with lime distilled and converted into sulphate in the usual way.

Fig. 55.—Ammonia Condensers, Langloan.

Tar from Blast-furnaces.—The temperature at the top of the furnace where distillation takes place being low, the tar obtained is poor in the aromatic hydrocarbons. The specific gravity is about ·954.

The following results of fractional distillation, given by Mr. Watson Smith,[1] will indicate the nature of the products obtainable:—

Temperature.	Volume of Distillates, C.C.	Weight of Distillates in Grams.	Specific Gravity.	% by Volume of Distillates.
Below 230° C., ...	Water, 8·29	835	1·007	30·60
	Oil, ·79		0·899	2·91
230° to 300° C., ...	„ 1·89	183·5	0·971	6·97
300° till oils solidify,	„ 3·53	351	0·994	13·02
Oils solidifying on cooling a soft paraffin scale, ...	„ 4·54	440	0·987	16·75
	Total, 19·04			
Coke, ...	... ...	555		
		2443·5		
	Loss,...	142·5		
		2586·0		

The coke was 21 per cent of the weight of the tar.

"The oils were quite transparent, the lower boiling and lighter fractions possessing an amber-yellow colour, whilst the higher boiling and heavier ones had a colour approaching that of port wine."

The heavier or creasote oils contain a considerable quantity of phenols, but the aromatic hydrocarbons are absent or present only in very small quantities.

Distillation for Production of Ammonia.—Ordinarily the distribution of the nitrogen, when coal is subject to destructive distillation, seems to be something like—

	Per Cent of Coal.	Per Cent of Nitrogen.
Nitrogen evolved as ammonia, ...	·251	14·51
„ „ cyanogen, ...	·027	1·56
„ in the gas, ...	·610	35·26
„ in the coke, ...	·842	48·67
	1·730	100·00

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[1] *J. S. C. I.*, 1883, p. 496.

Though the proportions may vary considerably with different coals and with the method of distilling.

It is possible to obtain a very much larger yield of ammonia under some conditions.

If a large excess of steam be used a much larger amount of nitrogen, amounting to nearly half the nitrogen in the fuel, may be obtained as ammonia. M. Mond obtained as much as 90 lbs. of ammonium sulphate per ton of coal consumed. The gas, however, was poor, containing about 15 per cent of carbonic acid (see p. 182, analysis No. 25).

In the Young and Beilby apparatus vertical retorts or producers are used, grouped together with passages for circulating the hot gases round the retort. The coal is fed into the top and distilled by the heat of the ascending gases. The coke is burnt in the lower part by air mixed with a large excess of steam, so as to produce ammonia. By this apparatus as much as 90 to 125 lbs. of sulphate per ton of coal has been obtained.

CHAPTER IX.

FURNACES FOR METALLURGICAL PURPOSES.

Classification of Furnaces.—It is very difficult to arrange a satisfactory classification of furnaces, (1) on account of the large number of forms that are in use, and (2) because the terms in common use are used so loosely that any attempt to give them a precise meaning is almost sure to fail.

It is most convenient at the outset to divide furnaces into groups according to the nature of the fuel they are designed to use.

1. Furnaces for solid fuel.
2. Furnaces for liquid fuel.
3. Furnaces for gaseous fuel.

Furnaces for Solid Fuel.

A. Furnaces in which the substance being heated is in contact with the fuel.
  1. The height is considerably greater than the diameter = Shaft furnaces.
    α No blast is used = Kilns.
    β Blast is used = Blast-furnaces.
  2. The height is not much greater than the diameter = Hearths.

B. Furnaces in which the substance being heated is not in contact with the fuel, but is with the products of combustion = Reverberatory furnaces.
  1. The charge is not melted. Roasting furnaces.
    α The hearth is fixed.
    β The hearth rotates.
  2. The charge is melted. Melting furnaces.

C. Furnaces in which the substance being heated is neither in contact with the fuel nor with the products of combustion.
  1. The chamber in which the substance to be heated is fixed and is part of the furnace = Muffle furnaces.
  2. The chamber in which the substance to be heated is placed is movable and independent of the furnace = Crucible furnaces.
  3. The substance is volatilized and escapes in the form of vapour = Retort furnaces.

Kilns.—These furnaces are used for many operations, in which a very high temperature is not required, as, for instance, the calcination of iron ore, lime-burning, and other similar purposes. They are made in a great variety of forms, according to the purpose for which they are to be used and the conditions under which they are to be worked. They are usually cylindrical in external form, and the interior is either cylindrical or conical. The charge mixed with the necessary amount of fuel is introduced at the top, and drawn in the solid condition at the bottom. Usually the charge rests on the solid floor of the kiln, and if the diameter is at all great an inner cone or wedge is used so as to throw the descending charge outwards and allow of its ready withdrawal, or in some cases the charge is made to rest on fire-bars. As the temperature required is not high the fuel consumption is small. In an iron-ore kiln, assuming that the ore contains no combustible material, the consumption is about $\frac{3}{4}$ cwt. of coal per ton of ore, and in a good lime-kiln about 1 cwt. per ton of lime. When the substance being calcined contains combustible material, organic matter in the case of blackband ironstones, or sulphur in the case of pyritous materials, no fuel may be necessary. As examples of kilns an ordinary Scotch iron-ore kiln and the Gjers kiln used for calcining iron ores in the Middlesborough district may be taken. These are sufficiently shown by the sectional drawings figs. 56 and 57, and no further description is necessary.

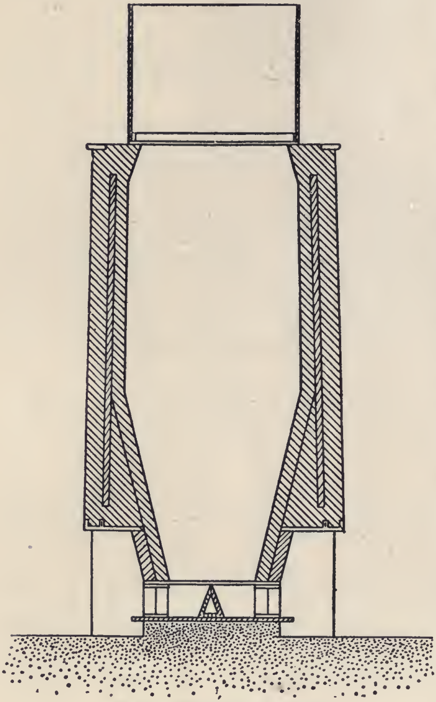

Fig. 56.—Scotch Iron-ore Kiln.

As an example of a more complex kiln the Hoffman kiln may be taken. "It consists of a circular tunnel, which can be divided into any number of compartments, M_1, M_2, &c., twelve or sixteen being the usual number. These compartments are, however, in direct communication with each other, except at one point where an iron plate *pp* placed across the tunnel interrupts the continuity. This plate may be inserted through the roof of the tunnel down grooves provided for its reception in the walls. Each space between two sets of grooves is provided with an internal flue n_1, n_2, &c., which by the removal of a damper can be placed in communication with a central chimney, and each space has also a door B B in the outer wall. Only two of these doors are open at a time. The whole of the tunnel is kept full of the material" to be burned and the fuel, "except one compartment which is always empty. The position of the empty compartment varies from day to day. Let the plate occupy the position *p p* shown in fig. 58. The

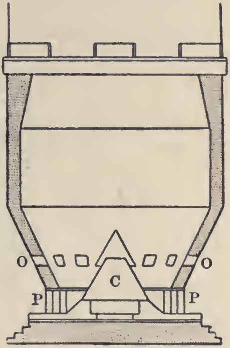

Fig. 57.—Gjers Kiln.

C, Cone. P, P, Pillars. O, O, Lateral openings.

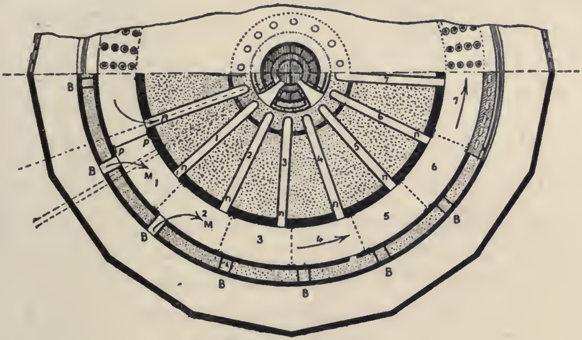

Fig. 58.—Otto Hoffman Kiln.

newest material has been charged in behind it into the compartment 16. Air enters in front of it through the open door of the empty compartment No. 1, and through the door, also open, of the next compartment, which contains finished material that has been longer in the furnace than the rest, and has but little heat to give up to the incoming current of air. This current is drawn by natural draught round the entire tunnel, and can only enter the chimney through one or more of the flues that have been opened behind the plate. After an interval of twenty-four hours from the last charging the compartment No. 1 has been filled, and the position of the iron partition is shifted to the next groove to the right, and the compartment No. 2 in front of the plate is emptied. Thus new material is continually kept behind the plate and finished material in front of it. Air entering comes in contact with material which gradually increases in temperature, for it will be obvious that the position of the hottest part of the furnace must be continually travelling round the circle, and that in a number of days, corresponding with the number of compartments, the zone of combustion will have travelled completely round the circuit. The air and the material to be treated enter and leave the furnace in a cold condition, so that there can be no waste of heat provided that the adjustment of the dampers in the flues through which the gases pass to the chimney is carefully effected. In order to remedy local irregularities of combustion air may, if necessary, be admitted through suitable orifices in the roof."[1]

The volume of each compartment may vary from 282 to 1765 cubic feet, and the height of the tunnel should not exceed 9 feet.

Owing to the small quantity of fuel used and the large amount of air admitted the atmosphere in a kiln is always oxidizing, so that the action is often roasting as well as calcining.

The Blast-furnace.—The blast-furnace, though in general resembling a circular kiln, differs from it in important points. The air is forced in under pressure, a much larger quantity of fuel is used, and the temperature is so high that the charge is melted, and has to be tapped out in the liquid condition.

The size and form of blast-furnaces varies enormously, from the large iron-smelting furnaces of Cleveland to the small

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[1] Roberts-Austen, *Introduction to the Study of Metallurgy.*

furnaces, six feet or so in height, used for lead smelting. To illustrate the general character of the furnace and the mode of action two types will be briefly considered: the blast-furnace as used for iron smelting, and the smaller water-jacket furnaces used for lead smelting in Colorado.

Iron-smelting blast-furnaces vary in height from 40 to 100 feet, and the other dimensions vary similarly. An ordinary blast-furnace consists of three parts: an upper conical part or shaft, a middle part in the form of an inverted cone called the bosh, and a bottom cylindrical portion or hearth. These portions may be separated by distinct lines of demarcation, or they may curve gradually one into the other. Small blast-furnaces may be of the same diameter all the way down, or they may taper gradually from top to bottom. The ratio of height to greatest diameter may vary very much, but in modern furnaces is usually about 3·5 or 4:1, varying down to about 3:1 and up to 6:1 in very exceptional cases.

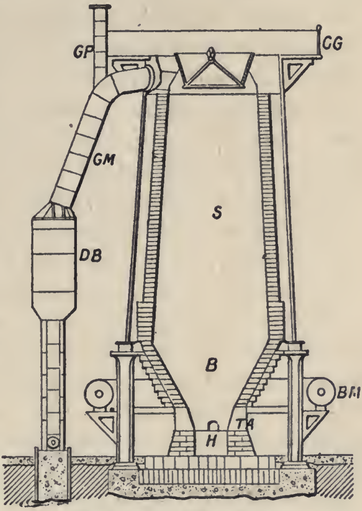

Fig 59.—Typical Blast-furnace.

S, Shaft. B, Bosh. H, Hearth. TA, Tuyere opening. BM, Blast main. CG, Charging gallery. GM, Gas main. DB, Dust box. GP, Waste-gas pipe.

The charge is introduced at the top, which is now almost always provided with some form of charging apparatus by which the gases can be drawn off, since these are combustible and are therefore of value. Air is blown in by a series of tuyeres just at the top of the hearth, leaving space below for the accumulation of the molten slag and metal which are tapped out periodically from tap-holes in the hearth, one at a higher level for the slag and another at a lower level for the metal. The air is supplied from the blowing engines or fans by a blast-main which passes round the furnace.

The chemical action which takes place in the blast-furnace is in the main simple. The air coming in contact with the fuel at a high temperature, its oxygen is at once converted into carbon monoxide, and if by chance any carbon dioxide should be formed it would be instantly reduced, so that the gas as it ascends will consist essentially of a mixture of carbon monoxide and nitrogen, having exactly the composition of simple producer-gas. In addition there will be a small quantity of hydrogen from the moisture contained in the air. These gases will be powerfully reducing, and therefore the atmosphere in a blast-furnace will be always reducing, and the oxide of iron or other metal charged into the furnace will be reduced by the carbon monoxide, thus adding carbon dioxide to the gases; and as this reaction takes place at a very low temperature, the reduction will be largely if not completely effected near the top of the furnace. Sulphides are not acted on by carbon monoxide or carbon, so that in the absence of special reducing fluxes sulphide ores are melted but not reduced in the blast-furnace.

The satisfactory working of a blast-furnace depends on several conditions, among which the regular ascent of the gases, the regular descent of the charge, and the proper cooling of the gases are of the utmost importance. The first two depend very much on the form of the furnace; and it is only by long experience that the forms now in use have been evolved. In the best modern furnaces, if the greatest diameter be taken as 1, the height will be 3·5, the width at the stock-line, *i.e.* at the top of the charge when the furnace is full, ·75, and the hearth about ·4; so that for an 80-foot furnace the dimensions would be—Height = 80 feet, diameter at bosh 23 feet, diameter at stock-line 17 feet, diameter of hearth 9 feet or thereabouts, and the angle of the bosh should be about 75°.

The proper cooling of the gases necessitates a sufficiently high column of material in the furnace to absorb the sensible heat of the gases as they rise. The hearth and boshes of the furnace are subjected to very great heat, and therefore must be built of very refractory materials; and in order to prevent them being rapidly cut away, water-blocks, *i.e.* iron blocks through which water can be made to circulate, are very frequently built into the masonry of the bosh.

The blast-furnace is a very economical machine, in spite of the fact that the carbon is only burnt to carbon monoxide, and therefore only evolves about $\frac{1}{3}$ the heat which it is capable of giving on complete combustion; but as the gases given off are combustible the remainder of the heat can be obtained by burning them.

Either charcoal, coke, or coal may be used in the blast-furnace under certain conditions, and the size and method of working to a very large extent depends on the nature of the fuel. The furnace must not be so high that the weight of the superincumbent charge will crush the fuel, or the blast will be impeded, and the working of the furnace therefore interfered with.

For charcoal about 30 or 40 feet seems to be the greatest satisfactory height, for coke the furnace may probably be any height that other conditions allow, if the coke be of first-class quality, but if it be of inferior quality the advantageous height will be much limited. In the case of certain American cokes the height of charge which would crush the coke was found to vary from 70 feet as a minimum to 128 as a maximum. The highest furnace in use using Durham coke in the Cleveland district is 101 feet, and this is found to be rather too high for satisfactory working.

Only certain qualities of coal are suitable for blast-furnace use. A strongly coking coal which softens and fuses is not satisfactory, as it impedes the blast; it is only the less strongly coking varieties, therefore, that are available, either the anthracitic or splint varieties. In America anthracite has been used, but its great density and lack of porosity renders it somewhat unsuited for blast-furnace work. The splint coals used in Scotland are quite suitable, but they yield comparatively little coke, and as this coke is soft and friable high furnaces cannot be used, so that about 60 feet is found to be the maximum height that is advantageous.

In the selection of a fuel for blast-furnace use it must be remembered that it is only the fixed carbon that is of any use for producing heat in the furnace, all volatile matter being expelled before the fuel reaches the zone of combustion, so that in estimating the fuel value of a coal for this purpose no notice must be taken of the portion which is volatile. As the splint coals of Scotland only yield about 50% of coke, their value is little more than half that of a coke.

In selecting a coke for furnace use attention must be paid to its actual heating power and to its physical condition, especially its crushing strength, and in selecting a coal attention must be paid to its coking properties, and to the amount and nature of the coke which it produces.

The following table of the properties of some American cokes will illustrate the variations which may take place:[1]—

Locality.	Pounds in One Cubic Foot.		Percentage.		Compressive Strength per Square Inch.	Height of Charge which it will support without crushing.	Hardness.	Sp. Gr.
	Dry.	Wet.	Coke.	Cells.				
Connelsville,	47·47	77·15	31·33	38·47	284	114	3·50	1·500
W. Virginia,	52·54	81·56	64·32	35·67	258	103	3·15	—
Broad Top,	44·81	76·88	58·27	41·73	240	96	3·35	1·342
Clearfield, ...	56·35	76·69	74·43	25·57	319	128	3·60	1·56
Cumberland,	48·61	82·41	58·99	41·04	215	86	3·00	1·750
Alabama, ...	50·70	69·01	73·77	26·23	225	87	3·50	1·493
Illinois, ...	42·02	65·09	63·79	36·21	180	70	3·20	1·215

A very important property of coke on which much of its value for blast-furnace use depends is its power of resisting the action of carbon dioxide. By the changes which take place at the top of the furnace—reduction of oxide of iron and decomposition of limestone—carbon dioxide is added to the gases. Under suitable conditions this attacks carbon and forms carbon monoxide, $CO_2 + C = 2\,CO$, thus consuming more coke without doing any good. The temperature at which this

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[1] Fulton, *Transactions American Institution of Mining Engineers*, vol. xii. p. 212–223.

action takes place varies with different forms of coke, and obviously the less readily it takes place the more efficient, other things being equal, will the coke be.

Sir I. Lowthian Bell, in some experiments on cokes made in the beehive and in the Simon-Carvès oven, found that though the two cokes differed very slightly in calorific power, the ratio being : 100 : 98·5, the amount required in the blast-furnace to do equal work was in the ratio 100 : 91; and on examining the gases from the furnaces he found that those from the former contained a considerably larger quantity of carbon dioxide than those from the latter. From examination in the laboratory it was found that the one form of coke was more readily attacked by carbon dioxide than the other.

Another important property is the cell structure of the coke. The calorific energy of a blast-furnace depends on the amount of surface which is exposed to the oxygen of the air, in the region of the tuyeres, and this depends on the amount of cell space; for this reason, charcoal, which is much more cellular, is more efficient fuel than coke.

The following table, by Sir I. Lowthian Bell,[1] will give an idea of the actual efficiency of an iron-smelting blast-furnace. The figures are for each 20 pounds of iron produced:—

	Centigrade units.	B.T.U.
Evaporation of water in coke,	313	563
Reduction of oxide of iron,	33180	59724
Carbon impregnation,	2400	4320
Expulsion of CO_2 from limestone,	4070	7326
Decomposition of CO_2 from limestone,	4244	7438
Decomposition of water in blast,	1700	3060
Reduction of phosphoric acid, sulphuric acid, and silica,	3500	6300
Fusion of pig-iron,	6600	11880
Fusion of slag,	15386	27095
Heat usefully employed,	70311	126560
Carried off in gases,	7900	14220
Otherwise lost,	8789	15820
Total,	87000	156600

giving an efficiency of about 80% of the heat evolved by the

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[1] *Principles of the Manufacture of Iron and Steel,* p. 95.

fuel consumed, only about 9% being carried off as sensible heat in the gases.

The amount of fuel actually consumed in smelting iron ores is about 18 to 21 cwts. of coke, or 30 to 36 cwts. of coal per ton of iron produced.

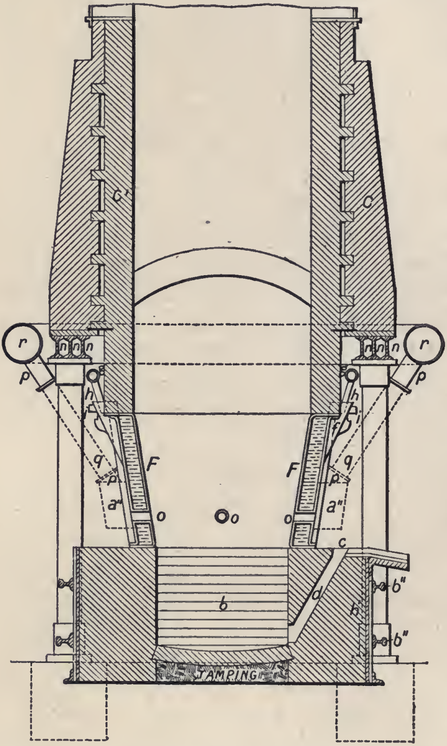

Fig. 60.—Blast-furnace for Melting Lead. From Hofman's *Lead*.
o, Tuyeres. F, Water-jacket. *d*, Siphon tap. *r*, Blast main.

The smelting of ores of lead and copper in the blast-furnace was for a long time unsuccessful, as the metallic oxides very rapidly corroded the brickwork. This difficulty has now been overcome by the introduction of the water-jacket. This is a casing of either wrought or cast iron, through which water is made to circulate. This has the effect of cooling the charge, so that the interior becomes covered with a layer of slag which is being constantly formed and melted away. The circulation of the water carries away some heat, and this reduces the actual efficiency of the furnace, but it has rendered the furnace available for purposes for which it could not be used before.

Most of the water-jacketed furnaces used for lead smelting in America are rectangular in form instead of circular.

The Hot Blast.—The hot blast was invented by Neilson in 1828, and very rapidly came into general use, as it led to very great economy in the use of fuel. The amount of heat developed in the furnace is far less with the hot blast than with the cold. The saving is due to the fact that much less air is passed through the furnace, and therefore there is less heat carried away by the waste gases; and also that the air being hot, there is less expansion to take place opposite the tuyeres, and as expansion absorbs heat there is thus less cooling. As the hot blast is only of practical importance in the smelting of iron, it will be fully described in the volume on iron.

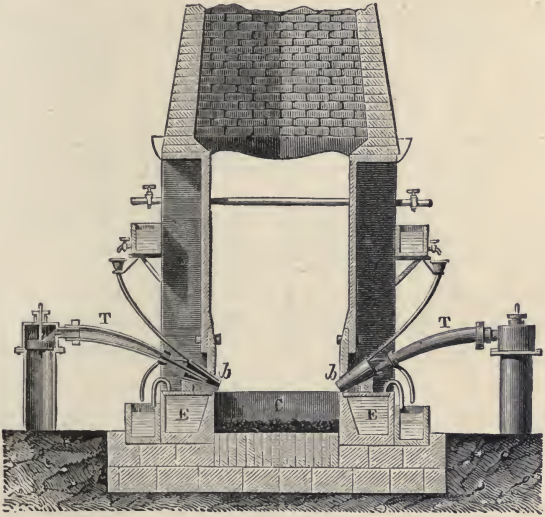

Fig. 61.—Refinery Hearth.

C, The hearth. E E, Hollow water-jacketed walls. T T, Blast-pipes. *b b*, Tuyeres.

Hearths.—The hearth resembles the blast-furnace in the fact that the fuel and the substance to be heated are in contact, but it differs in almost every other respect.

It is usually a shallow chamber or vessel in which the charge is placed. The air is supplied by means of tuyeres, and is either directed downwards on to the surface of the charge or horizontally just below the charge.

The combustion is usually more complete than in the blast-furnace, the carbon being to a large extent burnt to carbon dioxide, but the escaping gases usually contain considerable quantities of unconsumed combustible gases. Owing to the way in which the air is supplied, the atmosphere is not so powerfully reducing as that of the blast-furnace, or it may be actually oxidizing. The hearth, therefore, can be used for various operations: direct reduction, as in the Catalan forge; oxidation, as in the Yorkshire finery; or combined oxidation and reduction, as in the Scotch ore-hearth. The amount of fuel consumed is not large, and on the whole the hearth is a fairly economical furnace for those operations for which it is suited. It has the advantage also of being cheap and easy to erect, and it is therefore largely used in new districts or where labour and material are expensive.

The Reverberatory Furnace.—This furnace is entirely different in principle from those already described, the fuel not being in contact with the material that is heated. The fuel is burned on a separate grate, whilst the material to be heated is in a separate chamber, the hearth, into which the products of combustion pass. Between the grate and the hearth is a ridge of brickwork, the fire-bridge, and between the hearth and the chimney there is often another ridge, the flue-bridge, over which the products of combustion pass.

The whole furnace is covered with an arched roof, which is usually highest over the fireplace and slopes down towards the flue, so that the flame may be reverberated or reflected downwards on to the hearth, whence the name reverberatory furnace. The roof is usually a very flat arch springing from the side walls of the furnace. As the weight of this arch exerts a considerable outward thrust, the walls of the furnace must be securely tied. Usually the side walls are cased with iron plates, and strong vertical rods are fixed into the ground at each side and are tied by cramps into the masonry, and are held together at the top by strong stays passing across above the furnace roof. The vertical or buck stays may be of any form, but are preferably of T section, the projecting limb not extending quite to the top, and a hole being made at the top through which the head of the cross stay can pass. Where economy is an object old rails make excellent buck-stays. The cross stays are circular or square in section, and in the case of the first-named kind, they are held by a head at one end and a screwed nut at the other. When rails or similar buck-stays are used the cross stays are provided with eyes which pass over the top of the vertical stay and are wedged into position.

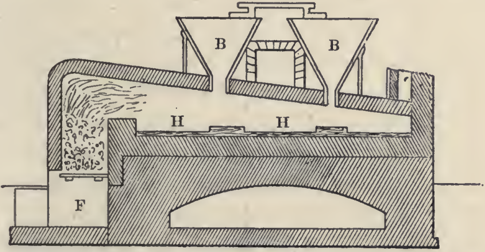

Fig. 63.—Reverberatory Furnace for Calcining Copper Ores. H H, Hearth. F, Fireplace. B B, Hoppers.

The cross ties must not be fixed rigidly, but must be capable of adjustment, for as the furnace gets hot the masonry of the arch will expand, and unless provision be made to allow for this the crown of the arch may be thrown up and broken.

The hearth itself is usually carried on an arch of brickwork, so that there is a vault or chamber under the furnace to which access can be obtained when necessary. The furnace will usually be provided with a series of working doors, one, two, or three at each side, and sometimes one at the end, in which case the flue is taken off at the side; all the doors are fitted into cast-iron frames securely built into the masonry. The doors themselves are iron or fire-brick plates, which are lifted up and down as required, and are luted air-tight with clay when necessary. The charge may be introduced through the side doors, or through a hole in the roof, which is usually provided with a hopper.

Reverberatory furnaces are in general used for two purposes, for roasting and fusion with or without reduction, and the form and size of the hearth will depend on the process for which it is to be used.

For roasting furnaces the hearth is usually flat, made of firebrick slabs carefully set in clay. The sills of the working doors are either level with the hearth, so that the charge can be raked out on to the floor, or if they are higher, openings are provided under each, by which the charge can be raked into the arched chamber beneath the furnace. This is always advisable when the roasted charge is likely to give off noxious fumes as it cools. In some cases iron receptacles for the charge are provided outside the furnace under the doors into which the charge can be drawn, and the escaping gases pass into the furnace by the doors and thus to the chimney.

The hearth may be rectangular or oval in form. It must not be so long that it cannot be uniformly heated—16 feet may be taken as being about the maximum length; and as the charge will have to be turned by the workmen, it must not be so wide that the rabbles have to be inconveniently long—about 10 feet is the maximum allowable width. It must be so shaped that every portion of it can be reached by means of a rabble or rake from the working doors, and therefore sharp corners are usually filled up with masonry, and in the spaces between the doors wedges of masonry are built. It sometimes happens, in cases where only a very moderate temperature is required, that the part of the charge nearest the fire-bridge may become overheated, and to prevent this a false or curtain arch may be built from the fire-bridge to about one-third the length of the hearth. As a copious supply of air is needed for roasting, various air-openings are often left through the side wall, or through the bridge, which is then called a "split bridge".

For roasting, furnaces with more than one hearth are often used. In this case two or more hearths are placed end to end, each being about three inches higher than the one behind, and each being provided with its own working doors. The charge is let down on the hearth furthest from the fireplace, and is moved forward and ultimately drawn from the hearth nearest the fire, so that there will always be, in a three-hearth furnace, three charges being treated at once. Two-hearth furnaces are often advantageous, three-hearth are sometimes useful, but furnaces with more than three hearths are very rarely satisfactory, and can only be used in cases where the material under treatment contains enough sulphur to evolve a considerable amount of heat on oxidation.

When the furnace is to be used for fusion, the arrangement is somewhat different. The hearth is smaller, may or may not be provided with working doors at the side or end, and instead of being flat it is made curved, so that melted material will all flow towards the lowest point—the well, where it will collect till it is tapped out by means of the tap-hole, or, as in the case of copper refining, ladled out into a metal pot or moulds. The form of the hearth is usually roughly given by bricks built in steps, and on this is laid the working bottom of slag or some other material not likely to be acted on by the charge. In many cases, where a very high temperature is required, the hearth is carried on iron plates so arranged that air can circulate quite freely under it, or in others the hearth may be merely an iron pan, lined or not with refractory material.

The fireplace is usually fed from the side. It should not be more than about 6 feet deep from the door, or it will be impossible to distribute the fuel evenly by hand. The ratio of the size of the fireplace to that of the hearth varies very much, and depends on the temperature which it is required to attain, and also on the nature of the fuel. It is largest in the case of the puddling furnace, a furnace with a very small hearth, and in which a very high temperature is required, and it is smallest in roasting furnaces, where it is often not more than one-twentieth, and between these there is every possible variation. The table on p. 214 gives the details of a few typical furnaces.

The height of the bridge above the hearth is about 1 foot to 1 foot 9 inches, and all details may vary very much,

	Puddling Furnace.	Reheating Furnace (Major Cuhills').	Calciner (Copper Ores).	Melting Furnace (Copper).	Flintshire Furnace (Lead).	Cupellation Furnace.	Copper Refining (Coal).	Copper Refining (Wood).
Fireplace—								
Length, ...	3·5	4·3	3·0	4·0	2·5	1·9	3·5	3·75
Breadth, ...	2·5	5·5	5·0	4·0	4·0	2·0	4·0	4·5
Area, ...	8·75	23·65	15·0	16·0	16·0	3·8	14·0	16·9
Hearth—								
Length, ...	6·0	15·0	19·0	13·0	11·0	2·5	14·0	13·5
Breadth, ...	3·75	5·5	11·0	9·0	10·0	4·0	9·5	9·0
Area (approximate), ...	20·0	75·0	200·0	112·0	104·0	10·0	12·6	117·0
Ratio-area of fireplace to area of hearth (approximate), ...	1:2·3	1:3·2	1:13·0	1:7·0	1:10·4	1·3	1:9	1:7
Height of arch above bridge, ...	1·0	3·9	1·5	1·67	·8	·8	—	—
Depth of fireplace below bridge,, ...	1·5	·8	2·0	3·0	2·0	1·4	—	—

according to the purpose for which the furnace is to be used, and the taste of the builder.

The arrangement of the fireplace will vary with the nature of the fuel and the temperature which it is required to attain. The area of the fireplace includes both that of the fire-bars and the spaces between them. The width of the space between the bars is determined by the nature of the fuel, that of the bars is limited by the need for making them sufficiently large to be durable and to resist warping. The fire-bars will usually be ¾ inch or more in thickness. They are made of cast-iron, and are cast with square lugs at each end, which fit together when the bars are in position, and thus regulate the distance between them, or they may consist of 1¼ to 1½ inch square bars of iron resting on bearers. The bars should be cast from gray pig-iron with the addition of scrap, and should not exceed 40 inches in length. The bars are almost always placed horizontally, but they may be slightly inclined backwards. For large coal the space between the bars may be up to ¾ inch, but with smaller coal the spaces must be much less. In the case of anthracite coal, if the bars were placed close enough to prevent great loss by falling through, the draught would be unduly impeded, and to prevent this, in South Wales, where such coals are used, a deep layer of clinker is allowed to accumulate on the bars, which acts as a grate, and which also serves to heat the air as it rises, the clinker being from time to time broken up and removed through the bars, so as to maintain the bed at a convenient thickness.

The amount of fuel which can be burned on the hearth of a reverberatory furnace depends firstly on the nature of the coal, and secondly on the air supply. The more air, of course, the more rapid will be the combustion.

The more caking the coal, the less of it can be burned on a given grate area. "Of very caking coals not more than 12 to 14 lbs. per square foot per hour should be burnt; if less caking, from 14 to 16 lbs.; and if non-bituminous, from 16 to 20 lbs. may be used." Rankine gives the rate of combustion in various grates—

	Lbs. per Sq. Ft. per Hour.
1. Slowest rate of combustion in Cornish boilers, ...	4
2. Ordinary rate in these boilers, ...	10
3. Ordinary rate in factory boilers, ...	12 to 16
4. Ordinary rate in marine boilers, ...	16 to 24
5. Quickest rate of complete combustion, the supply of air coming through the grate only, ...	20 to 23
6. Quickest rate of complete combustion of caking coal, with air-holes above the fuel to the extent of one-thirtieth the area of the grate, ...	34 to 27
7. Locomotives, ...	40 to 120

Grüner gives—

	Lbs. per Sq. Ft. per Hour.
1. Furnace for roasting sulphides, ...	3 to 8
2. Fires for stationary boilers, ...	8 to 20
3. Furnaces used in smelting lead, ...	12 to 16
4. Furnaces for copper smelting, ...	15 to 30
5. Puddling furnaces, ...	20 to 30
6. Steel-melting furnaces, ...	41 to 81
7. Locomotive fires, ...	81 to 102

The thickness of the layer of fuel is also important. The thinner the layer of fuel, the better will be the draught, and the more coal can be burned; but if it be too thin, air may get through unconsumed, and thus the efficiency will be seriously reduced. "The limits of thickness over the grate are 1½ to 5 inches for bituminous coal, and 1½ to 8 inches for brown coal. Peat, which is not pulverized by fire, may be piled as high as the space around it will allow."[1]

One advantage of the reverberatory furnace is that the atmosphere can be regulated so as to fit it for various purposes. If a large excess of air be admitted above the fuel, combustion will be complete, and the atmosphere will be powerfully oxidizing; if, on the other hand, the amount of air be restricted, the combustion will be less complete, carbon monoxide and other reducing gases will be present, and the atmosphere will be powerfully reducing.

It will be seen that the heating in a reverberatory furnace is entirely produced by the flame of the fuel and the heat of the products of combustion. A flame could be obtained by burning coke on the hearth in sufficient thickness to ensure the production of a large quantity of carbon monoxide; but such a flame, being non-luminous, would have little radiative power, and therefore would be very inefficient. The coal used should be moderately caking, and should yield a considerable quantity of gas on distillation, so as to produce a large bright flame.

The reverberatory furnace is not by any means an economical form of apparatus, the losses of heat being always very high. Grüner states that the efficiency of a reverberatory furnace melting pig-iron is only 8·5 per cent; but Major Cubillo has recently pointed out that this estimate is too low, the data not having been accurate. Taking the puddling furnace as the type of a reverberatory furnace, Major Cubillo obtains in a special case the following results, which he states in the form of a balance-sheet:[2]—

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[1] Schmackhöfer and Browne, *Fuel and Water*, p. 96.

[2] *Proc. S. Staff. Institute of Iron and Steel Works Managers*, 1893–1894, p. 13.

GENERAL BALANCE OF THE REVERBERATORY FURNACE.

Heat Produced.			Heat Consumed.		
	Calories.	Per c.		Calories.	Per c.
Heat of fuel, ...	163957·85	98·12	Fusion of the iron, ..	26214	15·60
			Fusion of the slags, ..	2246·36	1·34
Heat of substances oxidized during the process, ...	3105·6	1·88	Vaporization of water in the fuel, ...	2133	1·27
			Heat carried off by gases, ...	128862	77·13
			Heat lost in ashes, ..	1990·2	1·13
			Loss by radiation, &c.,	5617·89	3·35
	167063·45	100·00		167063·45	99·82

The efficiency being therefore 16·94 per cent. In most cases of reverberatory-furnace work the efficiency is far less than this, the loss by radiation being usually very much higher.

Major Cubillo[1] has worked out the thermal values of the changes on a gas-fired puddling furnace, with a view of ascertaining its efficiency. The details cannot be understood without a consideration of the chemistry of the process, as heat is obtained not only from the fuel but also by the reaction in the furnace, but a summary of the results may be of value.

The heat received is thus summed up:—

	Calories.	Per Cent.
Heat brought in by producer-gas, ...	197·829	22·70
Combustion of 135·73 C O and 6·72 H,[2] ...	520·959	59·80
Heat introduced by air, ...	86·691	9·96
Oxidation of silicon, ...	26·074	2·90
" manganese, ...	1·966	·22
" carbon, ...	29·815	3·45
" phosphorus, ...	·201	·02
" sulphur, ...	·195	·02
" iron, ...	6·327	·72
	870·057	99·79

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[1] *J. I. and S. I.*, 1892, vol. i. p. 245, *et seq.*

[2] Per 100 kilogrammes of blooms.

Heat consumed:—

	Calories.	Per Cent.
Latent heat of fusion,	5·198	2·90
Heat of blooms,	20·068	
Heat of fusion of cinder,	23·052	2·64
Vaporization of water in ore,	5·371	·60
Lost up stack,	366·696	42·14
Vaporization of water in gas,	7·592	·87
Reduction of Fe_2O_3 to FeO,	14·083	1·61
Reduction of Mn_2O_3 to MnO,	3·344	·38
Heat of ash,	9·604	1·11
Radiation,	415·049	47·70
	870·057	99·95

These figures of course refer only to the one charge with which the experiment was made in the arsenal at Trubia; but probably others would not be far different. The efficiency as shown by the figures is only 2·9 per cent. It would be much larger probably with furnaces of larger size, the extreme shortness of the puddling furnace being very favourable to loss of heat in the gases.

The reverberatory furnace may be modified in various ways for various purposes. The hearth may be made circular, and may be made to rotate horizontally, or the whole working space may be made cylindrical and may be made to rotate vertically. These devices are to ensure constant stirring of the charge, and do not in any way alter the principles on which the furnace is based. When wood is the fuel used the fireplace is frequently made with a solid bottom, as air can find its way quite readily enough into a mass of wood without the use of fire-bars.

The draught is usually produced by means of a chimney, but artificial draught may be used. If the ash-pit be closed air-tight a blast can be sent in beneath the bars, and another supply of air may be sent in above the fuel, in order to ensure complete combustion of the products of distillation.

Another type of furnace, the Stetefeldt furnace, which is usually used for the chloridizing roasting of silver ores, belongs to this group. The ores are sulphides, and therefore no additional fuel is required, and the roasting takes place whilst the powdered mineral, mixed with salt, is falling down a vertical shaft which is kept hot by fireplaces G near the bottom; the roasted ore falls into a hopper and is withdrawn. The size of these furnaces varies; they may be up to 35 or 40 feet high and 5 feet square, and will treat from 40 to 50 tons of ore per day. Some of the most recent Stetefeldt furnaces are fired with gas.

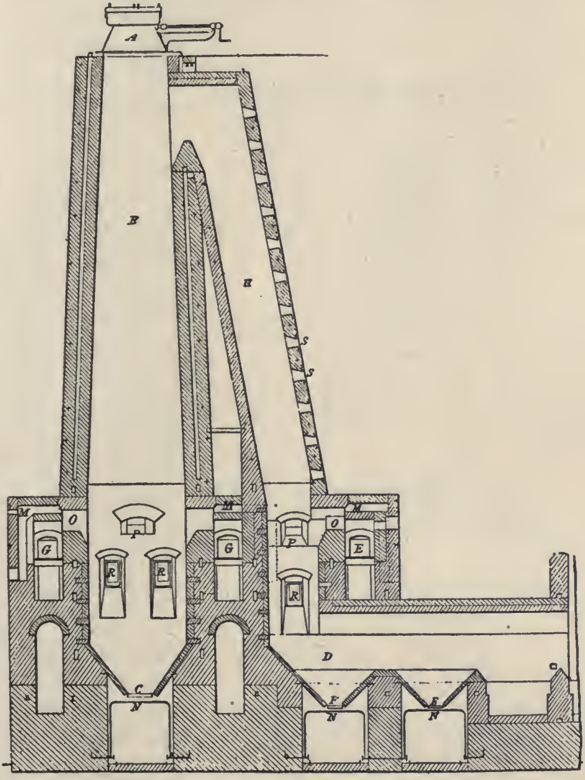


Fig. 63.—The Stetefeldt Furnace.

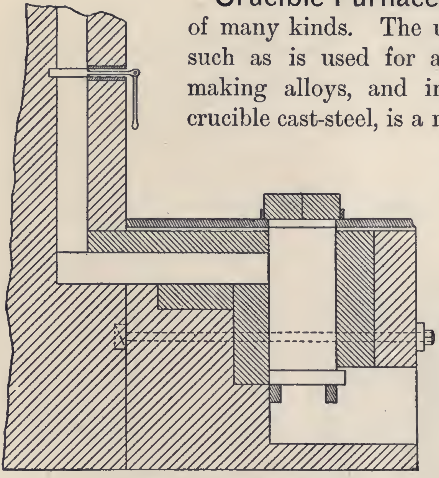


Fig. 64.—Crucible Furnace.

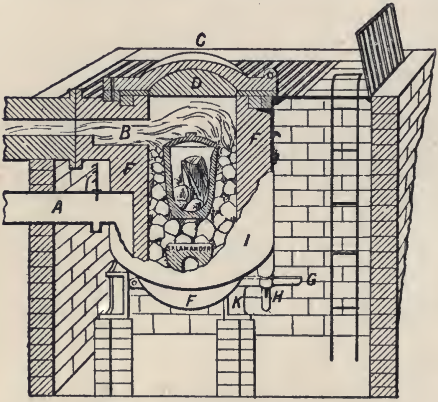


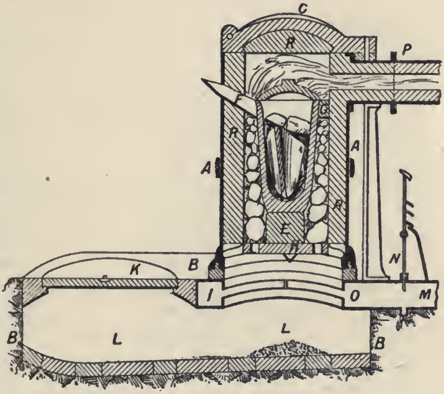
Fig. 65.—Fletcher's Patent Furnace.

A, Air tube. I, Iron casing of furnace. F, Fire-brick lining.
B, Flue. C, Cover with fire-brick lining D.

Crucible Furnaces.—These furnaces are of many kinds. The usual crucible furnace, such as is used for assaying purposes, for making alloys, and in the manufacture of crucible cast-steel, is a rectangular or elliptical chamber, provided at the bottom with fire-bars and at the top with a cover, whilst a flue in one side near the top serves to carry off the products of combustion. The crucible is placed in a furnace resting either on the fuel or on a brick placed on the fire-bars. The fuel used is coke or anthracite—generally the former. The combustion is imperfect, carbon monoxide only being formed, and owing to the small quantities of material which can be treated at once such furnaces are very wasteful of fuel. Crucible furnaces may be worked either with or without blast. With a blast a very high temperature can be attained. A very good example of a crucible furnace with a blast is Messrs. Morgan's Annular

Hot-air Furnace (Fletcher's patent). In this the fuel rests on a solid dished bottom, into which the air is supplied, the crucible to be heated being placed on a stand in the centre of the furnace. This furnace gives a very high temperature, and acts very quickly, thus leading to considerable saving in fuel.

One objection to the use of crucibles is that in order to pour their contents they must be lifted into the air. This not only cools them, thus causing loss of heat, but also often causes the crucible to crack. This difficulty is overcome in the Piat Oscillating Furnace. The furnace is a circular iron shell, cased with fire-brick; it is provided with a grate, and stands over an air-chamber from which air is supplied under pressure. The crucible rests on a block, and is provided with a spout which passes through the casing. When the charge is to be poured the blast is turned off, the chimney disconnected, and the whole furnace swung by means of a crane, and the molten metal poured out of the spout in to the moulds. With this furnace, owing to there being no cooling, the melting is very quick and the quantity of fuel used is small.



L, Ash-pit. K, Man-hole. M, Air main with valve N. I, O, Annular air ring. H, Perforated base of furnace. E, Support for crucible. P, Chimney. C, Cover with fire-brick lining R. A, Iron ring to which are attached the pins by which the casing is lifted. P, Detachable chimney. F, Spout.

Fig. 66.—Piat's Oscillating Furnace.

Crucibles may also be heated on the hearth of a reverberatory furnace.

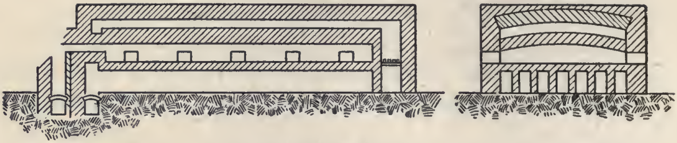


Fig. 67.—Muffle Furnace.

Muffle Furnaces.—In this type of furnace a separate large vessel is heated by means of a fire. The fire is usually placed underneath, or at one end of the muffle, and the products of combustion are made to circulate both above and below. Such furnaces are only used when either the substance being heated would be injured by contact with the gases, or where products are evolved which it is required to keep free from mixture with the products of combustion. Furnaces of this type are usually called close roasters. They are essentially reverberatory furnaces; but the charge is heated not by contact with or radiation from the flame, but by radiation from the hot walls of the muffle.

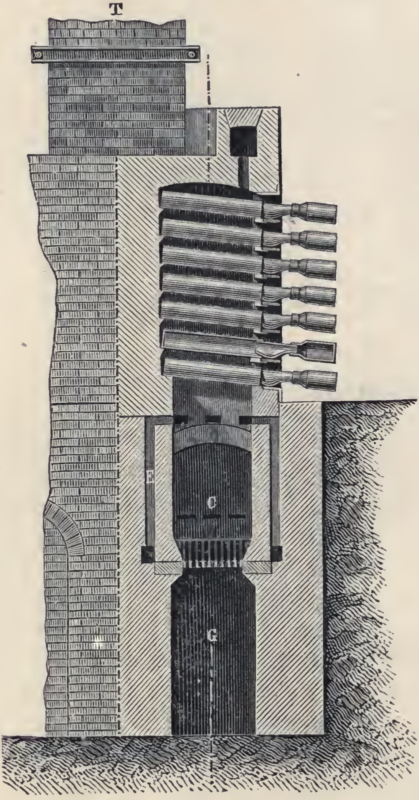


Fig. 68.—Retort Furnace for distilling zinc.

C, Fireplace. G, Ash-pit. E, Air passages. T, Chimney.

Retort Furnaces.—The only peculiarity of these furnaces is that all or part of the charge is volatilized and has to be condensed. They may be either of the type of muffle or crucible furnaces. Where there is a liquid residue which has to be poured out, furnaces of the crucible-furnace type are often used, and the body of the retort is lifted out after each charge, or to avoid this tilting furnaces are sometimes used.

Furnaces for Gaseous Fuel.—Many forms of furnace for the use of gaseous fuel have been suggested, the simplest of which are but slight modifications of a reverberatory furnace. In fact if the fireplace of a reverberatory furnace be made very deep, and be worked with a thick layer of fuel, it becomes a gas producer, as is seen in the Mond gas-fire.

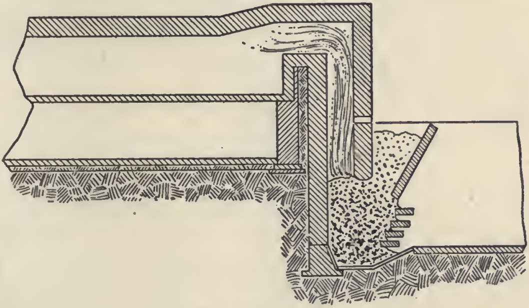


Fig. 69.—Mond's Gas-fire.

Boetius Furnace.—This furnace, patented in 1865, is intended to be used for all purposes for which a high temperature is required. It is an ordinary reverberatory furnace to which a gas producer is attached, but the side walls and roof are provided with passages through which the air can circulate so as to become heated before passing to the furnace, where it mixes with the combustible gases just as they enter. This furnace is said to be economical, and a high temperature can be obtained.

The Becheroux Furnace.—This is a modification of the Boetius furnace, in which the proportion of the parts is different, and a mixing chamber is provided for the air and gases before entering the furnace proper.

Furnaces fired in this way have not proved a great success owing to the low calorific power of the gas. Attempts have also been made with more or less success to work kilns by means of gas, the gas and air being admitted by two series of openings, one above the other.

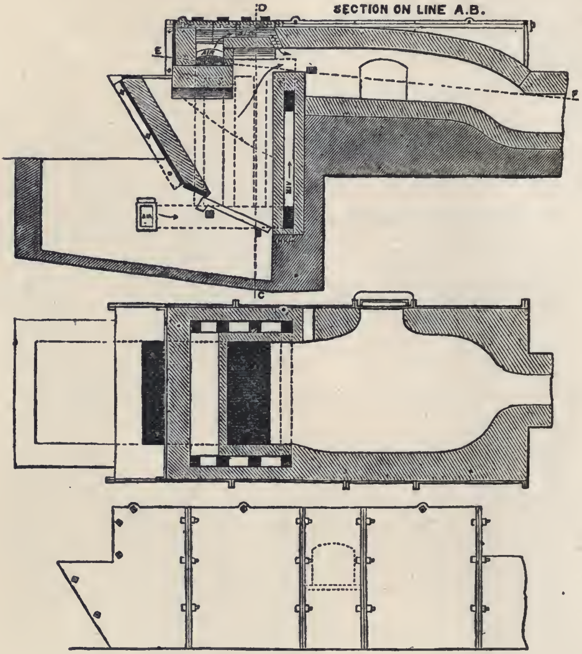


Fig. 70.—Boetius Heating Furnace. From D. K. Clark's *Fuel.*

Gas furnaces did not become a practical success till Siemens introduced his regenerative furnace. The principle of the regenerative furnace is very simple. Each furnace is provided with four chambers or regenerators, placed in any convenient position, and filled with a chequer-work of fire-brick. The air and gas are supplied at one end of the furnace, burn, and

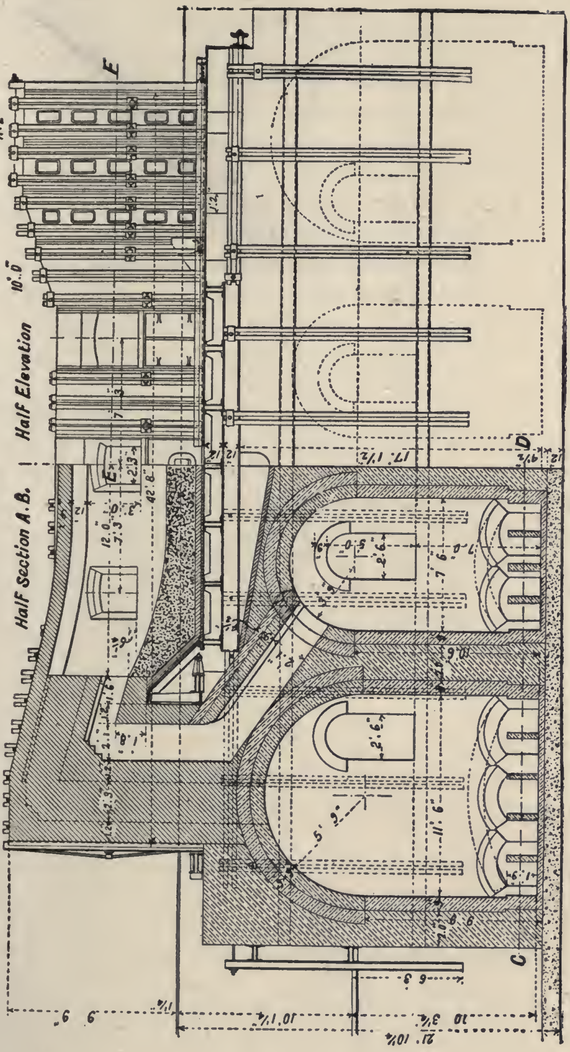


Fig. 71.—Steel Furnace at Wishaw Steel Works. From *Engineering*.

the products of combustion pass away at the other end to the chimney through one pair of regenerators. When these regenerators are hot the direction of the current is reversed, the air and gas are sent through the hot regenerators, and thus reach the furnace at a high temperature, whilst the products of combustion pass away through the other regenerators. The direction is reversed every hour or so, so that the regenerators are kept very hot, and whilst two are always being heated the other two are heating the air and gas.

Such a furnace consists of three essential parts—(1) the gas producer, (2) the furnace proper, (3) the regenerators with the necessary valves.

The gas producers have already been described. The furnace is simply a reverberatory furnace, but in place of a fireplace it is provided at each end with gas and air ports, which may open directly into the furnace or into a mixing chamber. The roof must be built of very refractory bricks, silica bricks being commonly used, whilst the hearth will either be of sand, dolomite, or other material according to the purpose for which the furnace is to be used. The whole furnace is preferably cased with iron and must be securely stayed. The gas and air are supplied from ports — rectangular openings at each end, the number varying, but always being odd—placed so as to break joint. The gas ports are below and the air ports above, so that the heavy air tending to descend and the lighter gas tending to ascend the mixture shall be complete. The roof in the furnaces designed by Siemens was depressed towards the middle of the furnace, so as to deflect the flame down on to the charge on the hearth.

The regenerators were placed underneath the furnace by Siemens, and have generally been built in the same position since. The four chambers may be all of one size, but usually the air regenerator is from 20 per cent to 40 per cent larger than the gas regenerator. The regenerators are filled up with refractory brickwork, set chequerwise, so as to allow free passages for the gas, and at the same time to ensure sufficient contact for thorough heating or cooling as the case may be. Siemens states that: "The products of the complete combustion of 1 lb. of coal have a capacity for heat equal to that of nearly 17 lbs. of fire-brick and (in reversing every hour) 17 lbs. of regenerator brickwork at each end of the furnace per lb. of coal burned in the gas producer per hour would be theoretically sufficient to absorb the waste heat, if the whole mass of the regenerator were uniformly heated at each reversal to the full temperature of the flame, and then completely cooled by the gases coming in. But in practice by far the larger part of the depth of the regenerator chequerwork is required to effect the gradual cooling of the products of combustion, and only a small portion near the top, perhaps a fourth of the whole mass, is heated uniformly to the full temperature of the flame, the heat of the lower portion decreasing gradually downwards nearly to the bottom. Three or four times as much brickwork is thus required in the regenerators as is equal in capacity for heat to the products of combustion. The best size and arrangement of the bricks is determined by the consideration of the extent of opening required between them to give a free passage to the air and gas, and" "a surface of six square feet is necessary in the regenerator to take up the heat of the products of combustion of 1 lb. of coal in an hour.

"By placing the regenerators vertically and heating them from the top, the heating and cooling actions are made much more uniform throughout than when the draught is in any other direction, as the hot descending current on the one hand passes down most freely through the coolest part of the mass, whilst the ascending current of air or gas to be heated rises chiefly through the part which happens to be hottest, and cools it to an equality with the rest.

"The regenerators should always be at a lower level than the heating chamber, as the gas and air are then forced into the furnace by the draught of the heated regenerator, and it may be worked to its full power either with an outward pressure in the heating chamber so that the flame blows out on opening the doors, or with a pressure in the chamber just balanced, the flame sometimes blowing out a little and sometimes drawing in."[1]

Roberts-Austen gives 14 to 15 square feet of regenerator brick surface as being necessary for each 2 pounds of coal burnt between two reversals.[2]

The arrangement of the valves is a matter of very great importance. The usual arrangement is shown diagrammatically in fig. 72. The butterfly valve is the commonest form, but many other forms have been suggested for the purpose, and have been described in the technical journals.

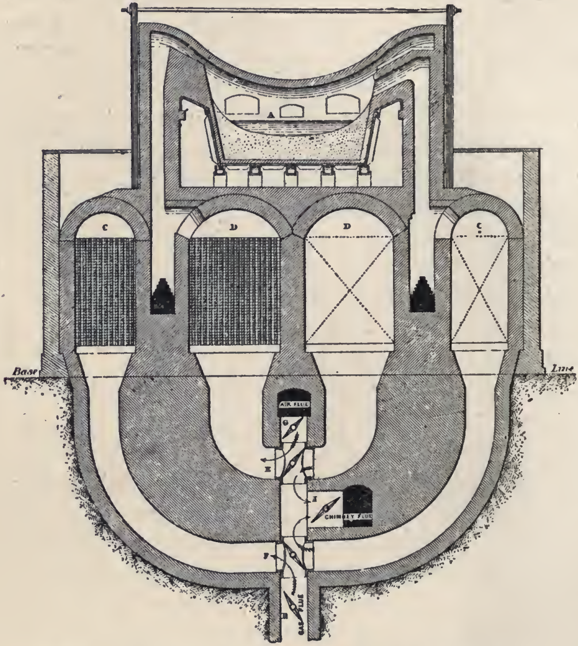


Fig. 72.—Section of Siemens' Steel Melting Furnace, with Valves.

The regenerative furnace has many advantages. Though the temperature in the furnace itself is very high the gases

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[1] *Collected Works*, vol. i. p. 227, 228.

[2] *Introduction to the Study of Metallurgy*, p. 261.

escape at a low temperature (212° F. to 300° F.), and therefore the heat which they carry away is small and the efficiency of the furnace is high. The flame can be kept perfectly steady for any length of time, and it can be made oxidizing, reducing, or neutral as required. Furnaces of this kind are now built of large size up to 40 feet long and 15 feet wide.

Very many modifications on the original form have been suggested.

In 1884 Mr. Frederick Siemens pointed out that the depressed roof and small combustion space in the ordinary type of furnace was disadvantageous, and that it would be better to make the roof a flat arch, or even to raise it in the centre instead of depressing it. He contended that in order to obtain a high temperature the gases should be allowed free space for combination, as contact with solid substances promoted dissociation, and if the surfaces were cold hindered combustion. He also pointed out that furnaces constructed on this plan, in which the heating was entirely by radiation instead of by contact, were much more durable. This form of arch has now become very general. Mr. Siemens also altered the arrangement of the ports, placing the air port vertically above the gas port and making it overlap on both sides. This arrangement is often called the "Hackney" port, the heavier air tending to deflect the flame down into the hearth.

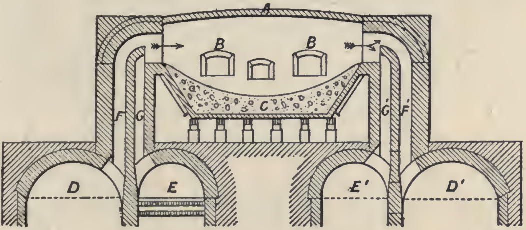

Fig. 73.—F. Siemens' Furnace.

B, Working doors. E, Gas regenerators. D, Air regenerators. G, Gas port. F, Air port. A, Roof.

In another type of furnace, usually called the Batho furnace, the regenerators are placed outside the furnace and on the same level, this arrangement having several advantages, among others the greater ease of access to the regenerators. In the Radcliffe furnace the regenerators are placed on the top of the furnace, an obviously improper position.

A new form of Siemens furnace was described by Mr. J. Head and Mr. P. Pouf in 1889, which differs very much in arrangements from the ordinary type. The gas producer is attached to and forms part of the furnace, and there are only two regenerators—those for air.

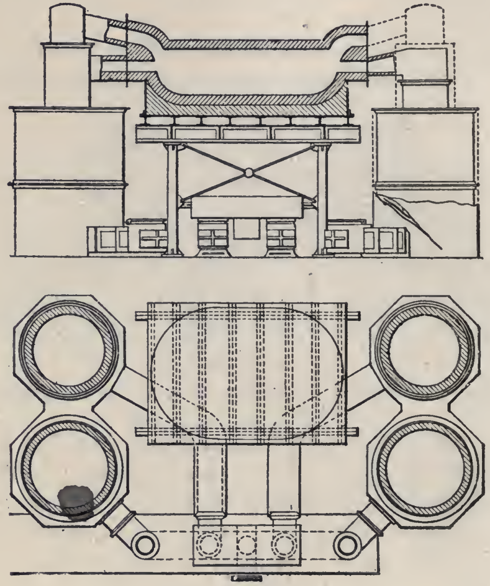
Fig. 74.—Batho Furnace.

Gas from the producer B passes through the flue C′ and valve A′ to the gas port, and thence into the combustion chamber *h′ g′*. Air for combustion passes through the regenerator A′, by an air flue, the air port H′, into the combustion chamber, where it meets the gas and combustion takes place. The flame sweeps round the chamber E, the products of combustion pass away by *h g*, and go partly through the regenerator A and partly into the gas producer B, to be converted into combustible gas. From time to time the direction is reversed as usual.

The products of combustion contain about—carbon dioxide 17 per cent, oxygen 2 per cent, nitrogen 81 per cent, and small quantities of water vapour. As they pass into the gas producer they are at a very high temperature, and the carbon dioxide is at once converted into carbon monoxide. A jet of steam is blown into the producer to enrich the gas.

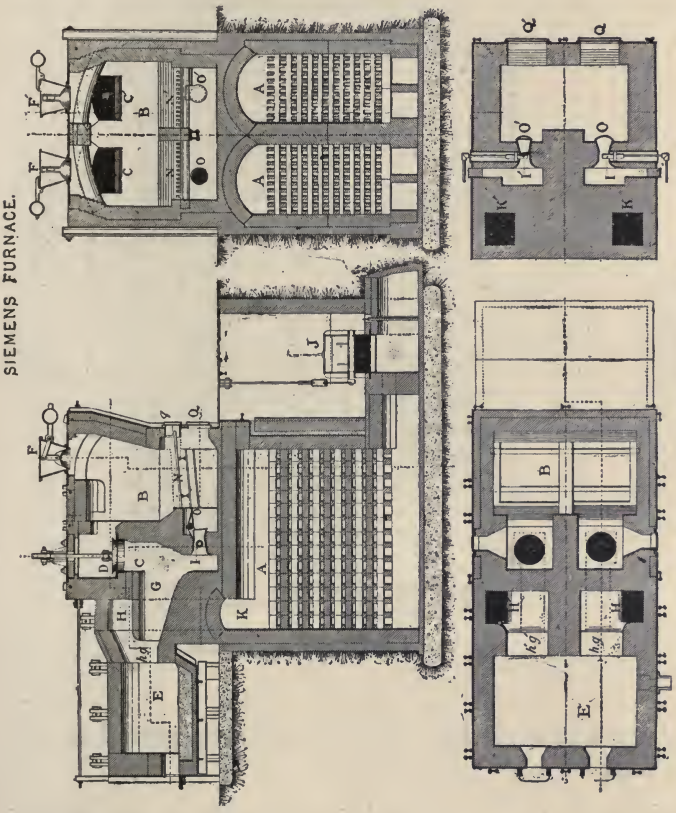

Fig. 75.—New Form of Siemens' Regenerative Furnace. From *J. I. and S. I.*

The new form of furnace is said to lead to considerable saving of coal and also in labour and repairs, and is said to "regenerate both the heat and the products of combustion". It has only been used for reheating and has not yet been applied to steel-making.

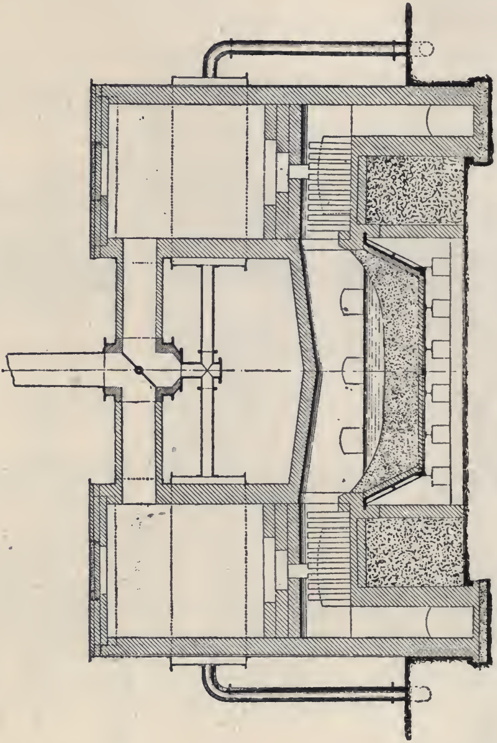

Fig. 76.—Thwaite's Ideal Furnace.

The Ideal Furnace.—Another type of furnace recently designed by Mr. Thwaite is known as the ideal furnace. In this two regenerators only are used—those for air. They are placed at the top of the furnace and are heated by the upward passage of the products of combustion. The gas is passed direct from the producer to the furnace. Mr. Thwaite claims that this furnace is most economical.

Other Forms of Regenerative Furnace.—Regenerators of other forms than chambers filled with a chequer-work of bricks are sometimes used.—In the Ponsard furnace the hot gases are made to circulate round perforated bricks, through the channels in which the gas or air to be heated is made to pass, and in Gorman's heat-restoring furnace the products of combustion are made to circulate round fire-clay tubes through which the cold air passes, it being made to traverse the tubes twice in different directions. This furnace has been used with success in several iron-works for reheating.

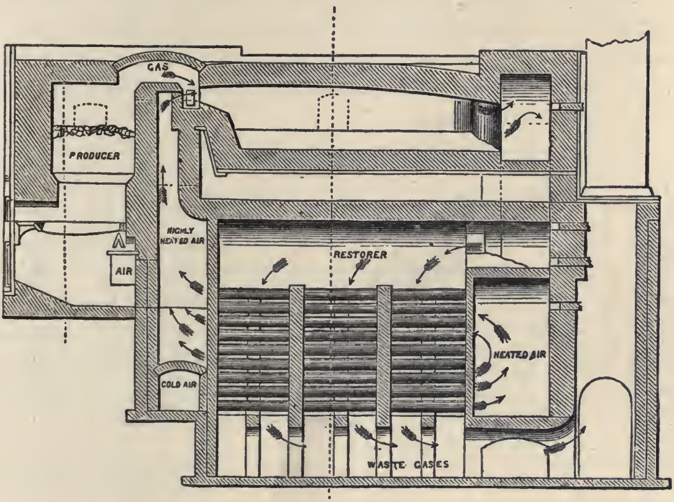

Fig. 77.—Gorman's Heat-restoring Gas Furnace. From D. K. Clark's *Fuel.*

Action of the Furnace.—The action of the regenerators, or recuperators as they are better called, is very simple. The temperature in the furnace is very high, and the products of combustion would escape at a high temperature and thus carry away a large amount of heat. The regenerators intercept this heat, and the gases escape comparatively cool, the heat being retained by the brickwork and given up to the incoming gases at the next reversal.

Position of the Regenerators.—This is a point about which, as already mentioned, there is great difference of opinion. They are usually placed beneath the furnace. This position, however, is not always convenient, and it is subject to flooding and to moisture from the ground. They are also difficult of access, and air and gas may mix through the brickwork and thus cause serious loss. On the other hand, if the regenerators are isolated and cased with iron, the loss from radiation may be greater.

The gases may be sent to the regenerator hot as they leave the producer, or they may be cooled. There is a general feeling that no advantage is to be gained by the former method of work, and it is attended with certain disadvantages. The gases as they leave the producer are charged with tarry matters which are partly deposited in the flues, and also with gaseous hydrocarbons from the coal. When the tarry matters and gaseous hydrocarbons are swept into the regenerators they are partially decomposed with deposition of carbon, so that the heating power of the gas is diminished, and the chequer work becomes choked with carbon.

Hence in many cases the gas regenerator has been abandoned, the gas being passed hot into the furnace.

Thermal Efficiency of Regenerative Furnaces.—M. Krause in 1874 published an investigation into the efficiency of a regenerative furnace, the results of which, converted into British units, are given below.

The composition of the coal, deducting ash, as deduced from the composition of the gas, was—

Carbon, ...	84·38
Hydrogen, ...	6·17
Oxygen, ...	6·90
Nitrogen, ...	2·55

The quantity of gas produced from 100 lbs. of coal was—

Carbon monoxide,	155·87
Carbon dioxide,	42·39
Hydrocarbons,	8·02
Hydrogen,	3·74
Nitrogen,	392·15
	602·17 lbs.

whilst 3·97 lbs. of tar, soot, and water was deposited.

To find the capacity of heat of these products it is only necessary to multiply the weights by their specific heats.

Carbon monoxide,	155·87 × ·2479 = 38·66
Carbon dioxide,	42·39 × ·2164 = 9·17
Hydrocarbons,	8·02 × ·5929 = 4·75
Hydrogen,	3·74 × 3·4046 = 12·73
Nitrogen,	392·15 × ·2440 = 95·69
	602·17 × ·2673 = 161·00

The formation of the gas in the producer evolved

66·803 lbs. C to carbon monoxide,	= 300603 B.T.U.
11·560 „ C to carbon dioxide,	168082 „
	468685 „

The total heat of combustion of the coal for 100 lbs. would be

84·38 lbs. C to carbon dioxide,	1226885 B.T.U.
5·2 „ H to water,	319924 „
	1546809

Dividing $\frac{1546809}{468685} \times 100 = 33$ per cent of the total available heat is evolved in the producer. Much of this is carried away as sensible heat, and is lost as the gases cool in the tubes. The balance, 1078124 units, is evolved on combustion of the gas in the furnace.

The products of combustion, allowing 20 per cent excess of air, are—

Carbon dioxide,	309·393 lbs.
Water,	47·205 „
Nitrogen,	999·527 „
Oxygen,	30·218 „
	1386·343 „

of which the capacity for heat can readily be ascertained.

		Units.
Carbon dioxide, ...	309·393 × ·2164 =	66·952
Water, ...	47·205 × ·4750 =	22·430
Nitrogen, ...	999·527 × ·2440 =	243·885
Oxygen, ...	30·218 × ·2182 =	6·593
	1386·343 × ·2452 =	339·862

That is to say, the products of combustion absorb 339·862 units of heat for each degree rise of temperature.

Distribution of Heat.—M. Krause analysed the work of a heating furnace at Soughland iron-works. The furnace heated about 18,000 lbs. of iron in twenty-four hours, and the quantity of coal used was 4000 lbs., or at the rate of about 4·44 cwts. per ton of iron heated.

The coal contained 10 per cent of ash, so that the 4000 lbs. was equivalent to 3600 lbs. of combustible matter. The valves were reversed every half-hour, so that between each reversal 75 lbs. of combustible was burned, developing 1160106 units of heat.

Losses by the Chimney.—Suppose the gases to leave the chimney at 392° F., they would carry with them 339·862 × ·75 × 360 = 91762 units of heat.

Losses by Transmission through Walls of Regenerator.—This M. Krause calculated, assuming the gases to leave the furnace at 2912° F., to be 27750 calories, or 110112 B.T.U.

Heat Absorbed by Iron.—To heat 18,000 lbs. of iron to 2912° F. from 32° in twenty-four hours, or 375 lbs. each half-hour, its specific heat being ·185, would absorb 375 × 2880 × ·185 = 199800 units.

Summary of heat evolution for each 75 lbs. of coal:—

	Units.	Per Cent.
Conversion into gas and loss in cooling-tubes,	382835	33
Loss by chimney, ...	91762	7·9
Loss by transmission through walls of regenerator, ...	110112	9·5
Taken up by the iron, ...	199800	17·2
Lodged in furnace and loss through walls, ...	375597	32·4
	1160106	100·0

Heat Intercepted by Regenerators.—The products of combustion leave the furnace at 2912° F., and carry off $2880 \times 254{\cdot}88 = 734023$ units in half an hour; of these the chimney takes off 91683, and the walls of the regenerators take up 110112, and the remainder 532237 is available for heating up the gas and air, so that if the regenerators are of equal size there would be 266118·5 stored up in each. The quantity of gas produced from 75 pounds of coal is 451·62 pounds, of which the capacity for heat is 120·75 units for each 1° of temperature, so that these gases are raised to the average temperature of 2236° F.

The thermal capacity of the air, including the 20% excess for the 75 lbs. of coal, would be 588·2 lbs., and its specific heat may be taken as ·24, so that for each degree 141·37 units of heat would be required, and the resulting temperature would be 1914° F.

As it is desirable that the air and gas should be at as nearly as possible the same temperature, the air regenerator is preferably made larger, so as to give a larger heating surface. The heat carried forward by the gases is of course added to that obtained by the above combustion.

Mr. Thwaite's Calculations.[1]—Mr. Thwaite has recently calculated the efficiency of the regenerative furnace under three conditions: (1) the gas supplied hot from the producer, (2) the gas cooled in cooling-tubes, and (3) the ideal furnace; and his results are given graphically in fig. 78. It will be noted in these that no allowance is made for loss by radiation from regenerators or furnace, all this being calculated as useful work.

Furnaces for Liquid Fuel.—Furnaces using liquid fuels have not yet been used to any extent for metallurgical purposes, though they may be so in the future.

In general there are two ways in which liquid fuels may be burned:

1. The oil may be passed through a retort or coil of pipe heated in the furnace or by external heat, by which it is vaporized and the gas is burnt. Such an arrangement is

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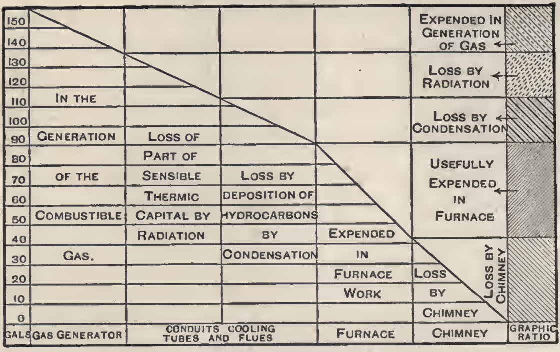
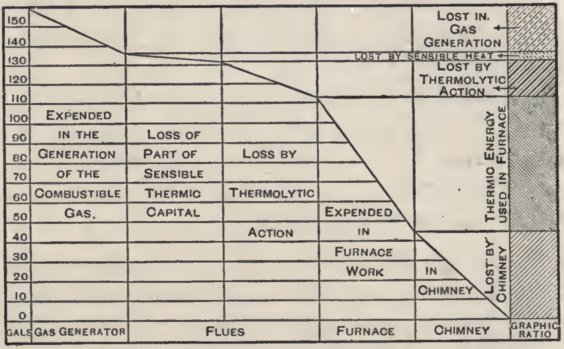
[1] See *Journal S. Staff. Institute*, vol. vi.

COLD GAS FURNACE.



HOT GAS FURNACE.



IDEAL FURNACE.

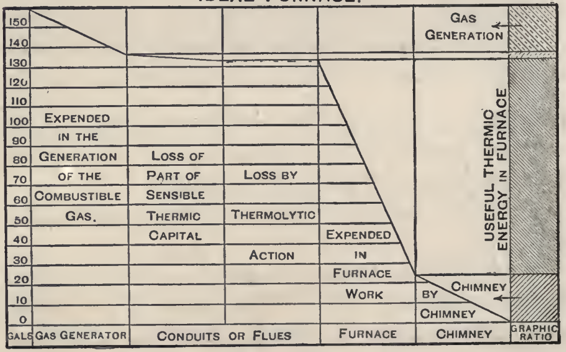


Fig. 78.—Thwaite's Diagrams.

merely a gas furnace in which the gas is made from oil. This process has the great disadvantage that it can only be used with oils which, on distillation, leave no solid residue, and few such are cheap enough to be used.

2. The oil in the liquid form is injected into the combustion chamber in the form of a very fine spray by means of a jet of steam. In this way combustion takes place at once, and there is no deposition of solid residue. Two forms of burner for this purpose are shown in figs. 79 and 79A.

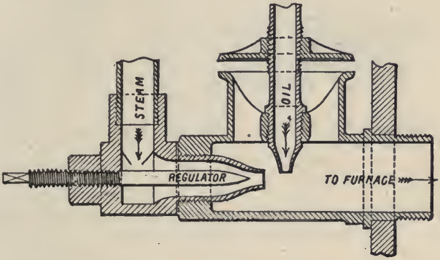


Fig. 79.—Aydon's Type of Injector as used at Messrs. Field's.

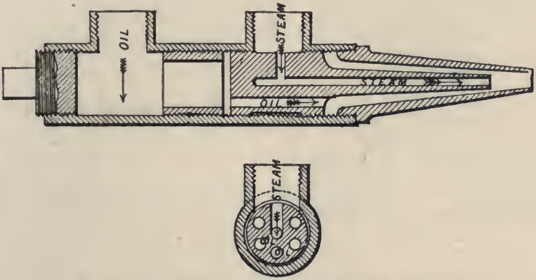


Fig. 79 A.—Aydon's Type of Injector as used at Woolwich.

Liquid fuel has been very successfully used for firing boilers, stationary, locomotive, and marine, by means of these injector burners.

As an example of the application of gas to metallurgical purposes, the Thwaite oil-fired forge may be mentioned. This is based on the gasification principle. Air or steam is blown

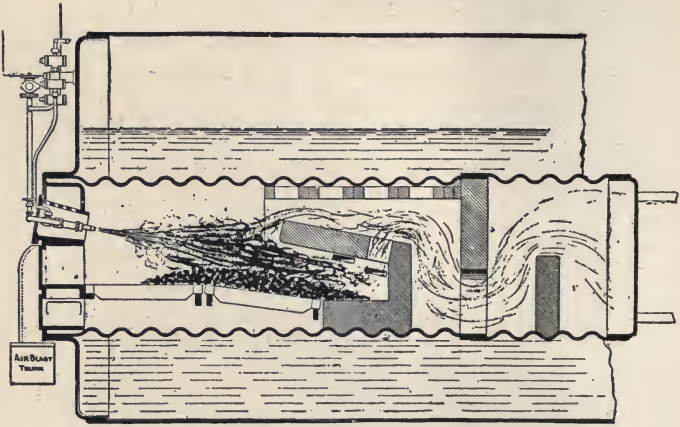


Fig. 80.—Oil Furnace as applied to a Steam Boiler.

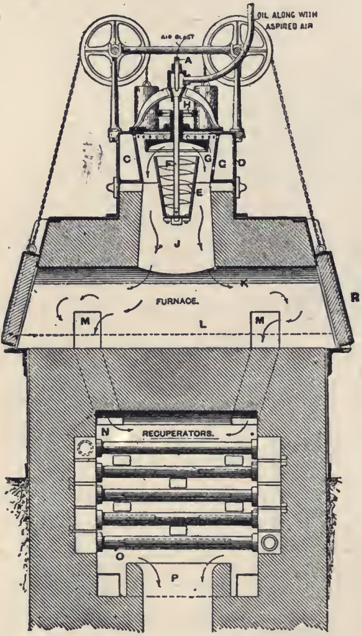


Fig. 80 A.—Thwaite's Oil Forge.

through the pipe A (fig. 80A) and draws in the oil; the mixture of steam and oil spray passes to the bottom of the retort E by the pipe F, and being there volatilized passes over into the space G, where it meets hot air from the recuperator. Combustion takes place, the flame plays down on the hearth of the forge, and the products of combustion pass through the recuperator to the chimney. The recuperator consists of a series of tubes which are heated by the products of combustion, and through which the air passes.

Fig. 81 shows the arrangements of an oil-fired steel furnace. The oil is blown into the chamber A as a spray, by means of a steam jet, and is at once volatilized, entering the furnace and burning exactly like gas.

Powdered Fuel.—Attempts have been made to burn powdered fuel by a process almost identical with that used for spraying oil. In 1868 Mr. Crampton patented a method of burning powdered fuel. The coal was powdered so as to pass through a 30-hole sieve, and the powder was blown into the furnace by means of a jet of air. The hearth of the furnace was so shaped that the currents were directed downwards, and were reflected up again over the fire-bridge; and a small fire was kept burning, at any rate until the temperature of the furnace was high enough to ensure combustion taking place. Mr. Crampton described his methods in a paper read before the Iron and Steel Institute in 1873. A new form of burner for burning powdered fuel, invented by Mr. Carl Wegener, which promises well, is described in *Engineering*, vol. lxi., p. 81, (1896).

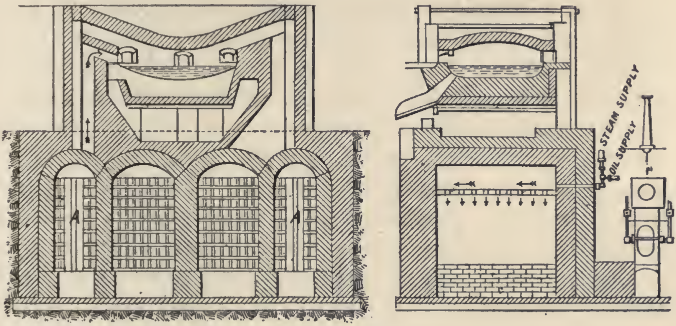


Fig. 81.—Oil-fired Steel Furnace.

CHAPTER X.

SUPPLY OF AIR TO THE FURNACE—REMOVAL OF WASTE PRODUCTS—SMOKE—PREVENTION OF SMOKE.

Chimney Draught.—Reverberatory and all other open-hearth furnaces depend for the supply of air for combustion on natural draught, that is, on the draught producible by means of a chimney. The theory of the chimney is very simple; it is simply that a column of heavy fluid will overbalance a column of the same height of a lighter fluid. In the chimney is a column of hot and therefore light air, outside is a column of cold and therefore heavier air, and the two are in communication at the bottom; the pressure of the heavier cold air therefore displaces the lighter hot air, and flows in to take its place, but as it passes through the fire it too becomes heated, and thus a constant circulation is set up.

About 24 pounds of air will be required to burn one pound of coal, assuming the excess of air to be equal to that actually required, so that the products of combustion from one pound of coal will weigh about 25 pounds, and the volume may be taken as being about 12½ cubic feet at 32° F. for each pound of air passing into the furnace; and as the volume of gas is proportional to its absolute temperature, the volume and pressure of gas can easily be calculated for any temperature. Rankine (*Steam Engine*, p. 286) gives an elaborate set of formulæ, based to a large extent on the work of Peclet. As, however, Peclet's constants were determined for special conditions, and it is uncertain how far they can be relied on under others, the formulæ are not of much practical value.

The active force which causes the circulation is the difference in weight of the two columns of air. The velocity of the current, neglecting friction, depends on the two factors, the height of the chimney, and the temperature of the gases, and varies as the square root of the increase in height and the square root of the difference of internal and external temperatures, and the actual value of v (the velocity) in feet per second, neglecting friction, is: $v = \frac{\sqrt{2gh(T-t)}}{459+t}$, where g is the acceleration due to gravity $= 32{\cdot}2$, h is the height of the chimney, T the temperature of the external air, t the temperature of the chimney gases in F.°, and 459° the zero (0° F.) in the absolute scale, and if the velocity is constant, the amount of gas which will pass will obviously depend on the area of section of the chimney.

It is calculated that the value of v reaches a maximum when the gas in the chimney has half the density of the gas outside, and therefore if the temperature outside were 32° F., the gas inside should be at $459 + 32 = 491°$, and the gas discharged will equal about 25 cubic feet per pound of air supplied, or about 600 cubic feet per pound of fuel.

As the draught-power varies as the square root of the height of the chimney, each equal addition to the height makes less and less difference in the draught; an increase, for instance, from 100 feet to 150 feet would only increase the velocity, if the temperature remained the same, in the ratio $\sqrt{1} : \sqrt{1{\cdot}5}$, *i.e.* $1 : 1{\cdot}22$.

As already mentioned, the friction of the gas and other resistances come into play and modify the results, and this is equivalent to a reduction of the area of the chimney. For round chimneys the effective area E may be taken as $E = A - {\cdot}6\sqrt{A}$, where A is the actual area. If additional resistances are to be overcome, as, for instance, thicker beds of fuel to be used or the gases be made to pass through more tortuous passages, a greater height will be needed to produce the same draught.

The draught may be measured by the height of a column of hot air which would be required to balance the cold air, or by the pressure which it is capable of producing either in pounds on the square inch or in inches of water. The draught produced by a good chimney is about 1·5 inches of water, of which a large proportion is used in overcoming resistances of various kinds. The draught F, measured in inches of water, will be $F = 192\, h\, (D - d)$, where h is the height of the chimney, D and d the weight in pounds of a cubic foot of the air outside and the gas inside the chimney. As the draught or the velocity depends on both height of the chimney and the temperature of the gases it may be improved by increasing either. The height of the chimney can be increased by building it taller, the temperature can be increased by either preventing loss of heat from the gases or by preventing cooling by admixture of air. As a rule the draught in an open fire, such as a domestic grate or a roasting furnace, is very poor because of the large admixture of cold air which takes place, thus reducing the temperature of the gases, whilst in a crucible furnace, in which almost all the air passes through the fuel, and therefore the gases become intensely hot, the draught is very strong.

In order to prevent loss of heat a chimney should be built as massive as possible, and should be of stone or brick, not of metal, which being a good conductor and also usually being thin, allows heat to be lost very readily. The height of the chimney will vary; it should reach above surrounding buildings, and as a rule should not be less than 50 feet, unless perhaps for small furnaces where there is but little resistance. Where there are resistances to be overcome, or where several flues pass into the same chimney, the height should be 100 feet or more.

The section of the chimney will, of course, depend on the amount of gas to be passed through, and this will depend on the grate area; it should be about ·10 to ·25 of the total grate area of the furnaces which feed it. A chimney 100 feet high and 30 inches in diameter, having therefore an area $A = 4{\cdot}91$ square feet, and an effective area $(A - {\cdot}6\sqrt{A}) = 3{\cdot}58$ square feet, should be capable of burning about 600 lbs of coal per hour.[1]

In metallurgical works the flues from the furnaces usually pass downwards into an underground flue, and several of these flues are attached to the same chimney. The greatest care must be taken in laying out the flues that at every junction the uniting streams of gas are travelling in the same direction, and if two or more flues unite at the foot of the same chimney,

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[1] See Kent, *Trans. A.S.M.E.*, vol. vi.

the chimney should be divided for some distance up, so that the currents may be all ascending before they mix.

Blast or Forced Draught.—When air is supplied under pressure a very much more rapid combustion can be made to take place, amounting in some modern marine boilers to 150 pounds per square foot of grate area per hour.

The blast may be supplied in various ways. In the blast-furnace for iron smelting, blowing-engines are usually used; for smaller cupolas and for supplying the necessary blast to reverberatory furnaces, fans, blowers, or steam jets are preferred. As a rule a blast is more economical than natural draught, as less excess of air need be passed in, and the gases can be allowed to escape at a much lower temperature.

Removal of Products of Combustion.—However the combustion be brought about, whether by natural or forced draught, the chimney is necessary to carry away the products of combustion.

Smoke.—When coal, wood, or other similar materials burn they are very apt, under certain conditions, to form smoke. Smoke is simply unburnt carbonaceous material, and its production is always due to incomplete combustion, this being caused either by undue cooling or by lack of air.

If the air supply be sufficient and the temperature high no smoke is produced, and in reverberatory roasting furnaces, in which these conditions are carried out, the flue dust is usually quite free from carbonaceous matter. On the other hand, in boiler fires where the cooling surface is large, so that the gases are easily reduced below the combustion temperature, the production of smoke is very common.

It may be laid down as a general rule, that to ensure smokeless combustion three conditions are essential:

1. The air must be in excess of that required for complete combustion.
2. The air and gas must be thoroughly mixed.
3. The temperature of the mixture must be kept above that necessary for combustion until all the carbon is consumed.

The necessity for a sufficient air supply is obvious, but unless the air be brought in contact with the gas its presence can be of no value. A lamp may burn with a smoky flame in the free atmosphere, where therefore there is ample excess of air, but this air not being brought in contact with it at a sufficiently high temperature combustion cannot take place.

In practice smoke is almost always produced by undue cooling, and this may be brought about in various ways. One of the most common is bad stoking. A thick layer of cold coal is thrown on the fire; the heat at once starts distillation, but the evolved gases being separated from the hot fire by the cold layer of coal cannot ignite and therefore escape, producing a dense smoke, which is mainly not carbon but tarry matters. To prevent the production of smoke from this cause the fuel should be supplied in small quantities at a time at the front of the fire, so that the products of distillation pass over the hot coke at the back and are thoroughly heated. In some furnaces, and especially with some kinds of coal, a dead-plate—*i.e.* a plate with no perforations for air—is placed at the front of the furnace, and on this the fuel receives a preliminary coking before it is pushed forward into the furnace. In the case of furnaces driven with a blast below the hearth an additional supply of air should be sent in above the fire so as to ensure combustion of the gases.

In order to ensure uniform stoking, mechanical stokers are often employed. By these the coal is either spread evenly over the fire, or it is supplied at a uniform rate on to a dead-plate, where it is coked, and then is gradually worked from the front to the back of the grate.

Another very common cause of smoke is insufficient combustion space. The gases must be allowed to mix freely, any contact with solid bodies will hinder combustion, and may determine the deposition of carbon. This takes place to some extent if the surfaces be hot, but to an enormously greater extent when they are cold, as in the case of boiler flues or tubes.

The amount of solid material carried away by the smoke is not large, rarely amounting to 1 per cent of the fuel. It does not necessarily follow that the combustion of this soot would increase the heating power of the furnace, since for many purposes, especially for steam raising, a luminous highly radiative flame seems almost essential for economical working, and it is impossible to have such a flame without at least the possibility of the formation of smoke.

Soot.—When products of combustion carrying smoke come in contact with cold surfaces they deposit soot. Soot is a black mass, and is usually regarded as being carbon. It, of course, contains a large quantity of carbon, but it is by no means pure, as the following analyses will show:—

	1.	2.	3.	4.
Carbon, ...	39	86·94	68·5	75·3
Hydrocarbons, &c., ...	14·3	3·3–5·2	4·4	3·9
Hydrogen, ...	—	—	—	—
Sulphuric acid, ...	4·33	—	—	—
Sulphur, ...	—	—	4·8	3·2
Mineral matter, &c., ...	36·67	8–9·7	22·7	16·3

1, Manchester Air Analysis Committee, Out-door Department. 2, Roberts-Austen Aspirated Fire Flue. 3 and 4, Cohen and Hefford.

The presence of sulphur in the soot is of great interest. It is at present not known exactly in what form it exists, but Cohen and Hefford think it is as organic sulphur compounds. They give the distribution of the sulphur in two samples of coal experimentally burned as being—

	1.	2.
Burnt, *i.e.* SO_2 in gases, ...	71·78%	60·0 %
In cinder, ...	13·71	28·13
In soot, ...	14·51	11·88

The production of soot is far larger from house fires than from any form of furnace used in the arts.

Prevention of Smoke.—Methods for the prevention of smoke have already been mentioned, but the only real remedy seems to be the larger use of gaseous fuel. It must not be imagined that gaseous fuel is necessarily smokeless; far from it. Coal-gas can be made to give as smoky a flame as coal;

indeed, as before remarked, any luminous flame is at least potentially—and often actually, to a small extent—a smoky flame, but gas can be far more easily regulated than can a solid fuel fire.

At the same time, though smoke may be prevented, the sulphur dioxide, sulphuric acid, and deleterious gaseous products of combustion cannot be avoided, and can only be diminished by a less consumption of coal.

CHAPTER XI.

PYROMETRY.

Pyrometry.—The measurement of temperature is the basis on which all knowledge of the quantitative effects of heating agents must be based, and yet it has been very much neglected, not only by the practical but by scientific metallurgists, and it is only within the last few years that serious attention has been given to it.

The temperature of a body may be defined as "its state with reference to sensible heat", or, in other words, its hotness or coldness. The terms "hot" and "cold" are useful enough in popular language, but they are used so loosely that it is impossible to give them a precise value, and thus fit them for scientific use, and at best they are only comparative. When the temperature of a body rises or falls, the body is said to become hotter or colder, and in this sense the terms may be used without fear of confusion, but they do not help us to understand what is meant by higher and lower temperature.

The only explanation that can be given is that based on the transference of heat. If two bodies be placed in contact, either there will be a flow of heat from one to the other, or there will not. If there be not, then the bodies are said to be at the same temperature. If there be, then the body from which the heat flows is said to be at a higher temperature, and that to which it flows at a lower temperature. Heat will always flow from a body at a high temperature to one at a lower temperature, until temperature equilibrium is set up, and both acquire the same temperature. The resulting temperature will depend—provided there be no loss of heat—on the relative capacity for heat of the two bodies.

On this law depend most of our methods of estimating temperature. The substance the change in which is to be used to indicate temperature, and which may be called the thermometer, is placed in contact with the hot body, the temperature of which is to be taken; interchange of heat takes place, and the thermometer acquires the temperature of the hot body, or rather a temperature resulting from the absorption of heat from the hot body by the thermometer itself. It is quite obvious that for any thermometer of this type to be of use, its heat capacity must be very small compared with that of the hot body, or it will so far reduce the temperature that the results which it gives will be valueless.

Temperatures cannot be measured directly, as there is no scale that can be applied to them; the sense of touch even, within the extremely narrow range for which it is available, is so vague and uncertain, so largely dependent on conditions other than temperature, that it is quite useless for measurement, or even for comparison.

Heat produces many changes in material substances, and gives rise to many phenomena which can be readily measured, and which therefore may be used to measure temperature. Some phenomenon or property is selected which varies with the temperature, or which is "a function of the temperature", and the measurement of the change produced serves to measure the rise or fall of temperature producing it, for it must be remembered that it is only change of temperature that can be measured. If everything were at one and the same temperature, either high or low, there could be no means of measuring it.

In order that various instruments of different construction, or based on different principles, may be comparable, it is essential that there should be a definite zero or starting-point, and some suitable unit in which the measurements may be made, and these should be designed so as to be quite independent of any particular form of thermometer.

There are in nature many fixed points, or changes taking place at a definite temperature, any of which could be taken as a convenient zero or starting-point. The one usually selected is the melting of ice or freezing of water. The temperature at which this takes place is taken as the zero on the Centigrade and Réaumur scales. The determination of the degree or unit may be made in several ways. The usual method is in principle as follows:—The freezing point having been selected as zero, another fixed point, usually the boiling point of water when the barometer stands at 29·905 inches, is selected, and called 100. The difference between the freezing and the boiling point of water being taken as 100°, the value of a degree can easily be defined. If 1 lb. of water at 100°—the boiling point—be mixed with 1 lb. of water at 0°, the result will be 2 lbs. of water at 50°, since the heat which is lost by the hot water will be gained by the cold; and similarly, if 1 lb. of boiling water be mixed with 99 lbs. of water at 0°, the result will be 100 lbs. of water at 1°.

Hence a degree might be defined as that increase of temperature which would be produced by mixing 1 part of water at the boiling point with 99 parts of water at the freezing point, the experiment being so conducted that there is no loss of heat. This assumes the constancy of the specific heat of water. Or it may be defined as the temperature which will cause an expansion of mercury (or, better, air) $\frac{1}{100}$ of that which takes place between the melting and boiling points of water.

The figures given to the Centigrade or Celsius scale, which is in common use in Europe, and which is used everywhere for scientific purposes. On the Fahrenheit scale, which is still generally used in this country, the freezing point of water is called 32°, the zero being an arbitrary point not coinciding with any fixed point in nature, and the boiling point is called 212°, the difference between the two being, therefore, 180°. On this scale the degree would be the increment of temperature produced by mixing 1 lb. of boiling water with 179 lbs. of ice-cold water (at 32°). The conversion of a temperature from one scale to another is very important and is very simple, if it be remembered that the ratio between the degrees on the two scales is 180 : 100, or 9 : 5.

Conditions for a Good Pyrometer.—Having decided on the zero point and the degrees to be used, the conditions which will be required in a good pyrometer can be considered.

1. It must indicate the temperature with sufficient accuracy for the purpose for which it is to be used.

2. It must have a sufficiently long range.

These are the fundamental and essential conditions, without which the instrument will be valueless. What degree of accuracy, and what range is necessary, can only be decided by a consideration of the exact conditions under which the instrument is to be used. It will be seen that a delicacy and range greater than that actually required will not only be useless, but will probably be attended with disadvantages in other directions.

3. Its indications must be fairly rapid.

4. It must always give the same indication at the same temperature, even after it has been a long time in use, *i.e.* there must be no displacement of zero.

5. It should allow of comparison with the mercury or air thermometer, or with the fixed points of temperature, so that a value for its indications may be obtained in ordinary degrees. Failing this, the scale will be an arbitrary one.

6. It should not be easily broken or put out of order, and should not be injured by being exposed to a temperature considerably above or below those which it is intended to indicate.

7. It should not require a specially-trained man to make observations.

8. It should be continuous in its indications—that is, it should not require a separate experiment for each observation.

The degree of importance which will be attached to each of these conditions will vary with the purpose for which the instrument is required, and with the taste of the user. It must be admitted that there is no instrument which fulfils all the conditions, but there are several which fulfil most of them, and the engineer, knowing exactly what he requires, should have no difficulty in selecting an instrument to suit his purpose.

Properties which have been used for Pyrometric Methods.—Almost every property of matter which varies with the temperature has been used or suggested as a basis for pyrometric methods. An exhaustive list has been given by Dr. Carl Barus,[1] to which those interested can refer. As, however, many of the methods suggested have not been applied to the production of instruments for technical use, a much briefer classification than that of Dr. Barus will answer the purpose here.

1. Change of volume, *i.e.* expansion of solids, liquids, or gases.
2. Vapour tension.
3. Fusion.
4. Method of mixtures.
5. Conduction of heat.
6. Optical methods.
7. Electrical methods.

In order that a phenomenon produced by increase of temperature may be available as the basis of a pyrometric method, it is essential—

1. That the change produced by change of temperature be capable of being measured.

2. That the law connecting the change with the increment of temperature producing it be accurately known for the temperatures at which the instrument is to be used. It is not sufficient that the law be determined, however accurately, for any other range of temperatures.

If a sufficient number of determinations be plotted suitably, and a curve be drawn through them, intermediate points may

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[1] *Memoirs U. S. Geological Survey.*

usually be obtained by measurements from the curve, but it is never safe to extend the curve in either direction beyond the extreme points which have been determined by experiment.

A large number of pyrometers have been devised based on changes of length or volume of selected substances produced by the change of temperature.

Expansion of Solids.—Many pyrometers have been based on the linear expansion of solids. If a bar of a solid be heated it will increase in length by a fraction of its length at 0° for each degree rise of temperature. For instance, a bar of iron 1 foot long at 0° would become 1·0000122 feet at 1°, 1·0000244 feet at 2°, and so on. In general, a bar of length L at zero would become $L(1 + \alpha t)$ at $t°$, where α is the fraction by which the length of the bar, 1 unit long, would be increased by a rise of temperature of 1° C., or the coefficient of linear expansion.

This formula would be quite correct if the value of α remained constant at all temperatures, which it does not, but usually increases as the temperature rises. The amount of expansion is very small, so that unless the bar be very long it is not easy to measure, and a long bar is usually quite impracticable.

Daniell's Pyrometer.—One of the earliest pyrometers suggested—that of Professor Daniell—was based on the expansion of a solid, and as the starting-point of such instruments it is of interest, though now of no practical value.

It consisted of a tube of graphite, in which was placed a metal rod. The upper part of the tube was slightly enlarged, and in this portion was placed a tightly-fitting plug of porcelain pushed down so as to be in contact with the rod. The instrument was placed in the furnace or other space the temperature of which was to be determined, and allowed to remain long enough to acquire its temperature; it was then removed and allowed to cool. As the temperature rose, the bar, expanding, pushed the plug before it, and as the bar contracted on cooling, it could not draw the plug back again. The plug, therefore, remained in the position to which it had been pushed by the expanding rod, and by means of a measuring instrument the distance by which it had been advanced could be measured. Obviously the observed expansion was differential—*i.e.* the difference between the expansion of the rod and that of the containing tube.

Schäffer and Budenberg's Pyrometer.—The same principle has recently been applied by Messrs. Schäffer and Budenberg in their expansion pyrometer (fig. 82), which depends on the differential expansion of copper and iron. This instrument consists of an outer tube of iron and an inner rod of copper, united at the bottom of the tube, the end of the rod being enlarged to the diameter of the tube, and projecting some distance beyond it, so that by its great conducting power it may help to heat the instrument rapidly. At the top of the iron tube is screwed an indicating dial, the pointer of which is actuated by mechanism attached to the top of the copper rod. For taking the temperature of furnace or other gases the outer tube may be made with slits to facilitate heating. The instrument is placed up to the fitting cone in the flue or other space, the temperature of which is to be observed. The iron tube first becomes heated and expands, carrying with it the copper rod, so that the pointer runs back. As the whole becomes heated the copper rod expands, the pointer moves forward, and in about twenty minutes comes to rest, indicating the temperature.

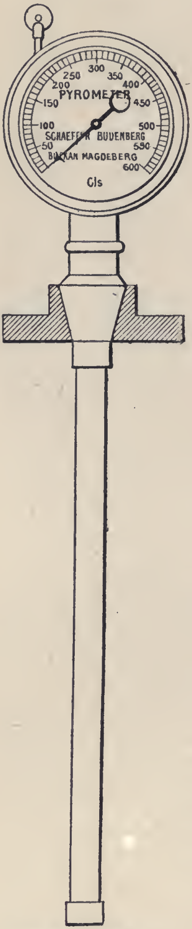

Fig. 82.—Schäffer and Budenberg's Pyrometer.

The amount of expansion which has to be measured is so small that it is found best to graduate the dial by comparison with a standard thermometer, and the instrument can then be verified at any time by heating to a known temperature, as, for instance, in steam, when the pointer should indicate 212°. As any permanent set would introduce a displacement of zero, verification at intervals is important. This pyrometer is obviously not capable of indicating sudden changes of temperature, owing to the time it takes to heat and cool, and readings taken before the pointer has come to rest, or in varying temperatures, will be uncertain. It can be used up to about 700° F., and the whole range of temperature, from 212° to 700°, is indicated on the dial. It gives the temperature continuously by reading the dial. The tube may be from 2 feet to 6 feet long; it cannot therefore be used in very confined spaces, and its capacity for heat is high. It is best suited for taking the temperatures of stills, flues, &c., where there is ample room, the temperature is fairly steady, and where a temperature above the maximum is not likely to be reached. In flues the outer tube would be likely to oxidize unless well protected by a coating of clay.

A form of instrument depending on the differential expansion of metals, but applied in a different way, is Breguet's metallic thermometer. This is often shown for class demonstration, though it is of no practical use. It consists of a fine ribbon made up of strips of gold, silver, and platinum rolled together, and coiled into a spiral, to the lower end of which is attached a pointer. These three metals have very different rates of expansion, the silver expanding most, and the platinum least. The instrument is very sensitive to temperature changes, the difference in the expansion of the metals causing the spiral to coil or uncoil, as the case may be, and thus move the pointer.

Messrs. Schäffer and Budenberg have also designed a pyrometer based on this principle. It consists of an iron tube containing a coil made up of a ribbon of two metals well secured together, and fastened at the lower end to the bottom of the tube, whilst the upper end is attached to an indicating mechanism, by which a pointer is made to indicate the temperature on a dial. These instruments are made to read up to 650° F.; they are very similar to those last described; they can be used for similar purposes, and can be made as short as 1 foot.

Thwaite Pyrometer.—This instrument consists of a hollow tube or cylinder *a* of mild steel, to the end of which is attached an ebony handle. In the centre of this steel cylinder there is a steel or platinum band or wire *c*, held under tension by a coil spring *d*. The end of the band or wire terminates in a steel bar *e*, working in close contact with a pinion *f*, the contact being maintained by a spring, which, whilst pressing the steel bar *e* against the pinion *f*, allows the free movement of the former. The other end of the tension band or wire *c* is attached to the inner end of the steel cylinder *a*, which is filled with lime dust to preserve the band from oxidation. The exposure of the steel tube or cylinder *a* to elevated temperature, to be measured for a period of one minute by a sand-glass, produces an elongation of the steel tube *a*. This is transmitted to the central steel wire *c*, which thus draws down the bar *e*, and the movement of the bar on the surface of the pinion is multiplied 1800 times by gearing, and is indicated on the dial.

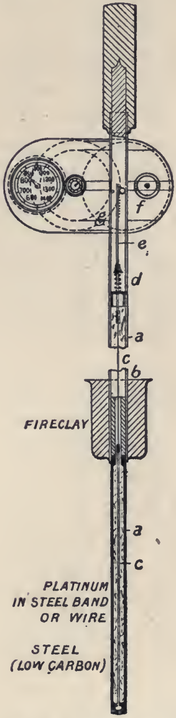

Fig. 83.—Thwaite's Periodic Dilatation Pyrometer, 500° to 1500° Cent.

Expansion of Liquids.—This is the most common means of measuring temperature, but is not often available for very high temperatures. The best example of an instrument based on this principle is the common mercury thermometer.

Mercury Thermometer.—This consists of a bulb containing mercury, to which is attached a stem with a very fine bore. When the bulb is heated the mercury expands and therefore rises in the stem, and as the capacity of the stem is very small compared with that of the bulb, a small expansion may produce a very considerable rise. The amount of mercury is so adjusted that it will not completely retire into the bulb at the lowest, or reach the top of the tube at the highest temperature to which the instrument is to be exposed. The instrument is always graduated by experiment: the bulb is put into melting ice, and the top of the column of mercury is marked 0° (or 32°); it is then put into boiling water or steam (the barometer standing at 29·908 inches), and the height to which the mercury rises is marked 100° (or 212°). The space between the two marks is (assuming the tube to be of exactly uniform bore) divided into 100 (or 180) equal parts, each of which represents a degree. For temperatures above 100° C. (or 212° F.) the divisions are continued upwards as far as required, and for temperatures below 0° they are continued downwards. Temperatures below zero are read downwards, and are indicated by the sign $-$.

Absolute Zero.—On the Centigrade scale the zero is the freezing point of water, on the Fahrenheit scale it is a point 32° F. below this; both these points are arbitrary, and much lower temperatures than either are obtainable, so that the negative sign has to be used. Is there no more convenient starting-point; is there no absolute zero, or point below which further cooling is impossible, so that if it were used as a starting-point the negative sign would never be required? There is such a point, and though it has never been reached experimentally, it has been fixed by several lines of experiment and reasoning as being about 273° C., or 459° F. below zero. This point is called the absolute zero, and temperatures measured from it are called absolute temperatures. The absolute temperature can always be obtained by adding 273 to the temperature in Centigrade degrees, or 459 to it in Fahrenheit degrees.

Expansion of Mercury.—The amount of expansion of mercury which measures a degree is determined between 0° C. and 100° C., and higher and lower temperatures are obtained by continuing the divisions upwards or downwards; but these divisions will only each represent the same increment of temperature, provided that the mercury expands at the same rate for all temperatures; but it does not do so; the coefficient of expansion increases as the temperature rises. The mean coefficient of expansion of mercury between 0° C. and 100° C. is ·00018153, and even between these limits it is not absolutely uniform; whilst at 300° C. the coefficient of expansion is ·00019464, a difference of about 7 per cent. If great accuracy is required, a table of the variation at each particular temperature must be prepared.

The question, however, is not quite so simple as would appear from this, for the mercury is contained in a glass bulb, which will expand and thus increase in volume. The observed rise of the mercury will not, therefore, be its absolute expansion, but will be the difference between this and the expansion of the glass.

If a mercury thermometer be plunged into melting ice, the mercury falls to zero; if it be then warmed and cooled again, and so on, a large number of times, it will be found that at last the mercury no longer returns to the 0 point. The bulb has taken a permanent set, and produced what is called a displacement of zero. This will introduce an error into all readings, which may, in some cases, amount to as much as 1°.

The mercury which the instrument contains, and the expansion of which is used in measuring temperatures, freezes at – 38·8° C. (– 37·9° F.), and boils at 350° C. (662° F.). These temperatures mark the extreme limits between which, only, the instrument can be used. Its upward range is therefore very small, only reaching to about the melting point of lead.

Other liquids may be used so as to give a longer upward or downward range, according as the liquid has a higher boiling or lower freezing point than mercury.

The upper limit of a thermometer of this type is the boiling point of the liquid; if this could be raised, the range would be increased. The boiling point depends on the pressure. If, therefore, the upper part of the tube were filled with some elastic fluid which would exert pressure, a somewhat higher range could be obtained. At a pressure of 30 atmospheres the boiling point of mercury is raised to over 500° C. The great strength of the tube which would be required to prevent fracture prevents the extensive use of instruments based on this principle.

Baly and Chorley's Thermometer.—Messrs. Baly and Chorley have suggested the use of a liquid alloy of sodium and potassium, which has a very high boiling point, and which can be used up to 600° C., and pyrometers on this principle are now made commercially.

Expansion of Gases.—Very many pyrometers have been based on this principle, and the most diverse methods of utilizing it have been proposed. Air pyrometers have some advantages, but in their usual forms they have also disadvantages, which often more than counterbalance the advantages.

Gases expand very much more than either liquids or solids, and, what is more important, the rate of expansion is much more uniform, at least within very wide ranges of temperature. In general the volume occupied by a gas is proportional to its absolute temperature, and the coefficient of expansion is ·003665 for each degree C. or ·002036 for each degree F. It is obvious that this is cubical expansion, or increase of volume, not mere increase of length, as in the case of solid bars. In all cases also the gas must be contained in an inclosing vessel, and the observed expansion will therefore always be the difference between the expansion of the gas and that of the inclosing vessel. The containing vessel also must be completely closed or cut off from contact with the outer air, and as the air in it has no visible surface, the use of a column of liquid or other index becomes essential if the expansion is to be observed directly.

Regnault made a very large number of extremely accurate determinations of high temperatures by means of an air thermometer. His method was to heat the vessel containing the air to the temperature to be measured and to ascertain the quantity of air which was expelled. A globe of glass with a long neck, drawn out to a very fine point, was taken and put in the place the temperature of which was to be determined. It soon got hot, and, owing to the expansion, a portion of the air was expelled. When equilibrium was attained the globe was removed, the neck sealed as rapidly as possible, and it was allowed to cool, the height of the barometer at the moment of sealing being noted. The neck of the globe was then broken off under mercury, and the globe with the mercury which had entered it was weighed. From this weight the volume of the air expelled could be calculated. The globe was then filled with mercury and weighed, and from this weight the capacity of the globe, and therefore the quantity of air it would contain, could be calculated from these data; and making the necessary corrections for barometric pressure, expansion of the globe, &c., the temperature could be calculated.

Deville and Troost used a similar method with porcelain globes in place of glass, and iodine in place of air. A method based on the expulsion of a volume of air by the vaporization of a known weight of a volatile solid or liquid, on the same principle as Meyers' method of determining vapour densities, has also been proposed. All these methods, however, necessitate trained observers, and involve an amount of calculation which renders them quite unfit for technical work.

Changes of pressure which have practically no effect on the volumes of liquids and solids have an enormous effect on the volume of gases. If a gas be heated and the pressure be maintained constant, it will expand at the rate indicated by its coefficient of expansion; but if the gas be so inclosed that it cannot expand, then it will exert a constantly increasing pressure on the containing vessel. The action of heat on gases may therefore be measured either by keeping the pressure constant and measuring the increase of volume, or by keeping the volume constant and measuring the increase of pressure.

In the constant-pressure methods a globe of glass of known capacity is connected by a capillary tube with the top of one leg of a graduated manometer, so arranged, by means of a flexible tube or otherwise, that the mercury can be brought to the same level in both legs, so as to ensure the gas in the globe being at the same pressure as the air outside. As the globe is heated the gas expands, and some of it passes out into the manometer tube. When the globe has attained the temperature to be measured, the manometer is adjusted so that the mercury stands at the same level in both legs, and the volume is read off. The calculations to be made are somewhat complex, and must take into account the volume of cooler air in the top of the manometer tube, the barometric pressure, &c.

In the constant-volume method a similar apparatus may be used, but as the temperature of the air in the globe rises the column of mercury in the manometer tube must be increased, so as to balance the expansive power of the air and keep it at a definite volume.

In either case many precautions must be taken to guard against error, and the methods, though accurate as standard methods, and very useful for comparing and correcting other forms of instrument, are not suitable for technical work, except in the laboratory.

The methods as described can only be used up to the temperature at which glass softens, say 600° C., unless bulbs can be made of some other material; glazed porcelain answers very well, so long as the glaze remains intact, which is not very long. Platinum, which, on account of its infusibility, might at first sight appear suitable, occludes gases, and also at high temperatures is porous to some furnace gases. Callander suggests[1] the use of bulbs made of pure silica; but these could only be made of very small size, and would be very difficult to make and to connect with other parts of the apparatus.

Heisch and Folkard's Thermometer.—A form of air thermometer suitable for technical use, in which some of the difficulties of the ordinary form have been overcome, has recently been introduced by Messrs. Heisch and Folkard. In this instrument, the length of the scale is much reduced,

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[1] *J. I. S. I.*, 1892, vol. ii. p. 165.

the whole range from 0° to 1000° F. being marked on one stem. The quantity of contained air, which is at a lower temperature than that of the bulb, is much reduced, and the influence of changes of barometric pressure is eliminated.

The bulb A contains air under very much reduced pressure —about 94 mm. at 40°. It is connected with the mercury gauge H by a capillary tube, the other end of the gauge being attached to another very fine tube for indicating the pressure, the upper end of this being sealed. As the air expands it displaces some of the mercury in the tube and causes the column D to rise, the amount of rise depending on the relative diameters of the tubes. The graduations of the scale are not uniform divisions, but become somewhat smaller as the temperature rises.[1]

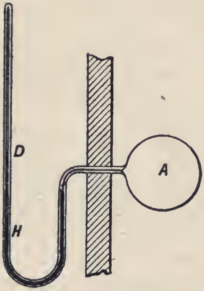

Fig. 84.—Heisch & Folkard's Pyrometer.

Dr. Hurter speaks very favourably of this instrument, and reports that with repeated heatings to 500°, and subsequent coolings, he has detected no displacement of zero. It is obvious that the instrument can only be used for temperatures below the softening point of glass.

Wiborg's Pyrometer.[2]—This is another form of air pyrometer recently introduced, and depends on a somewhat more complex adaptation of the law of gaseous expansion. It consists of a vessel of porcelain, or other material, which may be called A, heated to the temperature to be determined, and in free connection with the atmosphere; also a smaller vessel B containing air at the atmospheric temperature and pressure, and a manometer. If the air in B be forced over into A, the increased quantity of air will cause an increase in pressure, which will depend on the quantity of air introduced—which is constant—and the temperature to which it is heated. This

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[1] T. Hurter, *Journal of the Society of Chemical Industry*, 1886, p. 634.

[2] *Journal of the Iron and Steel Institute*, 1882, vol. ii. p. 110; *Journal of the Institution of Engineers and Shipbuilders in Scotland*, vol. xxxv. p. 126.

pressure is measured by a manometer, and the temperature can thus be obtained. All the necessary formulæ and calculations will be found in the papers to which reference is made.

The instrument is made in two forms: in one the manometer is a column of mercury; in the other, which is much more portable, it is in the aneroid form. Both forms as described are intended for taking the temperature of the hot-blast for blast-furnaces, for which purpose they are largely and very successfully used in Sweden, but they might quite well be applied to any other purpose.

The bulb V (not shown) holds about 12 c.c., and forms the end of a porcelain tube of very small internal diameter, but with very thick walls. To this is cemented a metal casing, from which a glass tube passes to the manometer; this is at first capillary, but widens out at *m* (fig. 85), then enlarges into a bulb B for holding the smaller quantity of air, having a capacity of about $\frac{1}{10}$th that of V. The bulb B opens below into a manometer tube *n*, which is connected with a caoutchouc ball K, containing mercury, which is inclosed in a metal box, the cap of which can be forced down by a screw so as to expel the mercury from the ball and force it up into the manometer. The manometer tubes are also inclosed in a box for safety, and a clamp enables the mercury to be shut off when the instrument is to be moved.

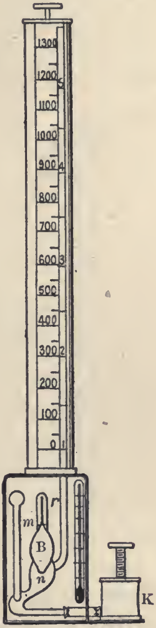

Fig. 85.—Wiborg's Pyrometer. From *J. I. and S. I.*

When the temperature is not being taken the surface of the mercury is below the mouth of B, so that both bulbs are open to the atmosphere and the vertical portion of the manometer tube is empty. When an observation is to be made, the screw cap of the mercury reservoir is forced down, and the mercury rises in the tubes. As soon as it reaches the mouth of B, the connection with the atmosphere is cut off, and when it reaches *m* the air in B will have been forced into V, and the column of mercury in the manometer will have risen to indicate the pressure produced. If V and B were at the same temperature, the mercury in the manometer would stand at the zero mark, this indicating the pressure due to the volume of air in B being forced into V without change of temperature; but if V be the hotter, as in practice it always will be, the mercury will stand higher, the height giving the temperature on the scale. The mercury must never be forced above *m*, and immediately after reading must be depressed below the mouth of B. The instrument takes from 20 to 30 seconds to come to rest. Variations of the temperature of the air in the small vessel and of the barometric pressure will modify the readings, but scales are attached for making the necessary corrections. This form of instrument is not very portable, and is best used in a fixed position. To meet the call for portability, an aneroid form of the instrument, fig. 86, has been designed. This consists of a vessel V and a tube, as before, but to the top of the tube is screwed a circular metal case containing the measuring apparatus. At the bottom of the case is a lens-shaped metal vessel

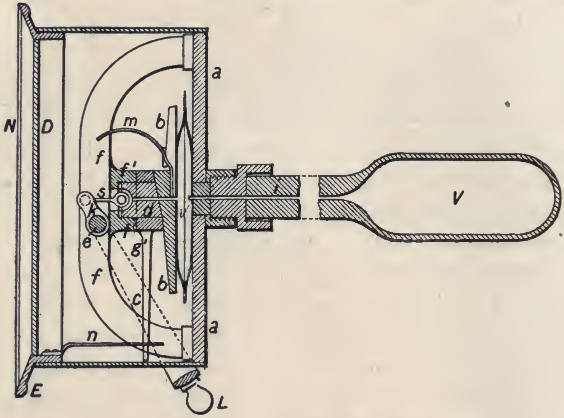

Fig. 86.—Wiborg's Pyrometer. Aneroid form.

V′ (the smaller air-vessel), connected with the tube on the one side and with a capillary tube open to the air on the other. This vessel can be pressed quite flat by the arm L, the link S at the same time securely closing the upper capillary tube, so that the air in V′ is forced into V, and it recovers its form when the pressure is removed. Connected with the capillary tube is the hollow spring *m*, which is a pressure-gauge, and by means of a toothed sector actuates the pointer which indicates the temperature on the dial D. The volume of V′ can be altered so as to allow for changes in the atmospheric temperature, by turning the ring *g*, which raises or lowers the plate *b*. On the dial is a temperature scale, indicating the distance through which the ring must be turned. In the outer case is also contained a thermometer, a small aneroid barometer, and a scale for correcting for changes in atmospheric pressure.

Frew's Pyrometer.—This instrument (fig. 87) is another application of the expansion of gases by heat, but the measurement is made on quite a different principle from that which is used in any other instrument. It is intended for measuring the temperature of the air supplied to blast-furnaces. The principle of the instrument is this: If a current of air be made to flow through a tube, so adjusted that the exit end can just deliver all that flows in at the inlet end when both are at the same temperature, if the temperature of the air in the tube be raised, the volume will be increased, the exit opening will not be able to deliver the air as rapidly as it enters, and a back pressure will be produced, which can be measured.

It is essential that air should be supplied at a perfectly constant pressure. The blowing-engine of the works will supply blast, but the pressure is so irregular that some method of regulating it must be adopted. The form of regulator used by Mr. Frew is very simple and efficient. It forms no essential part of the pyrometer, as any other efficient regulator might be used.

The blast from the blowing-engines enters by the pipe A into the pipe B, which reaches nearly to the bottom of the water cistern C, in which, by means of pipes D and E, the water is kept at a constant level. In this way a constant head of water is obtained, and thus a constant pressure is produced. The pyrometer itself is connected to the tube B by a pipe J.

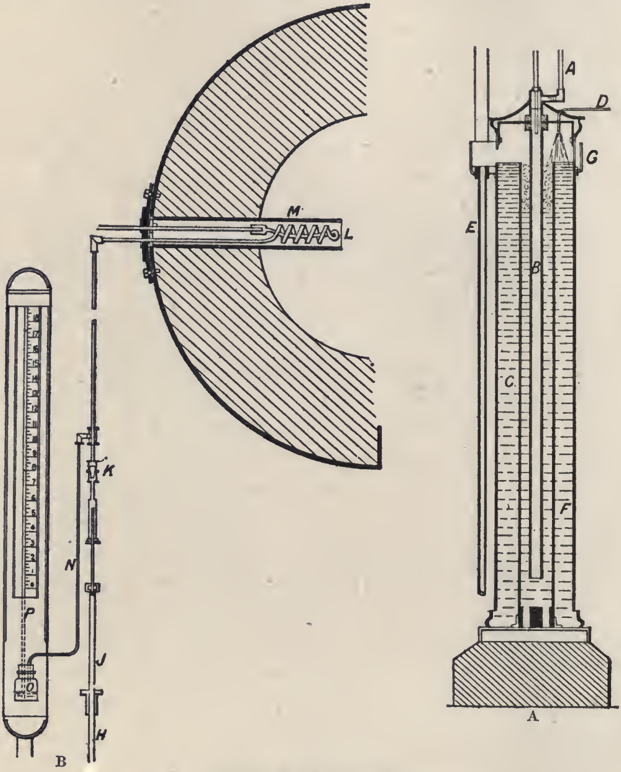

Fig. 87.—Frew's Pyrometer.

A, Pressure regulator. B, Pyrometer.

It consists of a tube, at one end of which is a coil L, which is inserted in the main, the temperature of which is to be taken. At the entrance to the pyrometer tube is a platinum nozzle K, and a similar nozzle, of somewhat larger bore, is placed at the end of the coil and opens into the air. Attached to the pyrometer tube beyond the first nozzle is a branch pipe N, which communicates with the pressure-gauge P, containing coloured water. The nozzles are so arranged that M can readily pass the volume of air delivered by K without increasing the pressure in the cistern O above that of the atmosphere when both are at the same temperature. If, however, the coil be heated, the air expands, the nozzle M is unable to pass the extra volume of air without increase of pressure, and any such increase is at once indicated on the gauge P, the pressure being directly proportional to the absolute temperature of the gas.

The apparatus is graduated by experiment. The coil is placed in cold water of known temperature, the blast is set going, and the height of the column of liquid in the pressure-gauge is noted. The coil is then placed in boiling water, the height again noted, the space between the two marks is divided into degrees, and the divisions are carried up the tube as far as may be necessary. The instrument thus graduated has been tested at many known temperatures, and has always been found to give concordant results.

The instrument is probably the best yet devised for taking the temperature of the hot-blast for blast-furnaces. It has been in use in several of the Scotch ironworks for some time, and has given perfect satisfaction. Though designed primarily for taking the temperature of the hot-blast, it could be equally well used for other purposes, provided a continuous blast of air at sufficient pressure could be obtained.

Vapour-tension Pyrometers.—These depend on the pressure exerted by a vapour in presence of its own liquid. All liquids give off vapour, which exerts a certain pressure or tension, the amount of this pressure depending only on the temperature. At a certain temperature the tension of the vapour becomes equal to or slightly in excess of the pressure of the air, evaporation then takes place very rapidly, and the liquid is said to boil. If the pressure be increased, the boiling will stop, until the tension of the vapour once more equals the pressure. There is, therefore, for every liquid a definite relationship existing between its vapour tension and the temperature to which it is exposed, and if this relationship be known, the pressure being determined, the temperature is known also, or *vice versa.* For instance, if the pressure of the steam in a high-pressure boiler be known, the temperature of the water can be found, or, if the temperature be known, the pressure can be found. The vapour tension of most liquids is known with considerable accuracy, and modern pressure-gauges can measure the pressure with great precision, so that this may be a good pyrometric method. Several instruments based on this principle are on the market, the best known being those of Mr. Murrie, and Messrs. Schäffer and Budenberg, the latter of whom call their instrument "The Thalpotassimeter".

Murrie's Patent Pyrometer.—This instrument depends for its action on the measuring of the vapour tension of certain liquids, and is constructed in a variety of forms.

"The most simple form consists of a hollow steel tube of indefinite length and very fine bore, one end being bent round and slightly enlarged so as to form a bulb, and the other end being also enlarged, flattened, and curved so as to form a Bourdon tube or coil. The extremity of the curved end is connected by means of a link to a quadrant fitted in the centre or axis of the bend, and the quadrant actuates or is in gear with a toothed pinion, to the arbor of which an indicating needle is fitted. The hollow tube is wholly filled with a liquid, and the enlarged end, or bulb, is almost wholly, but not quite, filled with the same liquid. In taking indications of temperature, the bulb-end is immersed in the heated space. The liquid confined in the bulb is partly vaporized, the vapour acting on the surface of the liquid, the pressure of the vapour is transmitted to the curved end, with the result that the flattened curved end tends to straighten itself, and the extent of this straightening is shown by the needle, which indicates on a dial the temperature corresponding to the internal pressure.

"For very low temperatures liquid nitrogen is the fluid employed, and for higher temperatures liquid anhydrous ammonia, water, or mercury. The range of temperature ascertainable with this instrument begins at 250° F. below and rises to 2000° F. above zero.

"An important feature in this instrument is that the bulb part can be made of very small bulk, and can be placed in the centre of a furnace, and the temperature existing at that point ascertained irrespective of the distance of the indicator or the degree of heat to which the intervening part is subjected; the instrument could if necessary be placed several miles from the furnace. This pyrometer is very durable, and does not require adjusting, even after being years in continuous use."

It is obvious that the lowest temperature which can be indicated will be that at which the pressure is sufficient to cause the gauge to indicate, and the highest that above which the pressure would distort or rupture the gauge. As the pressure of most vapours is very low at low temperatures, and increases very rapidly at high temperatures, the range of each instrument is somewhat restricted, and great care must be taken to select suitable liquids for the temperatures at which the instrument is to be used.

The Thalpotassimeter.—This instrument is based on the same principle, but differs in detail from that of Mr. Murrie.

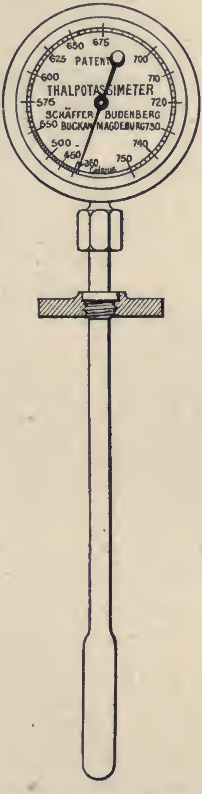

Fig. 88.—Schäffer and Budenberg's Thalpotassimeter.

Commercially three forms of thalpotassimeter are in use, three different liquids being used—

Ether	indicating	from 92° F.	to	250° F.
Water	,,	,, 212°	,,	650° ,,
Mercury	,,	,, 650°	,,	1400° ,,

The accuracy of instruments of this type depends entirely on the accuracy of the pressure registration. What is the extreme amount of accuracy to which a pressure-gauge can be depended on is a question for the engineer, and the author is unable to express a decided opinion upon it.

The water and ether forms of the instrument are thoroughly satisfactory; as to the mercury form, differences of opinion have been expressed, some writers having stated that after a time the mercury is apt to escape.[1] For temperatures below 600° F. the instrument may be left permanently in place, and therefore gives continuous readings; but for higher temperatures this cannot be done, as the tube would soon be destroyed. It must therefore be placed in position when a reading is to be made, and the tube should be protected by a coating of clay. Great care must be taken that the instrument is not heated above the maximum point which it is to indicate.

It will be understood that the readings in these cases are not differential, as expansion of the containing tube has no effect on the pressure.

Fusion Pyrometers.—The melting points of all fusible substances are fixed and definite, and, once having been accurately determined, can be used as a means of estimating temperature. The simplest method of using the fusion of substances in pyrometry is to take a clay dish provided with a number of depressions or cavities, in each of which is placed a fragment of a substance—usually a metal or alloy—of known melting point, care being taken that the melting points have sufficient range to cover the temperatures likely to be met with. The dish is placed in the furnace or space the temperature of which is to be measured, left long enough to acquire the temperature, then withdrawn and examined. Obviously the pieces which have melted have lower, and those which have not melted have higher melting points than the temperature to which they have been exposed; a minimum and maximum temperature is thus fixed between which the temperature to be

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[1] "Dittmar Pressure Thermometers," *J. S. C. I.*

determined must lie, and which will usually be a sufficiently close approximation for practical purposes.

For determining the temperature of the hot-blast, the metals and alloys are made into coils of wire, which are introduced into the main the temperature of which is to be taken.

Among the metals and alloys suitable for this purpose the following may be mentioned, though the selection will obviously depend on the temperatures it is required to estimate.

METALS.

Tin, ...	M.P. 227° C.
Bismuth, ...	„ 268° „
Lead, ...	„ 325° „
Zinc, ...	„ 415° „
Antimony, ...	„ 440° „
Silver, ...	„ 945° „
Copper, ...	„ 1050° „
Gold, ...	„ 1045° „

Tunner gives the following:—

LEAD—SILVER ALLOYS.

9 parts lead,	1 part silver......	M.P. 400° C.
8 „	2 parts silver ...	„ 470° „
7 „	3 „	„ 540° „
6 „	4 „	„ 610° „
5 „	5 „	„ 680° „
4 „	6 „	„ 750° „
3 „	7 „	„ 818° „
2 „	8 „	„ 885° „
1 „	9 „	„ 955° „
·6 „	9·4 „	„ 980° „
	10 „	„ — „

SILVER—GOLD ALLOYS.

9·5 parts silver,	·5 parts gold, ...	M.P. 1030° C.
7 „	3 „	„ 1050° „
4·5 „	5·5 „	„ 1070° „
2 „	8 „	„ 1090° „
	10 „	„ 1100° „

Seger uses slender clay pyramids, 3 inches high, standing on a base $\frac{5}{8}$ inch wide. The fusibility of these is graduated, and the temperature marked on them is that at which the point bends over and touches the surface on which the pyramid stands.

Method of Mixtures.—This method has been applied in many ways. The principle is that something is heated to the temperature which is to be measured; then mixed with some other substance in such proportions as to produce a mixture the temperature of which can be measured by a mercury thermometer.

In most instruments based on this principle the substance heated is a ball or cylinder of metal, which is cooled in or mixed with water the temperature of which is afterwards taken by means of a thermometer.

Let W be the weight of the metal ball or other body, S its specific heat, T the temperature to be determined, W′ the weight of the water, t its temperature before the experiment, and t' the temperature of the mixture after the experiment.

The heat lost by the hot body will be $W \times S \times (T - t')$—that is, its weight multiplied by its specific heat and by its fall of temperature. The heat gained by the water will be its weight multiplied by its gain in temperature—that is, $W' \times (t' - t)$; and if there be no loss of heat these must be equal, so that

$$W\,S\,(T - t') = W'\,(t' - t);$$

therefore,

$$T = \frac{W'\,(t' - t) + t'}{W\,S},$$

whence T can be calculated, since all the other values are known.

Instruments based on this principle are sometimes called specific-heat pyrometers, because the specific heats of the substances mixed must be known, and because the accuracy of the method depends on the assumption that the specific heat remains constant at the highest temperatures which have to be measured, an assumption which is certainly not absolutely correct.

Siemens' Pyrometer.—The form of apparatus most commonly used is that of Siemens, fig. 89, which consists of a copper vessel made with double walls, to avoid as far as practicable loss of heat. This is fitted with a thermometer and a set of copper or iron cylinders; platinum would, of course, be better, but is very expensive. The cylinders are heated to the temperature which is to be determined, and are transferred as quickly as possible to the water, the temperature of which is taken without delay.

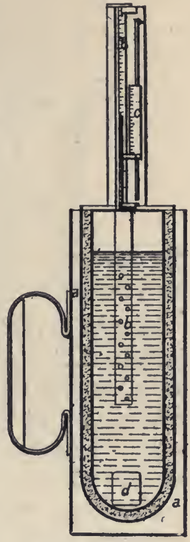

Fig. 89.—Siemens' Pyrometer.

This method, in spite of its obvious defects, was until recently the most accurate pyrometric method available, and it is fairly convenient for some purposes, though too troublesome for ordinary work.

It is not continuous, a special experiment being required for each determination, and these take some time, and require a skilled experimenter to conduct them, and therefore cannot be trusted to an ordinary workman. There is always some loss of heat in removing the ball from the furnace to the water, however quickly it may be done, a loss which it is impossible to estimate, and which may vary very much, so that a single determination can never be relied on. If a furnace temperature is being taken, it is often difficult to fish out the ball. The result will always have to be calculated, tables being of little use, as the balls used change in weight, and must be weighed before each set of experiments.

Murrie's Pyrometer.—This instrument is intended to be used in cases where continuous readings are not required. It is a modification of the Siemens form already described. The body to be heated is in this case a platinum ball, and the liquid in which it is to be immersed is mercury. The platinum ball is placed in the iron tube B, and is allowed to roll to the end A, which is usually perforated, and this is placed in the space the temperature of which is to be measured. When it has been in position about five minutes the stem is tilted up and the ball rolls along the tube into the mercury which is contained in the tube D, the thermometer F, which dips into the mercury, shows the rise of temperature, and from this the temperature of the ball can be calculated.

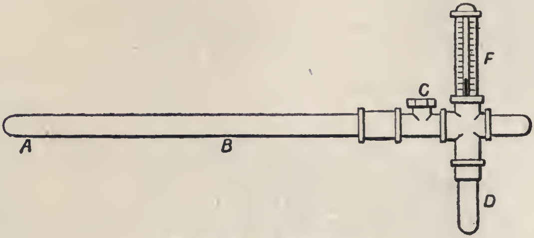

Fig. 90.—Murrie's Pyrometer.

Krupp's Pyrometer.[1]—This instrument, which is used for the determination of the temperature of the hot-blast, is based on the principle of mixtures. The hot-blast is mixed with air at the atmospheric temperature in such proportions as to reduce the temperature of the mixture so low that it can be determined with a mercury thermometer.

The blast enters at A, and is throttled down to a suitable pressure, which is indicated by the pressure-gauge P G, and rushes through the nozzle F, drawing in cold air through the pipe P, the temperature of the inflowing air being registered by the thermometer T. The mixture of hot and cold air escapes at F, its temperature being indicated by the thermometer T′. The formula which gives the required temperature is—

$$H = c\,(F - A) + A,$$

where H is the temperature required,
A is the temperature of the cold air,
F is the temperature of the mixture,
c a constant depending on the pressure of the blast.

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[1] Von Bergen, *Journal Iron and Steel Institute*, 1886, vol. i. p. 207.

Each instrument is graduated by comparison with a standard pyrometer.

This instrument is said to be very successfully used at some continental ironworks, and is obviously only suitable for taking the temperature of a current of hot gas supplied at a sufficient pressure.

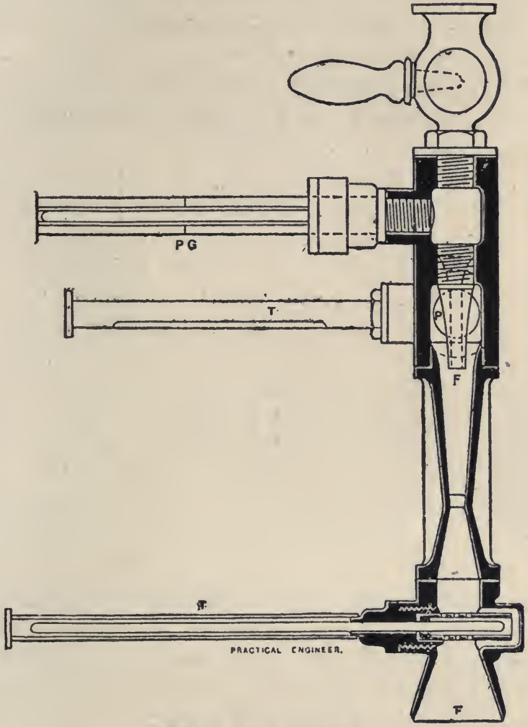

Fig. 91.—Krupp's Pyrometer.

Conduction Pyrometers.—Several methods of measurement of temperature based on the laws of conduction have been suggested. The principle used is that of conducting away part of the heat, and, when the temperature is sufficiently reduced, measuring it by means of a thermometer.

The method of Jourdes consists in inserting a bar of metal into the furnace the temperature of which is to be measured; in the part of this bar projecting beyond the furnace are cup-like depressions containing mercury, in each of which a thermometer is placed, and from the temperatures indicated that of the furnace is calculated, the law according to which heat flows along a metal bar being known.

Carnelly and Burton's Pyrometer.—A pyrometer depending on the heating of a current of water has been suggested by Carnelly and Burton (fig. 92). The principle is very simple: a stream of water under a constant pressure flows through a coil placed in the space the temperature of which is to be determined; it, of course, is heated in its passage to a temperature depending on that of the coil and the rate of the current; this last being fixed, the temperature to be measured is the only variable. The apparatus is simple. The water flows from the reservoir under a definite pressure, and its temperature is registered by the thermometer T. It passes through the tubes to the coil C in the space the temperature of which is to be taken, and escapes through the nozzle B, its temperature as it leaves being indicated by the thermometer T′. From the two thermometer readings the temperature can

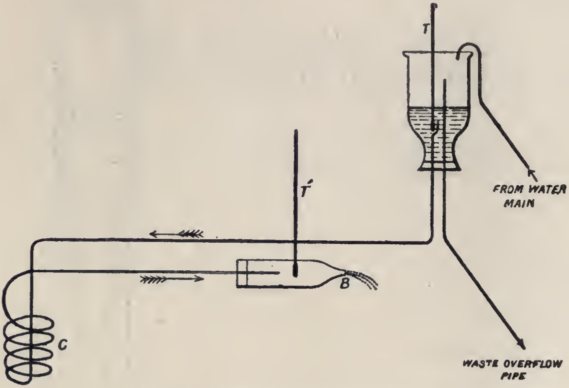

Fig. 92.—Carnelly and Burton's Pyrometer.

be obtained by reference to a table prepared by experiment for each instrument.

Optical Pyrometers.—Several methods of thermal measurement have been suggested, dependent on the radiation of light from strongly heated bodies. Indeed the rough-and-ready method of indicating temperature by its colour is based on this principle. We speak of a dull red heat, a red heat, or a white heat as indications of temperature. These terms are, however, so vague that they are of little real value; they depend entirely on the judgment of the individual, and are incapable of verification or measurement. Attempts have been made to fix definite temperatures corresponding to the colour indications. Those usually given are:—

Red heat, ...	525° C.
Cherry-red heat, ...	800 „
Orange-red heat, ...	1100 „
White heat, ...	1300 „
Dazzling white heat, ...	1500 „

These numbers are, however, only the very roughest approximations. As the change in colour depends on the nature of the rays emitted, the spectroscope would give valuable information, and no doubt a scale might be drawn up giving the approximate temperature at which particular parts of the spectrum made their appearance as the temperature increased.

Cornu-Le-Chatelier Pyrometer.—This instrument (fig. 93) depends on the comparison of the light emitted by the substance the temperature of which is required with that of a standard lamp, the brightness being taken as the test of temperature. It consists of two telescope tubes placed at right angles. One of these is for observing the body to be examined; the other is for the standard lamp.

The observing telescope has an objective O, in front of which is an adjustable diaphragm or stop, and an eye-piece V. The rays from the lamp L are reflected by the mirror M into the eye-piece V, so that the two sources of light are observed together. As varying colour would interfere with the judgment of brightness, a monochromatic red glass is placed over the eye-piece. If the observing telescope be directed towards the object radiating light, the apparatus being so fixed that the image of a spot in the brightest part of the lamp flame is seen at the same time, two bright spots of light will be seen, one of which will probably be brighter than the other. The diaphragm or stop is adjusted until the two spots are equally bright, the size of the opening in the diaphragm is read off, and the corresponding temperature is obtained from a table.

The brightness of the spot of light from the object being tested will depend on—1. The temperature which is to be measured. 2. The distance of the luminous object. 3. The size of the opening in the stop. The two last can be measured, and thus the first can be obtained. It is quite obvious that the lamp must be quite constant, and the tables must be prepared by comparison with a standard pyrometer.

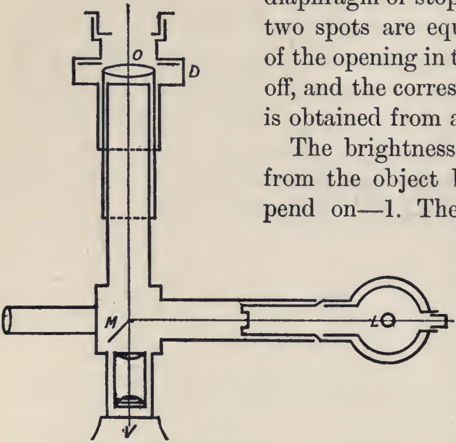

Fig. 93.—Cornu-Le-Chatelier Pyrometer.

The temperatures corresponding to the light intensities of a particular instrument are given below. The ratio will remain the same in all cases, though the actual temperature values will necessarily vary with the unit light, and the constants of each instrument.

Intensity.	Temperature. Deg.	Intensity.	Temperature. Deg.
·00008	600	1·63	1300
·00075	700	3·35	1400
·00466	800	6·7	1500
·02	900	12·9	1600
·078	1000	22·4	1700
·24	1100	39	1800
·64	1200	60	1900
1	—	93	2000

If the source of light is not at the standard distance, it must be borne in mind that the intensity varies inversely as the square of the distance. If the light be too intense for observation, it may be reduced by coloured glasses, the coefficients of absorption of which are known.

Owing to the influence of distance and the lack of portability, this instrument is not likely to come into general use. It may, however, be useful for some purposes, and it may be used to estimate the temperature of small sources of heat, to which ordinary pyrometers could not be applied without disturbing the heat equilibrium too much. It must also be remembered that the intensity of the light depends on the nature of the radiating substance as well as on the temperature.

Mesure and Noel's Pyrometer. — This instrument depends on the rotation of the plane of a ray of polarized light by a plate of quartz. In the tube of a telescope are fixed two Nicol prisms, or other polarizing apparatus, and between these a plate of quartz. If the analyser A be placed parallel to the polarizer P, and a bright object, illuminated by monochromatic light, be viewed, they will have no effect; if they be placed at right angles, they will completely extinguish the light, and the field will appear dark. If now a plate of quartz Q be put between the Nicols, the field will be illuminated, and the analyser will have to be turned through an angle to cause extinction of light. This angle will be that through which the quartz plate has rotated the plane of polarization. This angle depends on the thickness of the quartz plate, which is fixed for each instrument, and on the wave-length of the light, which is a function of the temperature. If the light is not monochromatic, then, instead of absolute darkness, a series of colours will appear, and one definite tint is taken as the standard.

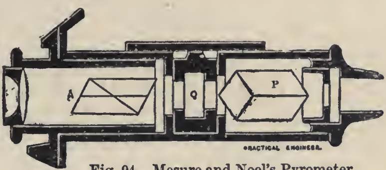

Fig. 94.—Mesure and Noel's Pyrometer.

The source of light, the temperature of which is to be measured, is viewed through the instrument, the analyser is rotated till the standard tint appears, the amount of rotation required is read off on the graduated circle, and the temperature corresponding is obtained from a table. The results seem to be fairly accurate, and it is, at any rate, a convenient method of determining the temperature by inspection.

Neither of the two last-described pyrometers are available below a red heat, and therefore they cannot be directly compared with the mercury thermometer.

Electric Pyrometers.—Two of these are in use, depending on quite different electric principles.

The Siemens Pyrometer.—When an electric current is made to flow through a conductor, the conductor offers a certain resistance to its passage. This resistance increases as the temperature rises, the rate of increase varying with different conductors; with platinum, which is almost always used, the resistance at 1000° C. is about four times as great as its resistance at 0°. This increase of resistance is easily measured, and if the law connecting it with the increase of temperature be known, a pyrometer can be readily based on this principle.

The pyrometer will consist of three parts:—

1. The battery for producing the current.
2. The pyrometer proper or coil, the resistance of which is to be measured.
3. The apparatus for measuring the resistance.

The battery may be of any form, but should be as constant as possible. As absolute constancy is unattainable, the reading apparatus must be compensated for small variations in the battery powers.

The pyrometer proper consists of a coil of platinum wire wound on a cylinder of some refractory material, which is contained in an iron tube. Clay was at first used, but it has been found that after a time the elements present in the clay attack the platinum, render it brittle, and alter or destroy its conducting power. Mr. Callendar has suggested plates of mica as being the best material with which to make the core, as this does not cause any deterioration of the platinum, and also that it should be inclosed in a porcelain tube instead of an iron one.

The apparatus for measuring the resistance is the most complex part of the instrument, but as it is essentially an instrument for electrical measurement, full details of it would be out of place here; indeed, for those familiar with methods of electric measurement they would be superfluous, for others they would be useless. The method of determining the resistance almost always used is that known as the bridge method, which consists in adding accurately known resistances to the circuit till these are equal to the resistance to be measured. As this can be done with very great accuracy, the temperature can also be accurately determined.

The instrument can be made to give readings over any required range, and may readily be compared with the mercury or any other standard thermometer. The law of the instrument must, of course, be known, in order to obtain accurate readings in degrees. Mr. Callendar states that the increase of resistance is nearly proportional to the absolute temperature. Readings can be obtained to $\frac{1}{10}$° C. at 1000° C., and it is therefore one of the most delicate pyrometers obtainable.

Le Chatelier Pyrometer.—This instrument, which was invented in 1886 by M. Le Chatelier, and which has been introduced and made popular in this country by Prof. Roberts-Austen, is based on an entirely different principle. If bars of different metals be placed in contact, or soldered together at one end, the other ends being connected by a wire, and the joined ends be heated, a current will be found to flow through the wire. This principle has long been known, and was applied in the thermo-pile of Melloni, which has been much used in physical research, rods of bismuth and antimony being there used. It is quite obvious that, from the low melting point of these metals, this instrument could be of no use as a pyrometer.

In the Le Chatelier pyrometer, in place of these metal rods, wires of platinum and of an alloy of platinum with 10 per cent of rhodium are used. The junction of these, when heated, gives rise to an electric current, depending on the difference in temperature between the hot and cold ends, and, as this current can be measured, it gives a means of determining the temperature of the junction. It is essential that the relationship existing between the current and the temperature should be accurately known, and many investigators have been at work determining it. Dr. Carl Barus, who has thoroughly investigated the matter, comes to the conclusion that the current is very nearly, if not exactly, proportional to the absolute temperature of the junction.

As the current to be measured is a feeble one, delicate apparatus is essential, a galvanometer of the reflecting type being always used. The junction of the wires, which are either twisted together or soldered with gold, and contained in a suitable protecting case, is placed at the spot the temperature of which is to be taken. As the junction gets hot the current flows and deflects the galvanometer needle, the position of which is read by the spot of light on the scale; or, if a permanent record is required, the spot of light may be made to register its movements on a strip of properly sensitized paper. This form of pyrometer has come largely into use, and has been popularized by the splendid work which Prof. Roberts-Austen has done with it. He states that he is satisfied that it is accurate to 1° at temperatures over 1000°, and that it can be made accurate to $\frac{1}{10}$°.

The instrument is calibrated by determining the currents at known temperatures. Prof. Roberts-Austen gives the following as being fixed points sufficiently accurately known for the purpose:—

Boiling point of water, ...	100° C.
Melting point of lead, ...	326 „
„ „ mercury, ...	358 „
„ „ zinc, ...	415 „
„ „ sulphur, ...	448 „
„ „ aluminium, ...	625 „
Boiling point of selenium, ...	665 „

Melting point of silver, ...	954° C.
„ „ potassium sulphate, ...	1015 „
„ „ gold, ...	1045 „
„ „ copper, ...	1054 „
„ „ palladium, ...	1500 „
„ „ platinum, ...	1775 „

These two forms of pyrometer are thoroughly reliable instruments, and their introduction has given a vast impetus to the study of high-temperature phenomena, which will do much to solve many important metallurgical problems. They have one enormous advantage over most other forms of pyrometer—that is, that the reading instrument need not be in the immediate neighbourhood of the spot the temperature of which is being taken, but may be any distance away. The pyrometers themselves may be fixed in furnaces or flues wherever required, and all the reading instruments may be in the laboratory. By means of proper shunts one reading instrument may be made to do duty for a number of pyrometers, and may be transferred in an instant from one to another. With the Le Chatelier instrument a photographic record of temperature variations may be obtained. The junction also may be made so small that the temperature of small objects or experimental apparatus may be obtained.

These instruments require a trained and educated man to look after them, and cannot, therefore, be trusted to a workman, and a special room for the reading instruments is necessary; they are therefore more likely to be used for experimental work than for routine work, except in very large works.

CHAPTER XII.

CALORIMETRY.

Calorimetry is the measurement of quantity of heat as distinguished from thermometry or pyrometry, which is concerned only with measurement of temperature. Of the many cases in which heat measurement is required, it is only necessary here to deal with the measurement of heat evolved by combustion, that is, with the determination of the calorific power of fuel.

Various forms of apparatus have been devised, from the time of Count Rumford till to-day, and all, except that of Berthier, depend on the combustion of a known weight of the fuel in oxygen, and the cooling of the products of combustion in a known weight of water. Some of the forms of apparatus have been designed only for extremely accurate work in the research laboratory, whilst others are intended for practical purposes.

Berthier's Process.—This method stands alone in principle. It is based on the assumption that the heating power of a fuel is proportional to the amount of oxygen with which it combines, an assumption which, as already pointed out, is not correct. Berthier thus describes his process:[1]—

"Mix intimately one part by weight of the substance in the finest possible state of division with at least 20, but not more than 40, parts of litharge. Charcoal, coke, or coal may be readily pulverized, but in the case of wood the saw-dust produced by a fine rasp must be employed. The mixture is put into a close-grained conical clay crucible, and covered with 20 or 30 times its weight of pure litharge. The crucible, which should not be more than half-full, is then covered and heated gradually, until the litharge is melted and the evolution of gas has ceased. When the fusion is complete, the crucible should be heated more strongly for about ten minutes, so that the reduced lead may thoroughly subside and collect into one button at the bottom. Care must be taken to prevent the reduction of any of the litharge by the gases of the furnace. The crucible while hot should be taken out of the fire and left to cool, and when cold it is broken, the button of lead detached, cleaned, and weighed."

Forchammer recommends the use of a mixture of 3 parts litharge and 1 part lead chloride as being more fusible and not corroding the crucible so much.

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[1] *Traité des Essais*, 1828, as quoted by Percy, *Fuel*, p. 166.

Rumford's Calorimeter.—This is one of the very early forms of apparatus, and with it Rumford did good work. It is of historical interest, and being simple will serve to illustrate the principle on which all instruments for the purpose must be based.

It consisted of a vessel of thin sheet-copper, 8 inches long, 4½ inches broad, and 4¾ inches deep, which was filled with water, and in it were three horizontal coils of a flat copper pipe, 1 inch broad and 1½ inches thick; one end, passing through the bottom of the box, had attached to it a copper funnel, and the other end projected above the water in the box. The substance to be tested was burned under and within the funnel, the products of combustion, passing through the coils, heated the water, and the rise of temperature gave the amount of heat absorbed by the water. The data required for the calculation are—F the weight of the fuel consumed, W the weight of water, C the weight of copper in the instrument, S specific heat of copper, T initial temperature of the water, T′ final temperature of water, H the heat evolved by the combustion of one unit weight of substance: then

$$FH = (W + CS)(T' - T)$$

$$\therefore\ H = \frac{(W + CS)(T' - T)}{F}.$$

Berthelot's Apparatus.—This form of apparatus, which has been much used in recent work, consists of a cylindrical vessel of hard glass about 400 c.c. capacity, provided with two necks, one for the admission of oxygen and the other for the introduction of the substance to be burned. From the bottom of the vessel a glass spiral tube is made to wind, by which the gaseous products of combustion pass away. The apparatus is placed in 1000 c.c. of water contained in a platinum vessel. This vessel is supported on pieces of cork in an outer vessel of silver, which is itself contained in a double-walled vessel of iron, the space between the walls of which is filled with water.

A small platinum crucible hung by a wire contains the fuel, and this is lighted either by a small piece of slow match or by dropping down a small piece of hot charcoal. The products of combustion passing away heat the water, and the result is calculated exactly as above.

Thomson's Calorimeter.—This instrument is intended for technical work, for which purpose it is admirably suited, and it has now come into general use. The fuel is not burned in oxygen, but in a mixture of potassium chlorate and nitrate which readily gives up its oxygen.

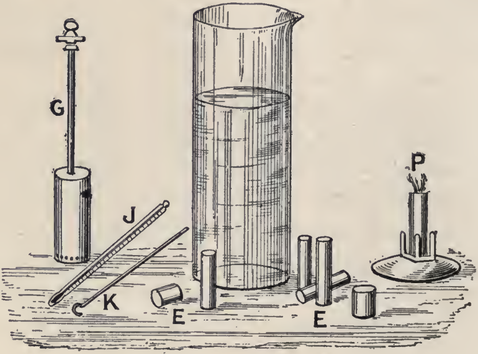

Fig. 95.—Thomson's Calorimeter.

It consists of a glass vessel graduated to contain 2000 grammes of water, a copper cylinder E capable of holding the mixture of 2 grammes of fuel, with the necessary amount of fusion mixture; a copper base, on which the cylinder can be placed, and a copper cylinder G, with a row of holes round the bottom, to be placed over it. This cylinder is held in place by a set of springs on the base, and is also provided with a tube which reaches above the surface of the water, and which is fitted with a stop-cock.

Two grammes of the fuel will require from 20 to 24 grammes of the fusion mixture.[1] The mixture is put into the cylinder,

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[1] The best fusion mixture is 3 parts chlorate of potash and 1 part nitre, and it and the fuel should be quite dry. The slow match is readily made by soaking ordinary wick in a solution of lead nitrate and drying.

tapped down, and placed on the base; a piece of slow match is put on the top and lighted; the cover G is quickly placed over it, and the whole is quickly put into the jar of water, combustion takes place, and the products of combustion pass up through the water and escape with a dense white smoke. Combustion once started should proceed vigorously and should be complete in about two minutes; the stop-cock is then opened so as to admit water into the interior of the cylinder. This is raised quickly up and down once or twice so as to thoroughly mix the water, and the temperature is read with the thermometer J. The temperature having been taken before the experiment, the rise of temperature in F. degrees × 1000 gives the number of B.T.U. absorbed by the water.

There are various sources of loss—heat of decomposition of the fusion mixture, heat absorbed in warming the apparatus, and heat lost by radiation. To compensate for the last-named loss a blank experiment is first made, and then a second experiment, the water being cooled before starting about as much below the atmospheric temperature as it will be above it after. To allow for other sources of loss an addition of 10 per cent is made, which is said by the makers of the instrument to cover them.

The glass vessel is usually also graduated to contain 1932 grammes of water, and if that quantity be used, the reading gives at once the evaporative power of the fuel.

Temperature after experiment, ...	61·5
,, before experiment, ...	47·5
	14·0
+ 10 per cent, ...	1·4
	15·4 × 1000 = 15400

The quantity of combustion mixture required will vary with the nature of the fuel being treated, and charcoal, coke, or similar fuels should be burnt in a shorter and wider copper "furnace".

W. Thomson's Oxygen Calorimeter.—In this apparatus the fuel is burned in oxygen. The apparatus consists of a glass jar *a* capable of holding 2000 c.c., or any other convenient known weight of water, a platinum crucible *g* in which the fuel is burned, and which rests on a clay cylinder; a bell-glass *f* which covers the crucible and contains the atmosphere of oxygen in which the combustion takes place. It is provided at the top with a neck, through which passes a glass tube *i*, by which the oxygen enters; it is provided with a stop-cock *k*, and can be raised or lowered as required. It rests on a perforated base, and is surrounded by a series of rings of wire-gauze to break up the ascending current of gas. A thermometer *d* and a stirrer *j* are suspended in the outer vessel of water.

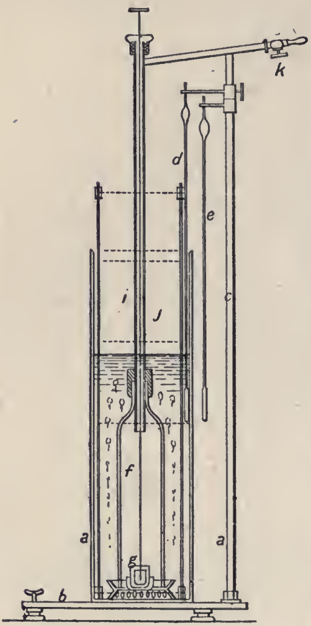

Fig. 96.—W. Thomson's Calorimeter.

It is necessary to ascertain the heat capacity of the apparatus—that is, the amount of extra water to which the absorptive power of the apparatus is equal,—which can be done once for all.

Two thousand grammes of water, at about 25° F. above the temperature of the air, is poured into the apparatus, and the whole is well mixed. The water is left about the time which will be occupied by an experiment, and the amount by which the temperature is lowered gives the data for calculating absorptive power of the apparatus sufficiently nearly for practical purposes.

Thus, to take an example:

Temperature of room, and therefore of the calorimeter before water is added, ... $\}$ 84° F.
Temperature of water, ... 95° ,,
Temperature after experiment, ... 94° ,,

Therefore the fall of 2000 grammes of water 1° has raised the temperature of the calorimeter 11°, and the heat capacity of the apparatus is $\frac{2000}{11} = 181{\cdot}8$ c.c. of water.

This weight must therefore be added to the amount of water used and the 2000 grammes calculated as 2182 grammes.

To make a determination.

About 2 to 5 grammes of the powdered fuel is carefully weighed and placed in the crucible, a short piece of slow match or an ignited vesta is placed on it, and the bell-glass is inverted over it. The whole is gently lowered into the water and the oxygen is turned on, the delivery-tube being pushed down to near the fuel if necessary. Combustion at once begins. When combustion is over, the oxygen apparatus is disconnected and the stop-cock is opened so as to admit water, the bell-glass is moved up and down vigorously to ensure perfect mixture, and the temperature is taken.

Suppose 10 grammes of fuel were taken, and the rise of temperature of the water was 9°. Then since the 2000 grammes of water is equivalent to 2182 grammes, taking into account the absorptive power of the apparatus, the calorific power is

$$\frac{9 \times 2182}{10} = 1963{\cdot}8.$$

This apparatus gives excellent results.

The Berthelot-Mahler Calorimeter.—This is another excellent form of apparatus, and is described by Mr. B. H. Thwaite in a paper read before the Iron and Steel Institute in 1892.[1]

The combustion chamber B is of mild steel. It is 8 mm.

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[1] *Journal*, vol. i., 1892, p. 189, *et seq.*

thick, and has a capacity of about 654 c.c. It is enamelled inside and nickel-plated outside, and is provided with a cover in which is a valve for the admission of oxygen. Wires also pass through the cover, by which a short coil of iron can be heated to ignite the fuel, which is contained in a platinum crucible or capsule C. The whole is contained in a vessel of water D, provided with a spiral agitator S, and this again is placed in an outer vessel of water A.

The fuel is weighed and lowered into the combustion chamber; the igniting wire is weighed and adjusted, and the top is screwed down. Oxygen is allowed to enter from the cylinder O till the pressure on the gauge M indicates 25 atmospheres. The temperature of the water is noted, an electric current is passed from the battery P, and combustion takes place instantly. The temperature of the water is taken at once, and at intervals until the maximum is reached, then observations are continued at intervals for another five minutes, the stirrer being kept going all the time.

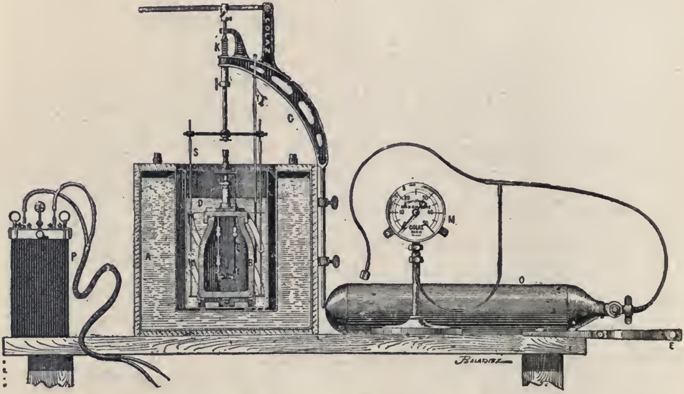

Fig. 97.—The Berthelot-Mahler Calorimeter.

After the observations are completed the combustion vessel or "bomb" is washed out, and any nitric acid present is determined volumetrically.

It is necessary to determine the correction due to the loss of heat from the calorimeter during the test. The loss can be calculated by noting the rate at which the temperature rises to a maximum and then falls. The addition necessary to the observed rise is not large.[1]

Then if Δ = the rise of temperature corrected,
W = the weight of water in the calorimeter,
W' = the water equivalent of the apparatus, which must be determined by experiment,
n = the weight of nitric acid, HNO_3.
f = the weight of the spiral of iron wire,
$\cdot 23$ = heat of formation of 1 gramme of dilute nitric acid,
$1\cdot 6$ = heat of combustion of 1 gramme of iron,
x = the calorific power required,

$$x = \Delta(W + W') - (0\cdot 23\, n + 1\cdot 6\, f).$$

Carpenter's Calorimeter.—This is one of the most recent forms of calorimeter. It is so arranged that the instrument itself acts as a thermometer, the heating power of the fuel to be tested being measured by the expansion of the liquid to which the heat of combustion is imparted.

The fuel is burned in a central combustion chamber, and the products of combustion circulate through the spiral copper tube, and when cooled escape into the air. Surrounding the combustion chamber and cooling tube is a vessel of water, to the top of which is attached an open graduated glass tube. The top of the water vessel is fitted with a diaphragm, which

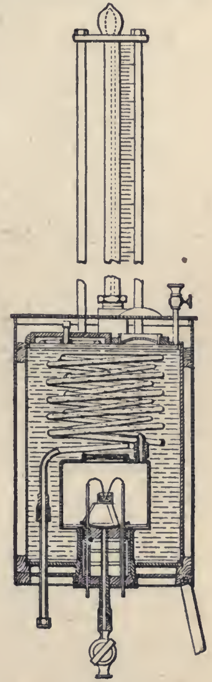

Fig. 98.—Carpenter's Calorimeter.

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[1] For further particulars, see Thwaite, *J. I. and S. I.*, 1892, i. 188.

can be raised or lowered so as to bring the level of the water in the graduated tube to the zero-mark. The fuel is weighed, placed in the combustion chamber, through which a stream of oxygen is passing, and is fired by an electric current. Combustion takes place rapidly, the heat is taken up by the water, which expands and rises in the graduated tube, the height which it reaches indicating the amount of heat evolved. The tube is graduated experimentally by burning known weights of pure carbon, which is assumed to have a calorific power of 14500 B.T.U.

Calorimeters for Fuel Gas. — The Thomson oxygen calorimeter may be used for fuel gas, so can the Berthelot-Mahler form. In the latter the bomb is filled with gas before the oxygen is introduced, the pressure of oxygen required for coal-gas being about 5 atmospheres, and for producer-gas about 1·5 atmospheres.

Junker's Calorimeter.—This is the latest and best calorimeter for taking the calorific power of gases. The gas is burned for a definite time, the amount consumed being measured by means of a meter, and a stream of water is kept flowing steadily through the apparatus, the rise of temperature of which supplies the necessary data for calculating the calorific power.

"A flame, 28, is introduced into a combustion chamber, formed by an annular copper vessel, the annular space being traversed by a number of copper tubes, 30. The heated gases circulate inside the tubes from the top to the bottom, whilst the current of water travels outside the tubes in the opposite direction, all the heat produced by the flame being thus transferred to the water, the spent gases escaping at the atmospheric temperature. The pressure of the water is kept constant by two overflows, 3 and 20, and the quantity of water is regulated by the stop-cock, 9. A baffle-plate, 14, at the lower end of the apparatus, secures an even distribution of the water. The water can be passed through the tube, 21, into a measured receptacle. To prevent loss by radiation the apparatus is inclosed in a nickel-plated cylinder. In addition to the calorimeter a meter capable of passing $\frac{1}{10}$ c. ft. for one revolution of the pointer, a water supply giving 1 to 3 litres per minute, and two measure-glasses containing respectively 2 litres and 100 c.c. are required. The quantity of gas burned should be regulated so as to give out about 1000 to 1500 calories per hour (4000 to 6000 B.T.U.), this is for illuminating gas 4 to 8 cubic feet, or producer-gas 16 to 32 cubic feet.”

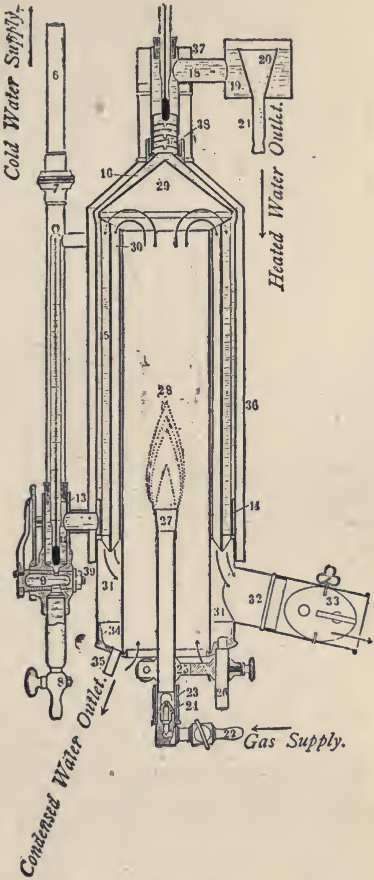

Fig. 99.—Junker's Gas Calorimeter.

The gas is lighted, the thermometer placed in position, and the water turned on. The temperature rises, and the mercury soon becomes stationary. As soon as the temperature is steady, the hot-water tube is shifted over the large measure-glass. As the water flows, the temperature indicated by the thermometer is noted from time to time. As soon as 2 litres of water have passed, the gas is turned off, and the quantity of gas which has passed is read. The following is an example given by the makers of the instrument:—

Meter Reading.	Cold-water Thermometer.	Hot-water Thermometer.	Water.
5 c.ft., ...	8·77	26·75	
	—	26·76	
	—	26·82	
	—	26·80	
	—	26·75	
5·344 c.ft.,...	8·77	26·80	2 litres.
Mean, ...	8·77	26·77	2 litres.

If H = calorific power of one cubic foot of gas,
W = quantity of water heated, in litres,
T = difference in temperature between the hot and cold water,
C = cubic feet of gas burned,

$$\therefore H = \frac{WT}{C};$$

or in the case given,

$$H = \frac{2 \times 18}{\cdot 344} = 104\cdot 65.$$

The quantity of water condensed should also be measured, as its latent heat must be deducted where the temperature of the products of combustion will, as in most cases, remain at a temperature above 100° C. The condensed water is drawn off by 35 into a measure-glass. In this case there was 53 c.c. of water. The latent heat of each c.c. may be taken as ·64, so that the latent heat of the condensed water would be

$$\frac{\cdot 64 \times 53}{2} = 16\cdot 96,$$

which must be deducted from the value obtained above, leaving 87·69 calories as the calorific power.

Comparison of Calculated and Determined Results.—For various reasons the results calculated from the various formulæ are not exactly correct, the variation being sometimes one way and sometimes the other. The following comparisons made by various workers will be of interest:—

EXPERIMENTS OF BERTHIER.

	Lbs. of Lead reduced by 1 lb. of Coal.	Lbs. of Water Heated from 0° to 100°.	Lbs. of Water Heated from 0° C. to 100°, calculated from Composition.
Coking coal, Dowlais, ...	31·8	72·0	—
Newcastle coal, ...	30·9	70·0	71·5
Rive de Gier, Grand Croix,	29·6	67·0	78
Cannel coal, Wigan, ...	28·3	64·1	76
Rochbelle, near Calais, ...	27·6	62·5	79·7
Epinai, Sâone et Loire, ...	26·8	60·7	72·8
Cherry coal, Derbyshire, ...	27·2	61·6	—
Coke, ...	28·5	65·6	—
Gas coke, ...	22·2	50·3	—
Anthracite, ...	31·6	71·5	72·8
,, ...	30·5	69·1	75·6

Comparison of heating power of coal determined by W. Thomson's calorimeter, with that calculated from the chemical composition:—

Coal.	C. units.		B. T. U.		Exp. diff. %
	Exp.	Calculated.	Exp.	Calculated.	
Nixon's Navigation,.....	8340	8459	15012	15146	1·4 –
Thakerley,................	6448	6972	11600	12549	7·5 –
Tyldesley,................	7069	7430	12724	13374	4·8 –
Upper Drumgar 1,......	6384	7493	13291	13587	1·4 –
,, ,, 2,......	7954	7166	13517	13898	2·9 –
,, ,, 3,......	7533	7443	13559	13397	1·7 +
Bickershaw, ...	7465	7778	13437	14808	4·0 –
Pemberton 5-ft.,..........	7242	7267	13035	13080	·3 –
Crombourke, ...	7456	6778	13420	12200	10 +
Wigan 4-ft.,...............	7552	7549	13593	13592	—
Bickershaw 7-ft.,.........	7417	7176	13351	12916	3·2 +
Pendleton 4-ft.,..........	7736	7819	14926	15074	1·6 –

Greatest, ...	– 7·5 %
Greatest, ...	+10 %
Average, ...	1 %

EXPERIMENTS OF PROF. LEWES.

Fuel.	Evaporative Power.		Per Cent.
	Actual.	Calculated.	
Coal, Nottingham cannel, ...	8·78	12·27	71·56
Yorkshire Silkstone, ...	10·01	14·24	70·30
Coke, cannel, ...	9·91	12·23	81·03
Gas coke, ...	11·15	13·83	80·62
Tars (steam-injected), ...	12·71	15·06	84·4
Creosote, ...	13·35	16·78	79·56

CHAPTER XIII.

UTILIZATION OF FUEL.

Mechanical Equivalent of Heat.—Fuel is always burnt for the purpose of performing some useful work, very frequently for conversion into energy. A given amount of heat is equivalent to a given amount of mechanical energy, and the efficiency of any machine will be the proportion of this energy which is utilized or usefully employed. The mechanical equivalent gives the maximum amount of heat which it would be possible to obtain if there were no loss. A unit of heat is equivalent to 772 foot-pounds, so that the energy given out by one pound of water cooling through 1° F. would raise 772 pounds through a height of one foot if it could all be converted into useful work.

First Law of Thermo-dynamics.—This may be thus stated: "Heat and mechanical energy are mutually convertible, and heat requires for its production, or produces by its disappearance, mechanical energy in the proportion of 772 foot-pounds for each unit of heat".[1]

Knowing the amount of heat which is evolved by the combustion of a fuel, it is quite possible for us to calculate the

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[1] Anderson, *Conversion of Heat into Work.*

amount of energy it will give. Thus carbon, with its C. P. of 14,500, would give for each pound consumed 11,204,000 foot-pounds of energy.

An expenditure of energy at the rate of 33,000 foot-pounds per minute is called a horse-power, and the work done in one hour when working at the rate of one horse-power will therefore be 1,980,000 units, which is called a horse-power-hour. It will be seen, therefore, that the combustion of one pound of carbon gives energy equivalent to about 5·6 horse-power-hours. From this statement it will be easy to realize the enormous amount of latent energy which is stored up in fuel.

In practice, for various reasons, the whole of this energy can never be realized.

Second Law of Thermo-dynamics.—This law, which is of equal importance with the first, may be enunciated: "It is impossible to transform any part of the heat of a body into mechanical work, except by allowing heat to pass from that body to another at a lower temperature".

Conversion of Heat into Work.—Heat is converted into work by means of machines of various kinds, in which the heat is allowed to flow from a hot body to a cold one, and to do work as it flows. In general there are two classes of prime-movers in use, with both of which the metallurgist may have to deal. They are steam-engines and gas-engines. Both are essentially heat engines, but they differ in the way the heat is obtained and employed.

The Steam Boiler.—In a steam-engine the first stage is to convey the heat of the fuel to steam, and this is done by means of a boiler. This is not a case of doing mechanical work, except in so far as the expansion of the steam may do work, but is merely the transference of the potential energy of the fuel into potential energy in the steam through the medium of combustion, a transference which can never be effected without great loss.

The sources of loss which render it impossible to convey all the heat into the steam are many:—

1. The furnace gases must escape at a sufficiently high temperature to create a draught, and as each pound of fuel requires about 25 lbs. of air for its combustion, this must always be very considerable. Assuming the temperature to be 400° F., which will be much lower than usual, and the specific heat of the gases to average ·25, this will amount to $25 \times 400 \times {\cdot}25 = 2500$ units for each pound of coal consumed, or, say roughly, 20 per cent.

2. Loss of heat by transmission into the walls and by radiation may be guarded against, but can never be actually prevented.

3. There is always loss by ashes falling hot from the firebars, ashes containing carbon, &c.

4. Evaporation of water in the fuel, though hardly being a loss due to the transference of the heat to the boiler, but rather a diminution of the heating power of the fuel, is often very considerable.

5. There may also be loss due to the formation of smoke, and to imperfect combustion, unburned combustible gases escaping with the products of combustion.

In order that a boiler may be efficient it is necessary that combustion should be complete, and that the flame should be luminous so as to radiate heat to the flues or tubes.

The examples of tests of boilers on p. 299 will show the measurements that are necessary, and the results which can be obtained.[1]

The Steam-engine.—This is a machine for converting the energy in the steam obtained from the combustion of the fuel into work. It usually consists of a cylinder in which a piston is fitted steam-tight, but so that it can move freely backwards and forwards. Steam is almost always admitted alternately at each end of the cylinder, so that a reciprocating motion is imparted to the piston which can be converted into the circular motion usually required by any suitable mechanism.

The potential energy of the fuel has been transferred in part

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[1] G. C. Thomson, *Pro. I. of E. and S. of S.*, 1895.

Boiler, ...	1. 1 Lancashire, 7×26 feet.	2. 1 Galloway, 7×28 feet.	3. Babcock and Wilcox Tubulous.
Heating surface, ...	570 sq. ft.	905 sq. ft.	2756 sq. ft.
Fire-grate area, ...	34·66	32·1	45
Steam pressure average, lbs.,	35·75	62·1	54
Temp. of feed-water, average,	135·2° F.	48·9° F.	126°
Feed-water per hour, lbs.,	3554·5	6202	11604
Name of coal, ...	Earnock tripping	Greenfield dross	Daldowie tripping
Condition, ...	dry and clean	small and nut	—
Fuel analysis volatile, ...	45·78	47·34	46·25
Fuel analysis fixed, ...	54·22	52·66	58·75
„ „ ultimate, C, ...	65·05	60·22	65
H, ...	4·49	4·40	4·38
O, ...	10·78	9·29	8·34
N, ...	1·78	1·96	1·61
S, ...	·54	·75	·81
ash,	9·70	13·18	9·72
moisture,	7·66	10·20	10·14
Fuel, specific gravity, ...	1·250	1·293	1·304
Fuel used per hour, lbs., ...	694·4	918·4	2132·85
Per cent of ashes and clinker,	9·67	13·62	7·70
Thickness of fire, ...	6–8 inches.	8 inches.	15 inches.
Fuel burned per sq. ft. of grate surface per hour,	20·03	28·61	47·39
Temp. of gases, ...	407° F.	633° F.	839° F.
Speed of air entering, feet per min., ...	531	744	798
Carbon monoxide in gases,	—	—	—
Ratio of air used to theoretical quantity,	1·69 : 1	1·65 : 1	1·75 : 1

Heat Expenditure.	B.T.U.	Per Cent.	B.T.U.	Per Cent.	B.T.U.	Per Cent.
Utilized in heating water,	5448	46·16	7823	70·77	5873	50·03
Loss by gases, ...	5326	44·36	1901	17·19	3358	28·01
Loss by imperfect combustion, ...	—	—	—	—	—	—
Loss by moisture in fuel,	94	·79	135	1·22	144	1·22
Loss unaccounted for, ...	1024	8·67	1145	10·36	2363	20·13
Calorific power, B.T.U.,	11802	99·98	11053	99·98	11738	100
Practical heating power,	6·92		6·22		7·26	
Theoretical heating power,	11·66		10·96		11·84	
Per cent used, ...	59·4		56·8		61·3	

to the steam, and by the steam-engine part of the energy can be reconverted into work.

In actual practice the consumption of steam varies from 13 lbs. per H.P. hour, in the best triple-expansion condensing engines, to 60 lbs. in small simple non-condensing engines. It is easy to see the many sources of loss by which the realization of anything like the full value of the steam energy is prevented without going into details of the methods of working. As we have seen, the efficiency of boilers is rarely much more than 60%, and taking the efficiency of an engine as 16%, the combined efficiency obtained from the fuel will be only $\cdot 6 \times \cdot 16 = \cdot 096 = 9\cdot 6\%$.

Amount of Fuel used per H.P.—One pound of coal, as has been shown, may have a calorific power of say 12000 B. T. U., which is equivalent to 9264000 foot-pounds, which is equivalent to about 4·5 H.P. hours; *i.e.* the combustion of one pound of fuel should give a power of 4·5 H.P. for one hour.

The following examples given by Mr. J. W. Hall,[1] Nos. 6 to 9 being quoted from Prof. Unwin, will show how far this is actually obtained:—

	Steam per I.H.P. hour.	Coal per I.H.P. hour.
1. High-pressure non-condensing engine; 100 lbs. pressure; 50 H.P. nominal,	32	4·27
2. High-pressure non-condensing engine; 120 lbs. pressure; 40 H.P. nominal,	24	3·20
3. Triple-compound non-condensing engine; 180 lbs. pressure; 30 H.P. nominal,	20	2·66
4. Compound condensing engine; 100 lbs. pressure; 30 H.P. nominal,	18	2·46
5. Triple-expansion condensing engine; 160 lbs. pressure; 20 H.P. nominal,	14	1·86
6. 7 Indicated H.P.,	—	8
7. 10 " "	—	5¼
8. 50 " "	—	2¾
9. 200 " "	—	2

Gas-engines.—The gas-engine is another means of converting the potential energy of fuel into actual energy. In

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[1] P. S. Staff, Institute of Iron and Steel Works Managers, 1894–1895, p. 41.

this machine a piston and cylinder are provided, but instead of admitting steam behind the piston, a mixture of gas and air is admitted, which being exploded forces the piston forward.

In the Otto engine the impetus due to the explosion is given only every fourth stroke. The Otto cycle consisting of four stages:—

1. The piston makes a forward stroke and draws in a supply of gas and air through a valve in the rear of the cylinder. At the end of the stroke the valve closes, and

2. The piston makes a return stroke, and compresses the air and gas into a chamber at the rear end of the cylinder.

3. The explosive mixture, consisting of gas and air, and the residue of the products of combustion of the previous stroke, is ignited, very rapid combustion rather than explosion takes place, and is barely complete before the piston reaches the end of its second forward stroke. The heated gases expand, giving out work, and accelerate the motion of the moving parts. When the end of the stroke is nearly reached the exhaust-valve is opened, and

4. The piston in its second return stroke partially drives out the products, and restores everything to the condition it was at the beginning of the cycle.

It will be seen that here the energy of the fuel is used directly, without the intervention of the wasteful boiler, and as the temperature of the burning mixture is very high, the conditions are favourable for the utilization of a large amount of energy. The temperature of the cylinder, however, becomes very high, and has to be cooled by a water-jacket, the water from which carries away from 30% to 50% of the heat.

Any combustible gas may be used. Coal-gas is usually used; but good producer-gas, provided it be free from tarry matters, answers equally well, gas made in the Dowson producers being very often used.

That gas-engines are much more economical than steam-engines is shown by the following table of engines worked with Dowson gas:—

Type of Engine.	H. P.	Fuel per H.P. Hour in pounds.
Crossley,	199	1·23
"	210	1·00
"	170	1·4
Otto,	52·25	1·67
Atkinson,	16·7	1·06
Tangye,	100·6	1·0

Blast-furnace Gas in Gas-engines.—Washed blast-furnace gas can readily be used in gas-engines, as it is quite free from tarry matter, and is quite as good as most producer-gas; and as in all ironworks there is more gas than is required for ordinary purposes, even with the wasteful method of using *via* the boiler and steam-engine, it would seem that a useful outlet could be found for the energy in some manufacturing operations.

Oil-engines.—In the Priestman engine, which is the best known of these, the Otto cycle is used, but instead of gas a fine spray of petroleum or other oil, ·780 to ·812 sp. gr., and having a flash-point not less than 75°, is forced in by means of compressed air. The waste heat is used in vaporizing the oil.

The consumption of oil is about ·8 lb. per indicated horse-power per hour.

CHAPTER XIV.

TESTING FUELS.

Fuels to be Tested.—The fuels to be tested in the laboratory are coal, coke, oils, and gaseous fuels. A mere chemical analysis is not what is usually required, but an examination such as will enable an idea to be formed as to the actual value of the fuel for the purposes for which it is to be used.

PROXIMATE ANALYSIS OF COAL.

Moisture.—A sample of the coal is powdered, about 20 grains (2 grammes) weighed out into a watch-glass, heated for one hour in the steam oven, and the loss is put down as moisture.

Coke.—This estimation may be made in several ways, according to the taste of the worker.

1. A hundred grains (10 grammes) of the coal is powdered and placed in a porcelain crucible provided with a cover. This is put inside a clay crucible, surrounded with charcoal, a cover put on the outer crucible, and the whole heated to strong redness in any ordinary furnace for about half an hour.

2. About five hundred grains (50 grammes) of the powdered coal is placed in a clay crucible, a lid put on and securely luted, and it is then strongly heated for half an hour in a furnace.

3. About twenty grains (2 grammes) of the powdered coal is placed in a covered platinum crucible, and heated over a Bunsen burner till gas ceases to burn at the lid; the heat is then increased for a few minutes by means of the foot blowpipe, the crucible is let cool and weighed.

In any case the loss of weight is moisture and volatile matter, and the residue is coke.

The coke should be carefully examined to ascertain its hardness, brittleness, &c., of which a judgment can readily be formed.

Methods 1 or 2 are to be preferred, but method 3 is useful in chemical laboratories where a wind-furnace is not available.

Ash.—Here again either of two methods may be used.

1. Weigh out about fifty grains (5 grammes) of the finely-powdered coal, put it in a platinum dish, or on a clay roasting dish, put the dish in a laboratory muffle—one without slits, or the draught may be too violent—and allow it to burn until all trace of carbon has disappeared, stirring from time to time with a thick platinum wire mounted on a glass handle. Remove the dish from the muffle, let cool, brush the ash into a watch-glass and weigh it.

2. Take twenty grains (2 grammes) of the fuel, put it into

a platinum crucible, put this in an inclined position on a triangle, with the lid leaning against the top of the crucible, so as to send a current of air into the crucible; heat at first very cautiously, and with frequent stirring till all gas is expelled, then continue the heating till all carbonaceous matter has disappeared, then cool and weigh.

If the coal is strongly caking it will usually be best to powder up the coke, take a weighed portion, burn it to determine the ash, and then calculate the amount of ash in the original coal.

Sulphur.—This element, as already mentioned, exists in coal in at least two forms, as pyrites and as calcium sulphate, the former being considered to be the most deleterious.

1. Mix about 2 grammes of the powdered coal with 2 grammes of pure magnesia and 1 gramme of pure sodium carbonate, put the mixture into a dish or crucible and heat, either in a muffle (without slits) or over a Bunsen burner, till all carbonaceous matter has disappeared; then let cool, brush the white mass into a beaker and dissolve it in dilute hydrochloric acid; filter, and wash, heat the filtrate to boiling, add solution of barium chloride, boil up, let settle, filter, wash, dry, ignite, and weigh the barium sulphate.

The weight of the barium sulphate × ·1373 will give the weight of sulphur.

Pure lime may be substituted for the mixture of magnesia and potassium carbonate.

In either case the reagents should be tested for sulphur before they are used, and where great accuracy is required a spirit-lamp must be substituted for the gas.

2. Weigh 20 grains (2 grammes) of the coal and mix it thoroughly with 50 grains (5 grammes) of pure potassium nitrate. Put 80 grains (8 grammes) of a mixture of potassium and sodium carbonates into a platinum or nickel crucible and heat to fusion. Add the mixture of coal and nitre in small portions at a time till all is added, then keep in a state of fusion for about five minutes. Let cool. Dissolve in water, acidify with hydrochloric acid; evaporate to dryness. Take up with

hydrochloric acid. Filter, and in the filtrate precipitate the sulphuric acid with barium chloride as above. Great care must be taken that the gas does not come in contact with any portion of the fusion mixture, or sulphur will be taken up.

The first method is much to be preferred.

Sulphur as Calcium Sulphate.—Weigh about 50 grains (5 grammes) of the coal, and boil for about half an hour with a 20-per-cent solution of pure sodium carbonate; filter. Acidify the filtrate with hydrochloric acid, and precipitate the sulphur as barium sulphate.

Chlorine.—Mix 20 grains (2 grammes) of finely-powdered coal with about 200 grains (20 grammes) of pure lime free from chlorine, and burn in a muffle at as low a temperature as possible till the carbonaceous matter is all destroyed; let cool. Dissolve in pure dilute nitric acid. Filter, heat to boiling, and add a little silver nitrate solution. Filter, wash, dry, ignite, and weigh the silver chloride. The weight of the silver chloride × ·24729 will give the amount of chlorine.

Specific Gravity.—This may be determined either by direct weighing or by means of the specific-gravity bottle, the former being the preferable method.

1. *Direct Weighing.*—Remove the ordinary pan from the balance, attach the specific-gravity pan, and balance it. Take the piece of coal, which should weigh about 200–400 grains, attach it by a horse-hair or a piece of the finest platinum wire to the hook at the bottom of the pan, so that it hangs in a convenient position, and weigh it. This gives W, the weight of the sample in air. Fill a beaker of convenient size with water which has been recently boiled and allowed to cool, and which should be as nearly as possible at 60° F. (15·5° C.). Put this under the balance-pan, so that the coal is immersed. Carefully remove any adherent air-bubbles by means of a camel's-hair brush, and weigh again. This will give W′, the weight in water, and the specific gravity will be—

$$S = \frac{W}{W - W'}; \ \textit{e.g.}\ \frac{20}{20 - 4{\cdot}66} = \frac{20}{15{\cdot}34} = 1{\cdot}31.$$

2. *The Bottle Method.*—The specific-gravity bottle is a small flask, graduated so as to contain a known weight of water when quite full. The stopper is perforated so as to allow of the escape of excess of water without leaving an air-bubble. Most bottles are graduated to contain 50 grammes or 500 grains at 60° F.; but before use each bottle should be carefully tested. Dry the bottle thoroughly and weigh it. Fill it up with recently boiled pure water, at about 60° F.; wipe the outside quite dry and weigh it again. The increase of weight will be the contents of the bottle.

Break the coal up into pieces which will go into the neck of the flask, and weigh about 10 grammes. Transfer the weighed sample to the bottle; shake well so as to ensure removal of air-bubbles, or, better, put the bottle into a partially-exhausted receiver, or let soak for twelve hours. Then fill up the bottle with water, dry the outside, and weigh again. If $W =$ weight of coal, $B =$ weight of the bottle + water, $B' =$ weight of the bottle + water + sample; then $W + B - B'$ will be the weight of the water displaced, and $\frac{W}{W + B - B'}$ will be the specific gravity.

Coke.—The determinations required for the valuation of coke are almost identically the same as those required for coal. The determination of volatile matter may usually be omitted, as coke should lose nothing on heating. Very frequently, however, if the coke be powdered and heated in a crucible a quantity of volatile matter is expelled, and if the quantity is more than a trace it decreases the value of the fuel for blast-furnace use, as it is not burnt in the furnace but escapes with the gases.

Porosity of Coke.—The relative amount of coke matter and spaces is often of importance.

A piece of coke is selected, weighing about 40 grammes. This is dried in an air-bath and weighed. It is then put into a beaker of water, and this is gently boiled for some hours. The beaker is then allowed to cool, placed under the receiver of an air-pump and the air exhausted, this being repeated several times. The sample is weighed in water, then removed from the water, superfluous moisture wiped off, and it is weighed in air as quickly as possible.

The weights obtained are—

W = weight of dry coke.
W' = weight of dry coke in water.
W'' = weight of coke saturated with water in water.
W''' = weight of coke saturated with water in air.

$$\text{Apparent specific gravity of coke} = \frac{W}{W - W'}.$$

$$\text{True} \quad ,, \quad ,, \quad ,, \quad = \frac{W}{W - W''}$$

$$\text{Percentage of pores} = \frac{(W''' - W) \times 100}{W''' - W''}.$$

The results obtained are only approximate.

An approximation may also be obtained by determining the apparent specific gravity of the coke by weighing in air and water = S.

Then determining the specific gravity of a finely-powdered sample of the coke in the specific-gravity bottle, which will give nearly the real specific gravity = S′.

From which the relative space occupied by the pores can be calculated.

$$\text{Space occupied by 1 gramme of coke} = \frac{1}{S}.$$

$$\text{Space occupied by 1 gramme of solid coke} = \frac{1}{S'}.$$

$$\therefore \text{Space occupied by pores} = \frac{1}{S} - \frac{1}{S'},$$

$$\text{or percentage of the total} = \frac{1}{S} : \frac{1}{S} - \frac{1}{S'} :: 100 : n.$$

$$\therefore \left(\frac{1}{S} - \frac{1}{S'}\right) 100 \times S.$$

Liquid Fuels.

Specific Gravity.—This is very easily obtained by means of the specific-gravity bottle, which is filled with the liquid and weighed; or by means of hydrometers, which are tubes with a graduated stem, loaded with mercury, the specific gravity being indicated by the depth to which they sink in the liquid.

The Flashing Point.—This can only be accurately determined by means of apparatus specially devised for the purpose. It may, however, be approximately determined as follows:—

"Pour some of the liquid into a beaker (2 ins. × 2 ins.) to within about half an inch from the top; then cover with a disc of asbestos, through which a thermometer passes to within a quarter of an inch from the bottom of the beaker. The beaker, &c., is now put into a sand-bath, and surrounded with sand to the level of the liquid. A small flame is then applied under the bath, and the temperature allowed to rise about 2° a minute. After each rise of 1° the asbestos disc is turned to one side, and a small flame is quickly put into the vapour. The temperature at which it ignites is taken as the flash-point."[1]

Calorific Power.—This is most easily determined by means of Thomson's calorimeter, as previously described.

Ultimate Analysis.—The determination of carbon, hydrogen, oxygen, and nitrogen can only be made satisfactorily by a trained chemist provided with suitable apparatus, and the methods used are those of ordinary organic analysis with which all chemists are familiar.

Gaseous Fuels.—An analysis of gaseous fuels can also only be satisfactorily made by a chemist by the ordinary methods of gas analysis. It is therefore needless to describe them here.

Carbon-dioxide in Furnace Gases and Gaseous Fuels.—This determination is of great importance, and an apparatus has recently been introduced by G. Craig by which it can be determined with great readiness. It consists of two meters filled with oil passing about ·15 c.f. per revolution. The gas is passed into the first, then through an absorbing vessel containing soda-lime, and then through the second meter. The first meter gives the total gas, the second the gas after removal of the carbon-dioxide. It can readily be applied to any form of gas.[2]

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[1] Phillips, *Fuels*, 17.

[2] Sexton, *J. W. of S. I. and S. I.*, vol. iii. (1896), p. 188.

CHAPTER XV.

REFRACTORY MATERIALS—BRICKS—CRUCIBLES.

Refractory Materials.—The materials used for building furnaces, making crucibles, and similar purposes must be very refractory. A large number of refractory substances are found in nature, but comparatively few are of much use in metallurgy. Those that are used may be classified into groups, according to their chemical behaviour.

1. *Acid Substances.*—Those which, from the presence of a considerable quantity of silica, will combine readily with basic oxides. Among these may be mentioned: Dinas rock, flint, sandstones, ganister, sand, and nearly all fire-clays.

2. *Neutral Substances.*—Those in which the acid and basic constituents are so balanced that the substance neither combines with silica nor with basic oxides, or in which the substance itself is neither acid nor basic. The only important members of this group are graphite and chromite (chrome iron ore). Some fire-clays might be regarded as being neutral in composition, but almost all those used in practice are acid, and if measured by affinity for bases they are probably all best considered as acid substances.

3. *Basic Substances.*—Those in which the silica is absent, or at any rate present in such small quantity that the basic power of the basic-oxides is predominant. Among these may be mentioned lime, dolomite or magnesium limestone, and magnesite. As a rule they resist the action of metallic oxides, but are readily attacked by silica at high temperatures.

Fire-stones.—Many refractory rocks, usually rich in silica, for example, quartzites, and sandstones, such as millstone-grit, have been used in furnace construction, and refractory sandstones are now often used for the bottom of the hearth of blast-furnaces. The objections to the use of most of these materials are their liability to crack when heated, and the difficulty of working them into the required shapes. When used they should be built in in the same position as that in which they occur, *i.e.* with the lines of bedding horizontal.

Clay.—Clay has now become the almost universal material for furnace and other building, mainly on account of the ease with which it can be moulded into forms convenient for use.

Clay is a hydrated silicate of alumina, and in its purest form constitutes the kaolin or white china clay used in the manufacture of pottery. This material is perfectly white, has a soapy feel, adheres slightly to the tongue, has the characteristic clay odour, and is infusible at ordinary furnace temperatures. Its composition is about—Alumina, 39·7 per cent; silica, 46·4 per cent; water, 13·9 per cent; which corresponds to the formula, $Al_2 Si_2 O_7, 2 H_2 O$, or $Al_2 O_3, 2 Si O_2, 2 H_2 O$.

Clay appears quite dry, the water present being in combination, but if more water be added it becomes plastic, and can be moulded into any required form. On drying it loses the additional hygroscopic water and with it its plasticity, but can be made plastic again by the addition of water. If, however, it be heated to redness, the water of constitution is expelled, and a hard mass (or biscuit) is left, which, though very porous and capable of absorbing a considerable quantity of water, cannot be made plastic again.

Origin of Clay.—Clay is formed by the atmospheric decomposition of various rocks, but no doubt chiefly felspar. Common felspar (orthoclase) has the composition $K_2 O Al_2 O_3, 6 Si O_2$. When this is subjected for a long time to the action of air, moisture, and carbonic acid, it is broken down into a soft mass of china clay, all the potash and two-thirds of the silica being removed in solution, and water being taken up.

If the rock were a pure felspar, a pure kaolin would result, but pure felspars do not often occur; and if the rock contained other materials which resisted decomposition more strongly, these would remain with the kaolin. If, for instance, the rock were a granite, both silica and mica would remain mixed with the clay.

Clays found in the position of the rocks from which they are formed, such as these pure kaolins, are comparatively rare. The light material produced by the decomposition of the rock is washed down into the sea, carried out by currents, and ultimately deposited somewhere on the ocean bed, necessarily becoming more or less mixed with impurities in the process, and producing therefore different varieties of clay.

Clays belong to all geological periods. Some of the more recent ones are soft and plastic; those of greater age have usually lost their hygroscopic water, and therefore appear solid and dry, but can be made plastic by the addition of more water; whilst others, older still, have been subjected to the action of great pressure and perhaps heat, and have passed into the condition of hard clay-slate, have lost their water of combination, and therefore the power of becoming plastic.

Nearly all the clays that are used for metallurgical purposes occur in the coal-measures, where they often underlie the coal. This, not because equally good clays do not occur in other places, but because it is in the neighbourhood of the coal-fields that metallurgical industries are usually carried on, and therefore that the clays are required.

Carboniferous clays are usually dark-coloured, often black, from the presence of organic matter. They have a talcky lustre and a soapy feel, adhere strongly to the tongue, have a hardness of about 1·5, and therefore can be scratched readily with the nail. They can be easily powdered, and on mixing with water yield a stiff plastic mass. This power of becoming plastic with water is the characteristic of a clay. When these clays are fired they become white, the organic matter being completely burned away.

Fire-clays.—Pure kaolin is very difficultly fusible, the silica and alumina being present almost exactly in proportions which give great infusibility, but the presence of impurities, even in very small quantities, may increase the fusibility very much. Those clays which are free from such impurities, and therefore can be used for making fire-bricks or other articles which have to stand a high temperature, are called fire-clays.

Almost all fire-clays contain more silica than pure kaolin, and therefore may be considered as siliceous or acid clays. Stourbridge clay, for instance, contains about 63 per cent of silica. As a typical analysis of Stourbridge clay the following figures may be taken:—

Silica, ...	63·30
Alumina, ...	23·30
Lime, ...	·73
Ferrous oxide, ...	1·80
Moisture and organic matter, ...	10·30
	99·43

Calculating out the percentage of pure clay from these figures the analysis would become—

Clay, Al_2O_3, $2SiO_2$, $2H_2O$, ...	58·90
Silica in excess of that in clay, ...	36·10
Impurities, ...	2·53
Water in excess of that in the clay and organic matter, ...	1·90
	99·43

Excess of silica in a fire-clay is not very objectionable in most cases, though it decreases the refractoriness of the clay, the most fusible mixture containing the oxides in the proportion $1\ Al_2O_3 : 17\ SiO_2$ to about 86·2 % of SiO_2, but it should not be present in such a large quantity as to impair the plasticity.

Examples of Fire-clays.—The analyses on p. 313 will serve to illustrate the composition of fire-clays.

Impurities in Fire-clay.—There are several impurities almost always present, as will be seen from the analyses, and some of these have a deleterious effect on the refractoriness of the clay.

Alkalies.—These are always present, though sometimes they are not determined and therefore are not shown in the analyses; but as a rule an analysis of a clay that does not give the alkalies is worse than useless. Snelus[1] states that 1 per cent of

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[1] *J. I. and S. I.*, 1875, ii. p. 513.

	1.	2.	3.	4.	5.	6.	7.	8.
Silica,	55·61	56·42	58·00	62·35	44·37	65·10	48·04	48·99
Alumina,	27·50	26·35	30·85	18·47	38·59	22·22	34·47	32·11
Oxide of iron,	1·91	1·33	1·55	4·77	1·82	1·92	3·05	2·34
Lime,	·32	·60	·80	trace	·51	·14	·66	·43
Magnesia,	·79	·55	—	1·36	·30	·18	·45	·22
Potash,	·81	·48	—	2·47	—	·18	1·94	3·31
Soda,	—	—	—	—	—	—	—	—
Titanic acid,	·33	1·15	—	1·10	—	—	—	—
Organic matter or loss in calcinate,	3·34	—	9·70	5·22	11·78	·58	11·15	9·63
Combined water,	9·96	10·95				7·10		
Moisture,	2·12	2·80		4·15	2·69	2·18		2·33
	99·69	100·63		99·89	99·99			

1, Etherley (Riley). 2, Glenboig (Riley). 3, French Normandy, best (Greiner). 4, Derbyshire (Riley). 5, Garnkirk (Wallace). 6, Stourbridge, used for glass pots (Percy). 7, Stannington (Percy). 8, Poole, used for Cornish crucibles (Percy).

alkalies renders a clay too fusible to be used for purposes where high temperatures are required. There is, however, no doubt that many fire-clays in actual use contain more than this, and sometimes considerably so.

Lime and Magnesia.—These also have a fluxing effect, and should not be present in large quantity; it is, however, impossible to fix an actual limit.

Oxide of Iron.—The behaviour of oxide of iron is somewhat peculiar. Undoubtedly the less oxide of iron present the better, since it can do no good. It will be seen that some of the clays given in the table contain a very considerable quantity of oxide of iron. Snelus says that it may be present up to 2 or 3 per cent without affecting the fusibility of the bricks in a very serious degree, provided that only a small amount of alkalies is present.

The differences in the statements that have been made as to the effect of iron on the refractoriness of fire-clays have probably arisen from the fact, that it varies with the form in which the iron is present and the conditions under which the brick is to be used. If the iron be diffused through the clay in the form of oxide, it will impart a reddish colour to the brick when it is burned. Such a brick, provided the amount of iron be not too large, may be very refractory if heated in an oxidizing atmosphere, because ferric oxide ($Fe_2 O_3$) and silica do not combine, but if it be heated in a reducing atmosphere the ferric oxide will be reduced to ferrous oxide, which will combine with the silica and form fusible ferrous silicate, thus destroying the brick. Such a brick therefore would be quite useless for lining a blast-furnace, but might stand well in a reverberatory roasting furnace. The iron may, however, be present in the form of minute specks of pyrites scattered through the clay; its action will then be different, and either more or less injurious according to the purpose for which the brick is to be used. When the brick is fired the sulphur of the pyrites burns out thus, $Fe S_2 + 5 O = Fe O + 2 S O_2$, the ferrous oxide at once combines with some of the silica, forming ferrous silicate, which being liquid is at once absorbed by the brick; thus, where the speck of pyrites was a small hole is left, surrounded by a black stain of ferrous silicate. The ferrous silicate present in this form does not seem to seriously impair the fire-resisting power of the brick.

Alumina.—If in large quantity this gives the clay great plasticity, and a soapy feel, and makes it shrink very much on drying and firing, but such bricks afterwards undergo little change by heating or cooling. Alumina itself is very highly refractory.

Titanic Oxide, $Ti O_2$, is very frequently present in clay, but does not seem to have any injurious effect.

Combined Effect of Impurities.—Bischof measures the refractoriness of a clay by what he calls the refractory quotient, which he obtains by dividing the quotient of the oxygen of the fluxes into that of the alumina by the quotient of the oxygen of the alumina into that of the silica, *i.e.*

$$\frac{\text{O in } Al_2 O_3}{\text{O in } R\ O} \div \frac{\text{O in } Si\ O_2}{\text{O in } Al_2 O_3}.$$

In Bischof's standard fire-clays the coefficient is 13·95 in the most refractory and 1·64 in the least refractory.[1] The amount of fluxing impurities, *i.e.* RO oxides, must not exceed 6%.

Ganister.—With the introduction of the Bessemer process it became necessary to find a very refractory substance with which to line converters, and ganister was the material selected, and it is still very largely used. The ganister is an argillaceous sandstone occurring in the carboniferous series of various parts of the country, the best known being that which occurs near Sheffield, and is known as Lowood's Sheffield ganister. The following analyses will show its nature:—

	1.	2.	3.	4.	5.
Silica,	98·94	89·37	88·36	97·78	89·04
Alumina,	·57	6·36	7·00	·20	5·44
Oxide of iron,	·67	1·73	2·00	·21	2·65
Lime,	·62	·70	·22	·38	·31
Magnesia,	·21	·36	·15	·44	·17
Alkalies,	—	—	—	·26	—
Water, or loss on calcination,	·42	2·88	2·32	·73	2·30
	101·143	101·40	100·05	100·00	99·91

1, Hard (Riley). 2, Soft (Riley). 3, Lowood (Snelus). 4, Scotch, Bonnymuir. 5, Lowood.

The nature of such a material is easily seen. Assuming the formula for clay already given, analysis 5 works out—

Silica (in excess of that in clay), ...	81·28
Clay, ...	15·30
Impurities, ...	3·13
Moisture, &c., ...	·20
	99·91

It is therefore a siliceous material with just enough clay to make it bind, and when fired it yields a strong brick. Ganister bricks, owing to their very refractory nature and their much greater strength than silica bricks, are very largely used.

Ganister is properly the name of a special rock, but any similar material is called by the same name, and some ganister bricks are made of a mixture of a more siliceous material and clay.

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[1] See Hofman and Demond, "Refractoriness of Fire-clays", *J.A.I.M.E.*, xxiv.

Siliceous Materials.—Materials containing more silica are used for the manufacture of silica bricks and other purposes. When used for brick-making, they must be mixed with some binding material, as they have no cohesive power of themselves. Among the materials used may be mentioned Dinas rock, calcined flints, white sand, &c. White sand is used for the final layer in lining the Siemens steel furnaces, and less refractory sands containing iron are used for the under layers.

Siliceous Refractory Materials.

	1.	2.	3.	4.
Silica,	98·31	96·73	93·13	96·7
Alumina,	·72	1·39	4·30	1·3
Oxide of iron,	·18	·48	·29	
Lime,	·22	·19	—	
Alkalies,	·14	·20	·74	
Water,	·35	·50	1·55	2·0

1 and 2, Dinas rock (W. Weston). 3, Sand for Siemens furnaces. 4. White sand.

Neutral Refractory Materials.

Graphite.—Graphite is almost pure carbon; it is one of the few substances that have never been fused. It is black in colour with a metallic lustre; its hardness is about 1, it marks paper readily, and burns at a high temperature leaving a residue of ash. It is not plastic, and the powder does not adhere even on strong firing, so that if it is to be used for making crucibles, it must be mixed with clay or similar materials. Being quite neutral, it is sometimes used as a separating layer between the acid and basic portions of basic open-hearth furnaces.

Analysis of Graphites.

	1.	2.	3.	4.	5.
Volatile matter,	1·10	1·82	5·10	·158	·7
Carbon,	91·55	78·48	79·40	99·792	66·4
Ash,	7·35	19·70	15·50	·050	32·9
Specific gravity,	2·3455	2·2863	2·3501	2·2671	

1, Cumberland; 2, Canada; 3, Ceylon (these are by Mené, quoted from Percy). 4, Ceylon (Ferguson). 5, Austrian.

Carbon in the form of gas-retort carbon is sometimes used for crucibles, &c.

Chromite.—This material, which is a double oxide of iron and chromium, having the formula Cr_2O_3FeO, has often been suggested as a neutral lining for steel and other furnaces where the lining is required to stand a very high temperature. Norwegian chromite, which has been principally used, occurs with a gangue of serpentine, and this mixture is excessively infusible. The chrome ore has also been made into bricks by crushing, mixing with lime, and firing. The following analyses are of good chromite. There should be more than 40% of chromic oxide, and less than 6% of silica. Chromite is not acted on by siliceous fluxes.

	1.	2.
Chromic oxide,	51·23	62·20
Ferrous oxide,	36·63	28·10
Alumina,	3·17	2·60
Magnesia,	3·79	1·10
Lime,	5·10	3·07
Silica,	1·87	2·60

Basic Materials.—The introduction of the basic Bessemer and basic open-hearth steel processes led to a demand for basic materials, which could be used for lining furnaces or for making into bricks, and several such substances are now in use.

Lime.—Lime (CaO) is an extremely refractory substance, never having been fused or even softened, and, of course, it is basic; but there have been difficulties in using it which have prevented it coming largely into use, though it was the first material to be suggested for lining basic converters. The objections to it are that it is extremely difficult to get it to bind, a small quantity of silica not having the same fritting effect with it that it has with some other basic materials. It is used to some extent for lining basic converters, as, though inferior to dolomite for the purpose, it is much cheaper.

Magnesian Limestone.—The suitability of this material for lining basic Bessemer converters was discovered by Messrs. Thomas and Gilchrist, and at once made the process now known by their names a success. The material occurs in the trias beds of the north of England, and is usually, though improperly, called dolomite. Dolomite is a definite mineral, $CaCO_3$, $MgCO_3$, containing the carbonates of lime and magnesia in nearly equivalent proportions. The magnesian limestone is of uncertain composition, containing varying proportions of the two carbonates with a small and varying quantity of silica, which is essential to it for this purpose.

The following analyses of dolomite used for basic linings will be sufficient to indicate its character:—

	1.	2.	3.	4.	5.
Lime,	31·62	29·86	28·3	28·0	28·0
Magnesia,	20·19	20·17	18·6	17·0	17·0
Silica,	1·70	4·34	4·10	3·80	2·08
Alumina,	·09	—	3·00	4·00	2·57
Oxide of iron,	1·22	—	1·70		
Carbon dioxide,	45·35	45·64	44·2	45·00	45·00
Water,	—	—			

1 and 2, Wedding, localities not given. 3, Vairgey, France. 4, Bessèges, France. 5, Hörde, Germany. 3, 4, and 5, by Zyromski.

The more magnesia a dolomite contains the better. Zyromski believes that, other things being equal, the best dolomite for open-hearth furnaces should contain over 20% of magnesia. Such a dolomite agglomerates well, hardens rapidly, and is still very refractory. The calcination is more complete and easier, the nearer a total of 4% is reached for ferric oxide and alumina.

Magnesite.—This is probably the most valuable of all the basic materials. When calcined at a very high temperature it loses carbon dioxide, and the residue left is absolutely infusible at furnace temperatures; it is usually dark brown from the presence of oxide of iron; it agglomerates very little, far less than dolomite, and though necessarily very basic, it does not combine with silica when the two are heated in contact, so that when it is used in a steel furnace, the basic lining and acid walls may come in contact without danger. The only objection to magnesite is its expense, there being but few localities where it occurs. The best known, and probably the best for Bessemer converters, is the Styrian (especially that of Veitsch), which is sold by Messrs. C. Spaeter & Co., Coblenz. Furnaces lined with this material are far more durable than those lined with dolomite.

The following analyses will show the nature of the material:—

	1.	2.	3.
Lime, ...	1·50	1·68	1·72
Magnesia, ...	47·00	42·43	44·06
Silica, ...	·50	·92	1·93
Iron oxide	—	4·30	3·56
Alumina, ...	—		·31
Carbon dioxide, ...	51	50·41	48·02
Water, ...			

1, Eubœa, Greece. 2, Mittendorf, Styria. (1 and 2, by Zyromski.)
3, Veitsch, Styria.

Bauxite.—This abundant mineral is a hydrated double oxide of iron and alumina in very varying proportions—$x\,Al_2O_3$, $y\,Fe_2O_3$, $3\,H_2O$, the quantity of iron being small in bauxite, but increasing as the mineral passes gradually into aluminous iron ore, in which the iron is present in large quantity. It is usually yellow in colour, owing to the presence of oxide of iron, though pure white varieties occur which are almost free from iron. Bauxite for brick-making should contain but little iron or silica. A sample said to be suitable for brick-making contained—Alumina, 90 per cent; titanic acid, 5 per cent; silica, 2 per cent; oxide of iron, 1 per cent; lime, 1·5 to 2 per cent.

Other Refractory Materials.

Bull-dog.—This is a mixture of ferric oxide and silica made by roasting tap cinder with free access of air. Tap cinder is a basic silicate of iron—2 Fe O, Si O_2, or thereabouts—and on roasting it takes up oxygen, and gives a mixture of ferric oxide and silica. As these do not unite, the substance is infusible in an oxidizing atmosphere, but fuses in a reducing atmosphere, ferrous silicate being re-formed.

Iron Ores.—Some of these, especially hæmatite ($Fe_2 O_3$), magnetite ($Fe_3 O_4$), burnt ore and Blue Billy (artificial $Fe_2 O_3$), are occasionally used for furnace linings.

Fire-bricks.—These are bricks used for furnace construction or other purposes where a high temperature is required. They may be made of any of the refractory materials described.

The qualities required in good fire-bricks are as follows:—

"They should not melt or soften in a sensible degree by exposure to intense heat long and uninterruptedly continued.

"They should resist sudden and great extremes of temperature.

"They should support considerable pressure at high temperatures without crumbling.

"They may be required to withstand as far as practicable the corrosive action of slags rich in protoxide of iron or other metallic oxides."[1]

These qualities are not all shown in the highest degree by any one brick. In selecting a brick, therefore, attention must always be given to the conditions in which it will be placed, for one which would be good under one set of conditions may prove very bad under another.

Fire-clay Bricks.—These are the most generally used of all the refractory bricks. They are refractory enough for most purposes, and the plasticity of the clay allows of their being easily made of any required form or size.

Fire-bricks should be nearly white in colour, any tinge of red indicating an excess of iron; and should be as free as possible from small holes surrounded by black spots, though for most purposes these do not seem to be very injurious.

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[1] Percy, *Fuel*, p. 144.

Fire-clay bricks shrink very much on drying and firing. At St. Helen's, "for a 9 × 4½ × 2½-inch brick the mould is 9⅝ × 4⅞ × 3⅛ inches. For Glenboig clay a shrinkage of $\frac{1}{12}$ is allowed; that is, the mould for a 9-inch brick is made 9¾ inches long".[1]

Each clay has its own rate of contraction, which can only be learned by experience. Though clay bricks shrink so much in the firing, once finished they alter very little with changes of temperature. The more aluminous bricks seem to expand and contract less than the more siliceous, and therefore such bricks as Glenboig bricks are largely used for regenerators and other positions where change of form would lead to inconvenience.

Manufacture of Fire-clay Bricks.—The methods for the manufacture of fire-bricks are the same in principle, but differ in detail in different works.

The following is an outline of the process as conducted in a large Scotch fire-brick works:—

The clay as raised from the mine is perfectly dry, and is at once put into a mill, where it is ground to a coarse powder. It then passes through a sieve, any not sufficiently finely ground being returned to the mill. After this dry grinding, the powder is transferred to a pug-mill, and is thoroughly incorporated with the necessary amount of water to give it the required consistency. If large slabs are to be made, some ground burned clay is added, but this is not necessary for ordinary-sized bricks. The paste is raised by an elevator to a higher floor, where it is distributed by barrows to shoots, by which it passes down to the work benches. On each bench is fixed a plate to form the bottom of the brick mould. This is covered with felt, through which projects the brass die to form the name or other mark on the brick. On this plate is placed a rectangular bronze mould, the size required for the bricks being made. The workman cuts a piece of the stiff clay off the mass descending on to the bench from the shoot above, puts it into the mould, presses it firmly down, cuts off

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[1] Searle.

excess of clay from the top by means of a smoothing-board, and the boy in attendance at once carries the brick away, and sets it on edge on the drying-floor. A workman and boy can make about 2000 bricks a day by this process.

The drying-floor is of iron, heated by fireplaces and circulating flues, the floor immediately over the fires being protected by means of a curtain arch. The drying takes 24 hours, and the bricks are then ready for firing.

Many attempts have been made to introduce machinery for fire-brick making, but up to the present without great success.

The bricks are, after drying, fired in kilns. The ordinary kiln consists of a large chamber capable of holding 25,000 bricks, provided with a series of deep fireplaces, so deep as to be almost called gas-producers, on each side. The bricks are stacked in the kilns, the fires lighted, ample air being admitted to ensure the combustion of the products of distillation, and the products of combustion circulate through the loosely-stacked bricks on their way to the chimney. Such a kiln will take about ten days to work a heat—three days heating up, three days firing, and four days cooling.

At the Glenboig works Mr. Dunnachie's regenerative gas-kiln is used with great success. These kilns are built in sets of ten, in two rows of five each. The gas is supplied by Wilson producers, and is so arranged that it can be sent through the chambers in any order. The gas enters the kiln by a flue running along the bottom on one side, the hot air is supplied just above it, and combustion takes place. The products of combustion sweep across the kiln through the bricks stacked in it, and leave at the other side. When at work there will be two kilns cooling off, the air passing through these on its way to the kiln where burning is going on, and being heated on the way by the hot bricks; the hot products of combustion pass through two or three more kilns which are filled with unburned bricks, and which are therefore being heated up, and other kilns are being charged and discharged. As soon as the burning is complete the valves are adjusted, so that the second of the two cooling-off ovens is ready for discharging, the finished oven begins to cool off, and the oven which was being charged last begins to dry. In the illustration, Nos. 10 and 1 are cooling off; 2 is burning; 3, 4, 5, and 6 are in different stages of heating up and drying; 7, 8, 9 are being charged or emptied.

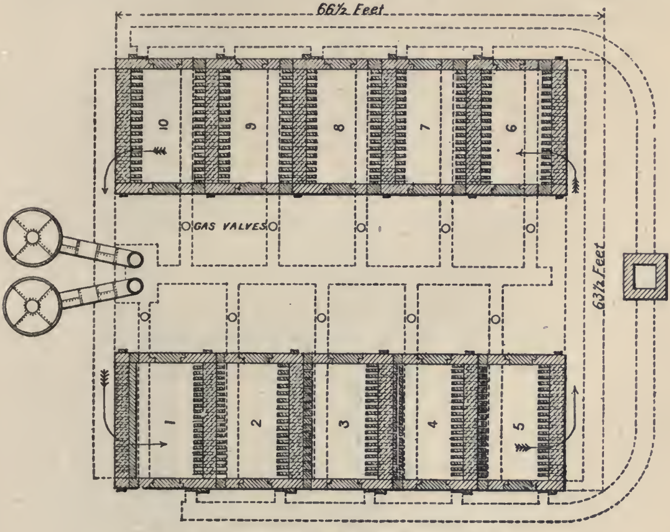

Fig. 100.—Dunnachie's Patent Regenerative Gas-kiln.

This kiln is worked continuously, and is found to be very convenient and economical.

Ganister Bricks.—These are made in much the same way, but are very tender before firing, and therefore require careful handling. The clay present in the ganister is enough to act as a binding material.

Silica Bricks.—Since silica has no binding power, it is necessary to add some material which will bind the silica together. A small quantity of clay has been used, but the usual agent is lime, a small quantity (about 1 per cent) of which is mixed with the material; on firing, this attacks the silica, forming a frit which binds the brick together. Silica bricks are weak and friable, but are capable of withstanding very high temperatures. Silica bricks expand on burning, so that the moulds have to be made a little smaller than the required brick. Silica bricks also expand and contract very much when subject to heat, and when steel-furnace roofs are built of them, care has to be taken to loosen the tie-rods of the furnace to allow for the expansion.

Manufacture of Silica Bricks.—The manufacture of Dinas bricks is described by Dr. Percy.[1] "The rock when not too hard is crushed to coarse powder between iron rolls. By exposure to the air the hard rock becomes somewhat softer, but some of it is so hard that it cannot be profitably employed." "The powder of the rock is mixed with about 1 per cent of lime and sufficient water to make it cohere slightly by pressure. This mixture is pressed into iron moulds, of which two are fixed under one press side by side. The mould, which is open top and bottom like ordinary brick moulds, is closed below by a movable iron plate, and above by another plate of iron which fits like a piston, and is connected with a lever. The machine being adjusted, the coarse mixture is put into the moulds by workmen whose hands are protected by stout gloves, as the sharp edges of the fragments would otherwise wound them; the piston is then pressed down, after which the bottom plate of iron on which the brick is formed is lowered and taken away with the brick upon it, as it is not sufficiently solid to admit of being carried in the usual manner. The bricks are dried on these plates upon floors warmed by flues passing underneath, and when dry they are piled in a circular closed kiln covered with a dome similar to kilns in which common fire-bricks are burned. About seven days' hard firing are required for these bricks, and about the same time for cooling the kiln. One kiln contains 32,000 bricks, and consumes 40 tons of coal, half free-burning half binding."

Silica bricks may be made by exactly similar methods from any siliceous material, ground flints, sand, and other similar materials being frequently used.

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[1] *Fuel,* p. 147.

Basic Bricks.—For lining basic Bessemer converters and other purposes dolomite bricks are made. The dolomite is calcined so as to expel all carbon dioxide, a much higher temperature being required than for calcining limestone. The more magnesia present the higher the temperature required, but the less the substance deteriorates on exposure to the air. The calcined material is ground mixed to a stiff paste with hot anhydrous tar, and the mixture is moulded into bricks under hydraulic pressure in iron moulds; the bricks are then carefully dried and fired at a high temperature. The brick press shown has three moulds on a rotating table, and when one mould is under the pressing ram, another is being filled, and the brick is being removed from the third.

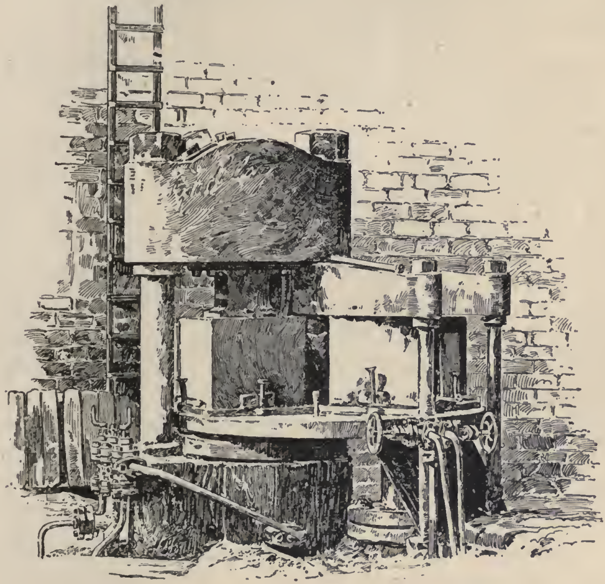

Fig. 101.—Basic Brick Press.

Magnesite is more difficult to calcine than dolomite, and must be calcined at an intense white heat. It is then ground, made into bricks in the usual way, dried, and fired at a very high temperature, the iron oxide present acting as a frit. These bricks are dark chocolate in colour, are strong, and have a very high specific gravity. Burned magnesite may be exposed to the air without fear of its absorbing water or carbon dioxide. Bauxite bricks are made by mixing the calcined mineral with enough clay to make it bind. These bricks are dense, but are usually friable.

Furnace Linings.—Some refractory materials are used for the linings of converters or furnaces directly without being made into bricks.

Ganister is used for lining converters for the ordinary or acid Bessemer process. The ground material is mixed to a paste with water, and is applied to the interior in several ways. The usual way, probably, is to put inside the converter a core of the shape it is intended to make the inside, and then to ram the ganister between this and the shell. Another method is to apply the well-worked ganister by hand, pressing it firmly against the inside of the shell, and when all is in, carefully smoothing the interior surface.

Dolomite is used for lining converters for the basic Bessemer process. When not used in the form of bricks, the hot mixture of dolomite and tar is rammed into place round a core by means of a hot-iron rammer.

For the hearth of basic open-hearth furnaces, the magnesian lime is spread in thin layers, each of which is fritted by the heat of the fire before another is put in. Magnesite is used similarly.

Sand.—This is used for making the hearths of Siemens furnaces. Several qualities are used, and they are spread in thin layers, the least refractory first, the most refractory last, each layer being fritted before another is applied. Bull-dog, iron-ore slag, and other materials used for furnace lining are similarly applied.

Mortars, &c.—In setting bricks of any kind that are to be exposed to a high temperature, care must be taken to use a mortar which has no action on them. Acid bricks must be set with an acid mortar, and basic bricks with a basic one. Fire-bricks are usually set in fire-clay, dolomite bricks in a dolomite tar mortar, and others in a material as nearly as possible the same composition as the bricks themselves.

Casting Sands.—These sands, used for making moulds for casting purposes, are not very refractory, as they must contain enough alumina to make them bind. The following examples are from Percy:[1]—

	1.	2.	3.	4.	5.
Silica, ...	79·02	92·083	91·907	92·913	87·87
Alumina, ...	13·72	5·415	5·683	5·850	2·13
Oxide of iron, ...	2·40	2·498	2·177	1·249	2·72
Magnesia, ...	·71	—	—	—	·21
Lime, ...	—	trace	·415	trace	3·79
Alkalies, ...	4·53	—	—	—	—
Carbonic acid and water,	—	—	—	—	2·60
	100·43	99·960	100·182	100·012	99·32

1, Ibsenberg. 2, Charlottenberg Foundry. 3, Used in Paris for bronzes. 4, Sand from Manchester. 5, Sand used for bed of copper furnace (Weston).

"According to Kaufman a good sand for moulds may be artificially made from the following mixture:—

Fine quartzose sand, ...	93
Red English ochre, ...	2
Aluminous earth, as little calcareous as possible, ...	5
	100"[2]

Crucibles.—Crucibles are open-topped vessels in which materials may be heated in furnaces, and of such a size that they can be lifted by means of tongs.

The qualities required in good crucibles may be thus enumerated:—

"1. They should resist a high temperature without melting or softening in a sensible degree, and should not be so tender while hot as to be liable to crumble or break when grasped with the tongs.

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[1] Percy, *Fuel*, p. 151.

[2] *Fuel*, p. 152.

"2. In some cases they should resist sudden and great changes of temperature, so that they may be plunged while cold into a nearly white-hot furnace without cracking; while in other cases it is only necessary that they should resist a high temperature after having been gradually heated.

"They may occasionally be required to withstand the corrosive action and permeation by such matters as molten oxide of lead.

"In special cases the material of which they are composed must not contain any ingredient that would act chemically upon the substances heated in them. Thus carbonaceous matter should not be one of their constituents when they are used in the heating of such oxidized matters as carbon would reduce, and reduction is not desired, or in the fusion of steel, when it is necessary that the proportion of carbon should not be increased."[1]

Clay Crucibles.—Various forms of crucibles are in use. At one time each form of crucible was made in some special locality, and of some special mixture of clays. That, however, is no longer the case. Crucibles of good quality can be obtained of any required forms.

Among the best-known forms of crucibles may be mentioned the following, made by the Morgan Crucible Company, Battersea:—

Cornish Crucibles.—These crucibles were made by Messrs. Juleff of Redruth for copper assaying, and acquired a great reputation, and they are now made from Juleff's formula by the Morgan Crucible Company. They are round, and of two sizes, the larger 3 inches in diameter at the top, and 3½ inches high, the smaller fitting into this.

They are nearly white in colour, spotted with brown spots. They are not very refractory, but Percy states that they can be plunged into a white-hot furnace without cracking, and will therefore stand sudden and violent alternations of temperature.

Percy gives the following as an analysis of a good batch of these crucibles:—

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[1] Percy, *Fuel*, p. 110.

Silica,	72·39
Alumina,	25·32
Sesquioxide of iron,	1·07
Lime,	·38
Potash,	1·14
	100·30

For more refractory crucibles of small size a little china clay is added to the mixture.

London Crucibles.—This is a deeper form of crucible than the Cornish. The original London crucibles are stated by Percy to be very liable to crack.

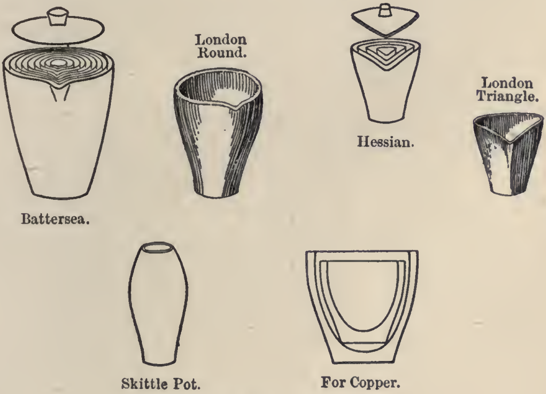

Fig. 102.—Forms of Crucibles.

Battersea-round.—These crucibles are very excellent for all ordinary laboratory purposes. They stand all assay furnace temperatures quite well, and are not liable to crack.

Hessian Crucibles.—These crucibles at one time had a high reputation, but are little used now. The name is retained to indicate crucibles which have a triangular top, quite irrespective of the materials of which they are made.

Among other types of small crucibles may be mentioned German assay crucibles, skittle-pots, gold annealing pots, &c.

Selection of Materials for Crucible-making.—The clay for making crucibles, whether large or small, must be very carefully selected. It must be very plastic so as to allow of ready moulding into the required form, and it is said to be best after weathering. It must be infusible, and must not contain iron pyrites, or the holes left by its decomposition may form channels through which the contents of the crucible might escape. Clay contracts so much on drying and firing that a crucible made of raw clay only would lose its shape. To overcome this defect the clay is always mixed with some non-contracting and infusible material, such as burned clay, silica, or graphite. Burned clay is the material generally used; but care must be taken not to add so much as to reduce the plasticity of the clay. The material must not be too finely powdered, as the more finely divided it is the more likely it is to fuse. Berthier states that if silica be used it may at a high temperature combine with the clay, forming a pasty mass.

Manufacture of Crucibles.—Crucibles are articles of pottery, and therefore they may be made by the usual methods for the manufacture of such ware. The methods of making Stourbridge-clay crucibles is thus described by Percy:[1]—"The workman sits before a bench, on which is a wooden block, of the shape of the cavity of the crucible. At the widest end of the block is a flange or projecting border, equal in width to the thickness of the crucible at the mouth, measured in the wet state. At the middle of the same end an iron spindle is inserted, which fits into a socket on the bench. The block may thus be made to revolve. It is not fixed, but may be taken out or dropped into the socket at pleasure. On the narrow or upper end of the block is placed a lump of tempered clay, which the workman then moulds round the block by first striking it with a flat piece of wood, and then slapping it with both hands so as to turn the block more or less each time as occasion may require. The clay is thus rapidly extended over the whole block down to the flange. A sliding vertical gauge is fixed in the bench, by means of which the thickness of the

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[1] *Fuel*, p. 116.

sides and bottom of the crucible may be regulated. As soon as the moulding is finished the block is lifted out of its socket and inverted, when the crucible, with a little easing, will gently drop off. The spout for pouring out metal is then fashioned with the finger. The clay may likewise be moulded upon a linen cap, wetted and slipped over the block, so that on inverting the block the crucible and cap slide off together, after which the cap may be pulled out when the crucible is dry." After this they are very carefully dried and fired.

Manufacture of Crucibles for Steel-melting.—The materials (each maker having his own mixture of clays) are thoroughly mixed with water, and tempered by mixing in a mill or by treading with bare feet for several hours, cutting and turning at intervals with the spade. The mass is then cut up into balls, each containing about enough for one crucible. The ball is placed in a "flask", the interior of which is the form of the outside of the crucible. A plug having the form of the interior of the crucible, with a spike which fits into a hole in the base-plate, is pressed down, then forced down by being lifted and let fall, and finally driven home by a hammer. The clay rises up in the space between the flask and the core. That which projects above is cut off neatly, the crucible is forced out of the flask and put to dry, after which it is used without firing, being placed on a brick sprinkled with sand, to which it adheres as soon as its temperature is high enough, and thus prevents any escape of metal.

Machines are now sometimes used. In these the core is forced down by machinery, and the centring-pin is dispensed with.

Small Crucibles for Laboratory Use.—These are made in a small brass flask by means of a wooden core. The brass flask A (Fig. 103) is fitted into a wooden base C, in the centre of which is a small hole, into which the centring-pin G of the core fits. A quantity of a well-kneaded mixture of clay and burned clay, enough to make a crucible, is put into the mould, the core F is pressed down, a rotary motion being given it, so as to force up the clay between it and the flask, till the neck of the core comes down on to the top of the flask, any excess of clay being forced out of an opening left in the head of the core. The core is then removed, a small piece of clay dropped in to stop the hole in the bottom, and the interior is smoothed off by means of an exactly similar core, without the pin. The crucible is then removed by lifting the flask from the stand, and applying slight pressure below. In order to prevent sticking, it is well to oil the flask and the cores.

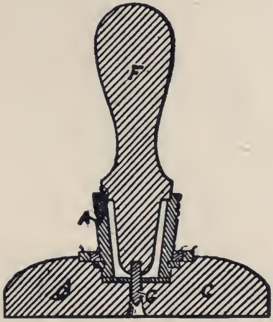

Fig. 103.—Laboratory Crucible-making Apparatus.

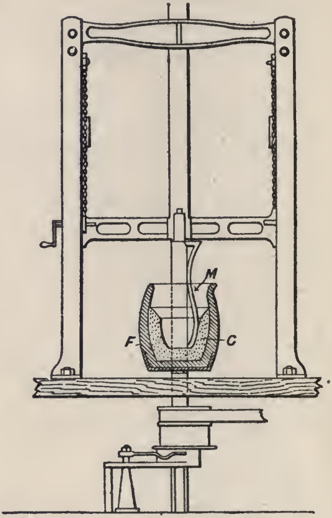

Fig. 104.—Apparatus for making Black-lead Crucibles.

Plumbago or Black-lead Crucibles.—These crucibles are made of a mixture of fire-clay and graphite, the graphite preventing shrinking, and at the same time adding very much to the refractoriness of the pot. Black-lead pots are very much more durable than fire-clay crucibles, and can be used several times, whilst clay crucibles can usually only be used once. They are also much less likely to crack in the furnace.

Manufacture of Plumbago Crucibles at Messrs. Morgan's.—A weighed portion of the mixture of clay and graphite in the plastic condition is introduced into an iron flask F (Fig. 104), which is so fixed that it can be rotated by machinery. A forming-tool or template of iron M, having the form of the interior of the crucible, is lowered into the flask till it just touches the ball of graphite and clay C, and the flask is rotated, the "former" being gradually lowered till the crucible is complete. Any excess of material is then cut off, the crucible is lifted out, the spout formed with the finger, and the mould, with the crucible in it, is set aside to dry. In drying, the crucible contracts and separates from the mould. When dry enough it is fired.

A crucible examined by Dr. Percy was found to contain 48·34 per cent of carbon.

Manufacture of Black-lead Crucibles in America.[1]—The mixtures used consist of about 50 per cent graphite, 45 per cent air-dried clay, and 5 per cent sand, and lose on burning from 5 to 10 per cent. Ceylon graphite is generally used. This is very pure, containing not more than 5 per cent of ash. The graphite is crushed in mills, pulverized between millstones, and passed through a 40 sieve.

"If the graphite be too coarse, the crucible is apt to become porous, and to be weakened by cleavage planes; if too fine, the crucible is too dense, and is apt to crack under the extreme changes of temperature to which it is exposed, and conducts heat slowly." The clay used is German. "It is at once very fat, refractory, and wholly free from grit."

The sand should be rather coarse, passing a screen of about 40 meshes to the inch. Burnt fire-clay has been found as good, but not better.

The clay is made into a thin paste with water, the sifted sand and graphite are stirred in with a shovel, and the mass is mixed by means of a pug-mill. It is tempered by a few days' repose in a damp place, covered with cloths which are moistened occasionally.

A weighed lump of the mass is slapped and kneaded, and put into the bottom of a thick plaster-of-Paris mould, the interior of which has the form of the exterior of the crucible, and centred on a potter's wheel. While it revolves, a cast-

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[1] Abridged from account by Howe in *The Metallurgy of Steel*, p. 299.

iron or steel profile of the interior of the crucible is lowered into the mass. The clayey mass is pressed against the sides of the mould, and raised gradually to its top, jointly by the revolution and by the moulder's hand. Any excess which comes above the top is cut off, and the lip is cut out. The crucible is left in the mould about three hours, the plaster absorbing its moisture, and thus stiffening it so that it can be handled. It is then air-dried for about a week in a warm room, and is fired. The firing takes a week; one day is occupied in charging, three in firing, and two in cooling down.

Firing Crucibles.—Crucibles, like all articles of pottery to be fired, are placed in earthen vessels or seggars, which are placed one above the other in the kiln. In the case of plumbago crucibles it is important to keep out air, so as to prevent oxidation of the graphite. For this purpose one seggar is often inverted over the other, some coke placed inside, and the joint luted with clay. The graphite should never be burned away more than just at the surface.

Using Black-lead Crucibles.—Black-lead crucibles require careful annealing before use. The fire should be allowed to burn down, and some cold coke put on, the crucible put on this mouth downwards, covered with coke, and the fire allowed to burn up slowly till the crucible is well red-hot. The carbon will be burned away from the surface of the crucible, leaving it gray or white.

Salamander Crucibles.—To avoid the necessity for annealing, the Morgan Crucible Company make crucibles known as the Salamander brand, which can be put into the fire at once without risk. They are covered with some waterproof glaze, probably a salt glaze, which answers its purposes thoroughly.

Carbon Crucibles.—For experimental work, Deville used crucibles about 4 inches high, turned out of solid gas-retort carbon, which were placed in a clay crucible for use, but retained their form even if the outer crucible melted away.

Brasqueing Crucibles.—Small crucibles for laboratory work can be readily lined with charcoal.

Powdered charcoal is mixed with a mixture of equal parts of warm water and treacle till it is just stiff enough to cohere by pressure, and is firmly pressed into the crucible, and a cavity is cut out in the centre. A cover is put on and luted, and the crucible is heated to redness and allowed to cool. The lining will separate from the crucible, but will remain perfectly coherent.

"Berthier states that he has occasionally lined crucibles with silica, alumina, magnesia, or chalk, previously moistened with water so as to make them sufficiently cohesive, and that a thin lining of chalk renders earthen crucibles less permeable to molten litharge."[1]

Alumina Crucibles.—These crucibles may be made, according to Deville, by heating alumina and strongly ignited marble in equal proportions to the highest temperature of a wind-furnace, and then using equal proportions of the substance thus obtained, powdered ignited alumina, and gelatinous alumina. Such crucibles do not soften at the melting point of platinum, and resist almost all corrosive materials.

Lime Crucibles.—Lime crucibles are made by taking a piece of well-burned slightly hydrated lime, cutting it by means of a saw into a rectangular prism 3 or 4 inches on the side and 5 or 6 inches high. The edges are rounded off, and a hole is bored in the centre.

Testing Clay as to its Fitness for Fire-brick and Crucible-making.—The clay must first be examined as to its plasticity by mixing a little with water and moulding it.

The clay, if its plasticity be sufficient, is rolled out into a sheet, and triangular portions are cut out with a knife, care being taken to leave the edges quite sharp. These are dried, put into a black-lead crucible, and heated to the highest attainable temperature for some hours. They are then allowed to cool and examined, and if the edges show no sign of softening, the clay may be pronounced sufficiently refractory.

For very refractory clays a higher temperature than that

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[1] Percy, *Fuel*, p. 141.

which can be obtained in an ordinary crucible furnace is required. A hot-blast gas furnace may then be used. Another method of testing clays is to grind finely, and mould into little prisms with varying proportions of some fluxing oxide, and the one which requires most oxide to make it fusible is the best clay. Richters tones up the clay with fine alumina till it is as refractory as a standard clay.

The refractoriness is often measured by making the clay into little pyramids having a triangular base, the sides of which are $\frac{7}{8}$ in., $\frac{3}{4}$ in., and $\frac{3}{4}$ in., and the height $2\frac{3}{8}$ in., and comparing their behaviour with pyramids of standard degrees of refractoriness, which are made commercially in Germany, and are known as "Segar" cones.[1]

If the clay is to be used for crucibles, the best method of testing is to make it into small crucibles in the apparatus described on p. 332, first burning some of the clay to mix with the raw clay; dry and fire them, and then subject them to the various tests.

1. Heat to the highest possible temperature inclosed in another crucible.

2. Heat to redness, take from the fire and plunge into cold water.

3. Half-fill with litharge, heat to fusion, keep fused for about five minutes, then pour off the litharge, and examine how far the pot has been corroded.

The finer the grain the better the pot will stand test 3, and the coarser the better will it stand tests 1 and 2.

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[1] See Hofman & Demond, *J. A. I. M. I.*, xxiv.

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This is not intended as a bibliography of the subject, but simply as a list of a few of the more important books and papers to which the student may refer for further information.

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This is the standard book on the subject. No one—especially one who received his early training in Metallurgy from the great metallurgist—can write on this subject without drawing largely, consciously and unconsciously, on this classic. It is unfortunately now somewhat out of date, and it is to be regretted that the publishers do not have it revised and re-issued.

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Heat Units.

British Thermal Unit, ...	1 pound	of water raised	1° F.
Centigrade Unit (often wrongly called a Calorie), ...	1	„ „	1° C.
Calorie, ...	1 kilogram	„	1° C.

To convert a sum given in Centigrade Units into the corresponding B.T.U.—

$$\times \frac{9}{5} \text{ or } 1{\cdot}8.$$

To convert Calories into B.T.U.—

$$\times\ 3{\cdot}968.$$

Thermometer Scales.

Fahrenheit, ...	F.P. of water	= 32° ...	B.P. of water	= 212°
Centigrade, ...	F.P. „	= 0° ...	B.P. „	= 100°

To find a reading F° on Fahrenheit scale corresponding to C° on Centigrade scale, or vice versâ—

$$F = \frac{9}{5}\,C + 32 \quad \text{or} \quad 1{\cdot}8\ C + 32.$$

$$C = \frac{5}{9}\,(F - 32) \quad \text{or} \quad {\cdot}\dot{5} \times (F - 32).$$

MECHANICAL EQUIVALENT OF HEAT.

1 B.T.U., ... = 772 foot-pounds.
1 Centigrade unit, ... = 1390
1 Calorie, ... = 3063 „
1 Foot-pound, ... = $1·356 \times 10^7$ ergs.
1 Horse-power = 33000 foot-pounds per minute = $7·46 \times 10^9$ ergs per second.

ENGLISH AND METRIC WEIGHTS AND MEASURES.

1 Metre, ... = 39·37079 inches.
„ ... ... = 3·28089 feet.
„ ... ... = 1·09363 yards.
„ ... ... = ·00006214 mile.
1 Litre, ... = 61·02705 cubic inches.
„ ... ... = ·035317 „ foot.
1 Gramme, ... = 15·43235 grains.
„ ... ... = ·032151 Troy oz.
„ ... ... = ·0022046 Avoir. lb.
„ ... ... = ·0000197 cwt.

To convert metres to yards, add $\frac{1}{11}$.
„ „ inches, ... × 40 (39·37)
„ inches to metres, ... × ·0254
„ kilogrammes to lbs., ... × 2·2046
„ litres to gallons, ... × ·22
„ gallons to litres, ... × 4·546
„ grammes to grains, ... × 15·432
„ grains to grammes, ... × ·0064
„ ounces to grammes, ... × 28·349

SPECIFIC HEAT OF GASEOUS SUBSTANCES.

Air,	·2375
Oxygen,	·2175
Nitrogen,	·2438
Hydrogen,	3·4090
Carbon monoxide,	·2450
Carbon dioxide,	·2163
Methane,	·5929
Ethylene,	·4040
Steam,	·4805
Sulphuretted hydrogen,	·2432
Sulphur dioxide,	·1540
Charcoal,	·2415

Amount of Oxygen required for Combustion.

		Oxygen.	Air.
Carbon, ...	1 part, ...	2·66	12·7
Hydrogen, ...	,, ...	8	38
Carbon monoxide,	,, ...	·57	2·71
Methane, ...	,, ...	4	19
Ethane, ...	,, ...	3·73	16·1
Acetylene, ...	,, ...	3·07	17·5

Calorific Power of various Combustibles.

	B.T.U.	C.U.
Carbon to carbon dioxide, ...	14500	8080
Carbon to carbon monoxide, ...	4327	2404
Hydrogen to water, ...	61524	34180
Methane to carbon dioxide and water, ...	24513	13063
Ethylene, ...	21345	11858
Acetylene, ...	...	...
Sulphur to sulphur dioxide, ...	3891	2162
Carbon monoxide to carbon dioxide, ...	...	...
Wood, ...	4500 to 7200	2500 4000
Coal, ...	11500 to 16200	6500 9000
Anthracite, ...	12900 to 14700	7200 8200
Coke, ...	615200 to 14400	6600 8000
Natural oil, ...	18000	10000
Coal-gas, ...	19800	11000

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