FUEL AND REFRACTORY MATERIALS

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NEW EDITION
COMPLETELY REVISED AND ENLARGED
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PREFACE

This book is a revised edition of Professor Sexton's well-known work on "Fuel and Refractory Materials."

In revising the book it has not been found necessary to make drastic alterations in the original text.

Slight inconsistencies in statistics and figures have been as far as possible eliminated, but it has not been considered advisable to adopt either the Centigrade or the Fahrenheit scale in thermometry to the exclusion of the other.

The quite recent new views as to the constitution of coal have not been incorporated, as it is felt the subject is still in its infancy; the same remark applies to some modern theories of the chemistry of coking.

The chapters on Liquid and Gaseous Fuels have been considerably modified and enlarged. Chapter VIII. on "Recovery of By-products" has been almost entirely rewritten, and is now entitled "By-products and Low-temperature Carbonization."

The Chapters on "Testing Fuels" and "Refractory Materials" have been brought up to date and enlarged.

Some of the old illustrations have been discarded and a few new ones introduced.

A Spanish translation by Señor C. de Madariaga, of Madrid, is in preparation.

W. B. D.

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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 exposing 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 difficult to burn ; 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-

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

gas must be mixed with at least 17 times its own volume of air to form an explosive mixture.

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 1100° F. (590° C.), when ignition will at once take place. Coal-gas ignites in air at a 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.[1]

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 an equal part, which being combustible and which supporter of combustion depending on circumstances.

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

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 750° 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 1830° 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_2H_4, which goes partly to hydrogen and acetylene, C_2H_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 is the usual cause 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 a compound flame is one 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.

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.

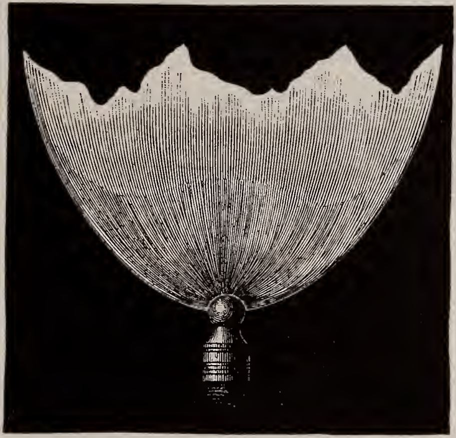

Fig. 1.—Gas Flame.

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 thoria and ceria 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, *e.g.* 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 71, 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 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.

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 in Fig. 2).

(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.

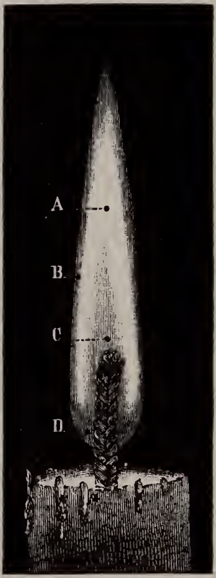

Fig. 2.—Candle Flame.

The explanation which has usually been given of the phenomena of luminosity 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

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

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 in 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 (1500 – 1800° 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 2130° 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.

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

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

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.	Hydrogen.	Temperature of Luminosity.
100	0	1440° F.
90	10	1650
80	20	1830
10	90	3090

The above "acetylene theory" of the chemical reactions on which luminosity of flame depends is not now generally accepted.[1] In any case the reactions are complex.

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 (usually $2\frac{1}{2}$ volumes) 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." [2]

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 " 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.

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[1] W. A. Bone and H. F. Coward, *J. Chem. Soc.* 1908, p. 1197.

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

	Air.		Nitrogen.	
½ inch above burner . . .	54° C.	129° F.	30° C.	86° F.
1½ ,, ,, ,, . . .	175	347	111	231
Tip of inner cone	1090	1990	444	831
Centre of outer cone . . .	1535	2795	999	1830
Tip of outer cone . . .	1175	2150	1150	2100
Side of outer cone level with tip of inner cone . . .	1335	2435	1235	2255

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

It does not follow 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. (1830° 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. (1830° F.) to 1300° C. (2370° 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 metre (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.

The velocities of explosion found by Dixon for mixtures with oxygen in the exact proportions for complete combustion were :

Hydrogen.	Acetylene.	Ethylene.	Methane.
2821	2391	2364	2322

metres per second.

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, it is possible from a knowledge of the heat which will be evolved on combustion 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 main 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. Another reason is the high and rather uncertain specific heat of steam at high temperatures.

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	2·64	Above melting point of silver	·2	21·3	78·5
54	2·13	Melting point of gold	6·2	28·1	65·7
44	1·73	Commencing white-heat of platinum	10	20	70
35	1·38	White-heat of platinum	17·3	24·8	57·9
28	1·10	Strong white-heat of platinum	19·4	26·5	54·1
18	·71	Intense white-heat of platinum	29	25·1	45·9
15	·59	Incipient fusion of platinum	40	32·9	27·1
12	·47	Melting point of platinum	47	36	17
10	·39	Sparkling of melted platinum	55·3	35·3	9·4
0	..	. . . .	64·4	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. (·39″) 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, $C + 2O = CO_2$, together with some carbon monoxide either formed directly, $C + O = CO$, or by the reduction of carbon dioxide, $CO_2 + C = 2CO$. 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 only because of the actual carbon which it contains, but also 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 very largely 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, sometimes 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 which has been shown to have a radiation efficiency of about 10 to 15 per cent.

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 per cent by volume and 23 per cent 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 1 lb., will be

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

The weight of air A will be

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

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 1 lb. of a fuel containing h per cent of hydrogen and no other combustible would be

$$(3) \quad W = \frac{h \times 8}{100}.$$

and A, the weight of air,

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

If the fuel contains c per cent of carbon and h per cent of hydrogen, then W, the weight of oxygen required for the combustion of 1 lb. of the fuel, would be

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

and the weight of air

$$(6)\quad A=c\times\cdot 116+h\times\cdot 348.$$

If the fuel contains o per cent 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 lb. (566·3 grains), the volume of air required for combustion would be

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

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 29·92[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

$$(8)\quad v'=\frac{v\times 29\cdot 92}{p}.$$

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

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

The law according to which gases expand by heat may be expressed in various ways; probably the simplest is to say

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[1] For ordinary purposes 30 inches may be taken and 30 substituted for 29·92 in the equations.

that the volume is proportional to the absolute temperature. The absolute zero is for the Fahrenheit scale -459, and for the Centigrade scale -273, so that any temperature t on the Fahrenheit scale will be $459+t$ on the absolute scale in F. degrees, and t' on the Centigrade scale will be $273+t'$ on the absolute scale in C. degrees.[1]

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

$$(9) \quad v = \mathrm{V} \times \frac{459+t}{459+32}, \text{ or } v = \mathrm{V}(1+0{\cdot}002037).$$

On the Centigrade scale the volumes would be

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

Combining the two equations, the volume of air v at 32° F., and 29·92 inches barometer, would become at t° F. and a pressure of p inches of mercury v', and

$$(10) \quad v' = \mathrm{V} \times \frac{29{\cdot}92}{p} \times \frac{459+t}{491}$$

$$= \mathrm{V} \times \frac{29{\cdot}92 \times (459+t)}{p \times 491}$$

$$\text{or } v' = \mathrm{V} \times \frac{29{\cdot}92}{p} \times (1+{\cdot}002037t-32)\,;$$

and for Centigrade degrees and millimetres

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

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

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 per-

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[1] The absolute temperature may also be determined from thermodynamic principles, almost identically the same zero being obtained.

centage of available hydrogen ; A and V the weight and volume of air required as before ; then

$$(11) \quad A = \cdot 12\,c + \cdot 36h\,;$$

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

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

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

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

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 little value no note need be taken of the latent heat of steam.

The heat carried away will be

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

and if it be required to take into account the latent heat of steam, then $\frac{(9h+w)\times 966}{100}$ 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 approximately 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 $(C+\underset{\square\square}{2O}=\underset{\square\square}{CO_2})$. 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

Thermo-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.Th.U.), and is the amount of heat required to raise 1 lb. 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 kilogramme of water 1° C.; this latter is usually called the *Calorie.* Sometimes also the amount required to raise 1 lb. 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

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

(2) To convert a quantity in B.Th.U. into pound-Centigrade units × ·$\dot{5}$.

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

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

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.Th.U., the weights are taken in lbs. The formation of 36·5 lb. of hydrochloric acid by the combination of 1 lb. of hydrogen with 35·5 lb. of chlorine evolves 39600 British Thermal Units, or if the weights be taken in lbs., 22000 lb. Centigrade units (C.), or if in grammes, 22000 calories.

This may be written

$$\mathrm{H} + \mathrm{Cl} = \mathrm{HCl}\,[1]\ (39600 +)\ \mathrm{B.Th.U.}\ (\mathit{22000} +)\ \mathrm{C.}$$

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

Laws of Thermo-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, 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[2] 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 lb. of chlorine will necessarily form 36·5 lb. of hydrochloric acid, and also will necessarily evolve the 39600 B.Th. 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

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[1] Values in B.Th.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.

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

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 70770 + B.Th.U., *39320* + C.; but this is made up of two parts :

Heat of combination of H, Cl	39600 + B.Th.U.	*22000* + C.
Heat of solution of hydrochloric acid in water	31170 +	*17320* +
Total	70770 +	*39320* +

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	10870 – B.Th.U.	*6040* – C.
Heat of solution of hydriodic acid in water	34580 +	*19210* +
Total	23710 +	*13170* +

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, $H_2S + 2Cl = 2HCl + S$. 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.Th.U.	C.
Decomposition of one molecule of hydrogen sulphide .	8530 –	*4740* –
Formation of two molecules of hydrochloric acid .	79200 +	*44000* +
Resultant . . .	70670 +	*39260* +

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

	B.Th.U.	C.
Removal of a molecule of hydrogen sulphide from solution	8210 –	*4560* –
Decomposition of hydrogen sulphide	8530 –	*4740* –
Formation of two molecules of hydrochloric acid .	79200 +	*44000* +
Solution of the hydrochloric acid in water . . .	62330 +	*34630* +
Total heat change. .	124790 +	*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. Hence 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 1 lb. (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 123000 B.Th.U., *68360* C. As this is the combustion of 2 lb. (or grammes) of hydrogen, the calorific power will be half this, viz. :

C.P. of H = 61500 B.Th.U., *34180* C.,[1]

more exactly, 61000 and 33900 liquid water being formed.

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[1] Thomsen's figures.

Combustion of Carbon.—The thermal value of the formation of a molecular weight of carbon dioxide from carbon and oxygen is $C+2O=CO_2$, 175100 B.Th.U., *97300* C. As twelve parts of carbon take part in the reaction, the calorific power will be these numbers divided by 12:

C.P. of C to (CO_2) = 14600 B.Th.U., *8110* 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 175100 B.Th.U., or *97300* C. If twenty-eight parts of carbon monoxide (the weight which contains twelve parts of carbon) be burnt to carbon dioxide it evolves 122400 + B.Th.U., or *68000* C., and the heat of formation of the carbon monoxide must obviously be the difference between the two:

$C+2O=CO_2$	175100 + B.Th.U.	*97300* + C.
$CO+O=CO_2$	122400 +	*68000* +
$\therefore C+O=$	52700 +	*29300* +

which, divided by 12, gives

C.P. of C to CO = 4390 B.Th.U., *2440* C.

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

	B.Th.U.	C.
1 lb. carbon burning to carbon dioxide	14600	*8110*
2⅓ lb. carbon monoxide burning to carbon dioxide . .	10210	*5670*
1 lb. of carbon burning to carbon monoxide . . .	4390	*2440*

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.Th.U.	C.
Heat evolved by combination of the second portion of oxygen with 1 lb. of carbon	10210	*5670*
Heat evolved by combination of the first portion of oxygen with 1 lb. of carbon	4390	*2440*
Latent heat of vaporization of carbon . .	5820	*3230*

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 1 lb. 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,

$$(17)\quad \text{E.P.} = \frac{14600\text{ F.}}{967} = \frac{8110}{537} = 15{\cdot}1.$$

In the case of hydrogen the relationship is not quite so simple, for each pound of hydrogen forms 9 lb. 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

$$(18)\quad \text{E.P. of hydrogen} = \frac{61500}{967} - 9, \text{ or } \frac{34180}{537} - 9 = 54{\cdot}6.$$

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 $6 \times 12 = 72$ lb. of carbon and 6×1 lb. of hydrogen, and converting these into carbon dioxide and water, the heat evolution must be $(175100 \times 6) + (61500 \times 6) = 1420000$. *(97300 × 6) + (68360 × 3) = 789000.*

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 1420000. 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 1420000 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, $C_6H_6 + 15O = 6CO_2 + 3H_2O$, is found to be 1418000 B.Th.U. (*788000* C.), so that

	B.Th.U.	C.
Heat of combustion of benzene	1418000	*788000*
Heat of combustion of carbon and hydrogen . .	1420000	*789000*
Heat of formation of benzene (approx.) . . .	2000	*1000*

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.

It will be noted that as heats of formation are calculated from differences they do not carry a high degree of accuracy.

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.

$$(19)\quad \text{C.P.} = \frac{c \times 14600}{100} \text{ in B.Th.U.}$$

$$(19')\quad \text{C.P.} = \frac{c \times 8110}{100} \text{ in C. units.}$$

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

$$(20)\quad \text{C.P.} = \frac{c \times 14600 + h \times 61500}{100} \text{ in B.Th.U.}$$

$$(20')\quad \text{C.P.} = \frac{c \times 8110 + h \times 34180}{100} \text{ in C.}$$

Since the calorific power of hydrogen is 4·21 times that of carbon, these equations may be written:

$$(21)\quad \text{C.P.} = \frac{(c + 4{\cdot}21h) \times 14600}{100},$$

or

$$(21')\quad \text{C.P.} = \frac{(c + 4{\cdot}21h) \times 8110}{100}.$$

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

$$\text{By (18)}\quad \text{C.P.} = \frac{70 \times 14600 + 30 \times 61500}{100} = 28670 \text{ B.Th.U.},$$

$$\text{or by (18')}\quad \text{C.P.} = \frac{70 \times 8110 + 30 \times 34180}{100} = 15950 \text{ C.}$$

Note.—The highest percentage of hydrogen possible is 25, found in methane, CH_4.

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

$$(22)\quad \text{C.P.} = \frac{c \times 14600 + (h - \frac{1}{8}o) \times 61500}{100} \text{ in B.Th.U.},$$

$$\text{or}\quad (22')\quad \text{C.P.} = \frac{c' \times 8110 + (h - \frac{1}{8}o) \times 34180}{100} \text{ in C.};$$

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

$$(23)\quad \text{C.P.} = \frac{\{c + 4{\cdot}21(h - \frac{1}{8}o)\} \times 14600}{100} \text{ in B.Th.U.}$$

$$(23') \quad \text{C.P.} = \frac{\{c' + 4{\cdot}21(h - \tfrac{1}{8}o)\} \times 8110}{100} \text{ in C.}$$

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

$$\text{C.P.} = \frac{50 \times 14600 + (26 - \frac{24}{8}) \times 61500}{100}$$

$$= \frac{730000 + 1415000}{100} = 21450 \text{ B.Th.U.,}$$

$$\text{or C.P.} = \frac{50 \times 8110 + (26 - \frac{24}{8}) \times 34180}{100} = 11920 \text{ C.}$$

If sulphur be present, then $s \times 4000$ may 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 ,,

Other investigators obtained values as high as 8140 for wood charcoal.

The value of 8110 may be taken, though it is impossible to say in what form the carbon exists in fuels.

The number 61500 (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.Th.U. and 9 × 80 in C.

units, so that the calorific power of hydrogen in solid fuels would become:

$$(24)\quad \text{C.P.} = 61500 - (9 \times 142) = 60220 \text{ B.Th.U.}$$
$$(24')\quad \text{C.P.} = \mathit{34180} - (\mathit{9} \times \mathit{80}) = \mathit{33460} \text{ in C. units.}$$

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

$$(25)\quad \text{C.P.} = \{c \times 14600 + (h - \tfrac{1}{8}o) \times 61500\} - 9h \times 142 \text{ in B.Th.U.,}$$
$$\text{or}\quad (25')\quad \text{C.P.} = \{c \times \mathit{8110} + (h - \tfrac{1}{8}o) \times \mathit{34180}\} - 9h \times \mathit{80} \text{ in C.}$$

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, 86700 – B.Th.U. (*48200* – C.), and carbon disulphide, 46800 – B.Th.U. (*26000* – 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:

$$(26)\quad \text{C.P.}_{212^\circ} = 61500 - (967 \times 9) = 5280 \text{ B.Th.U.}$$
$$(26')\quad \text{C.P.}_{100^\circ} = \mathit{34180} - (\mathit{537} \times \mathit{9}) = \mathit{29350} \text{ C.}$$

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:

$$(27)\quad \text{C.P.}_{\cdot t} = 61500 - \{(967 \times 9) + (\cdot 4805 \times 9 \times t)\} \text{ in B.Th.U.}$$

$$(27')\quad \text{C.P.}_{\cdot t'} = 34180 - \{(537 \times 9) + (\cdot 4805 \times t' \times 9)\} \text{ in C.}$$

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:

$$(28)\quad \text{C.P.} = 14600 - (3{\cdot}67 \times \cdot 209t),$$

$$(28')\quad \text{C.P.} = 8110 - (3{\cdot}67 \times \cdot 209t'),$$

and a fuel containing carbon, hydrogen, and oxygen:

$$(29)\quad \text{C.P.} = \frac{[(c \times 14600) - 3{\cdot}67c \times \cdot 209 \times t] + 61500(h - \frac{1}{8}o) - (967 \times 9h) + (\cdot 4805 \times 9h \times t)}{100} \text{ in B.Th.U.,}$$

$$\text{or } (29')\quad \text{C.P.} = \frac{(c \times 8110) - (3{\cdot}67c \times \cdot 209 \times t) + 34180(h - \frac{1}{8}o) - (537 \times 9h) + (\cdot 4805 \times 9h \times \text{C.})}{100} \text{ in C.}$$

In the above 0·4805 and 0·209 are the specific heats per unit weight of H_2O and CO_2 respectively. The formulæ do not apply at high temperatures because of the large increase in the specific heats.

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 1 lb. (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:

$$(30) \quad T = \frac{\text{C.P.}}{W \times S}.$$

If 1 lb. of carbon at 32° F. (0° C.) be burned in 2·67 lb. of oxygen it will form 3·67 lb. of carbon dioxide, which has a specific heat of ·209; so that

$$(31) \quad \text{C.I.}_{\text{F.}} = \frac{14600}{3{\cdot}67 \times {\cdot}209} = \frac{14600}{{\cdot}767} = 19040^\circ \text{ F.}$$

This is a rise of temperature, so that if, at starting, all the substances were at 32° the final temperature would be 19070° F.

In Centigrade degrees the figures would be:

$$(31') \quad \text{C.I.}_{\text{C.}} = \frac{8110}{3{\cdot}67 \times {\cdot}209} = \frac{8110}{{\cdot}767} = 10570^\circ \text{ C.}$$

The case of hydrogen is a little more complex. The heat evolution is 61500 B.Th.U., which has to be distributed over 9 lb. of steam produced by the combustion, having a specific heat of ·4805; but the 9 lb. 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:

$$(32)\quad \text{C.I.}_{\text{F.}} = \frac{61500 - \{967 + (1 - \cdot 4805)180\}9}{9 \times \cdot 4805}$$

$$= \frac{51970}{4 \cdot 3245} = 12020.$$

This is a rise of temperature, so that the temperature of products of combustion would be 12020 + 32 = 12050° F.

In Centigrade degrees:

$$(32')\quad \text{C.I.}_{\text{C.}} = \frac{34180 - \{537 + (1 - \cdot 4805)100\}9}{9 \times \cdot 4805} = 6680.$$

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

$$(33)\quad \text{C.I.}_{\text{F.}} = \frac{c \times 14600 + (h - \frac{1}{8}o)61500 - \{967 + (1 - \cdot 4805)180 \times (9h + w)\}}{(3 \cdot 67c \times \cdot 209 + (9h + w) \times \cdot 4805)100},$$

$$(33')\quad \text{C.I.} = \frac{c \times 8110 + (h - \frac{1}{8}o)34180 - \{537 + (1 - \cdot 4805)100 \times (9h + w)\}}{(3 \cdot 67c \times \cdot 209 + (9h + w) \times \cdot 4805)100},$$

where, in addition to the symbols used above, w is the quantity of moisture in 1 lb. 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,

$$(34)\quad \{2 \cdot 67c + 8(h - \tfrac{1}{8}o)\} \times \frac{77}{23} \times \cdot 248 \text{ must be added to the}$$

denominator of the fraction, and if there be an excess of air e, then $e \times \cdot 241$ must also be added.

The figures obtained by these formulæ are not results which would actually be obtained, because the specific heats of the various products of combustion are not constant but increase rapidly as the temperature rises.

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.
									C°.	F°.	
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

$$\text{C.P.} = \frac{8080\ \text{C}' + 11370\ \text{C}'' + 34180\ \text{H}}{100},$$

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

$$\text{C.P.} = \frac{14544\ \text{C}' + 20390\ \text{C}'' + 61524\ \text{H}}{100},$$

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 O. 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—

PERCENTAGE OF WATER

	$c=$		$c=$
(1) Less than 3 per cent .	4	(5) Between 12 and 20 per cent	8
(2) Between 3 and 4·5 .	6	(6) ,, 20 ,, 28 . .	6
(3) ,, 4·5 ,, 8·5 .	12	(7) Over 28 per cent . .	4
(4) ,, 8·5 ,, 12 .	10		

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 . .	7690 B.Th.U.	*4270 C.*
(2) ,, ,, solid carbon to carbon dioxide .	5475 ,,	*3040.*

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 44·42 per cent carbon, 6·22 per cent hydrogen, and 49·36 per cent 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. (C, H, O, and N are calculated on an ash-free basis.)

	Average.	Oak, 120 years.	Birch, 60 years.	Willow.
Carbon	51	50·97	50·59	51·75
Hydrogen . . .	6	6·02	6·21	6·19
Oxygen . . .	42	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 clubmoss, 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 per cent.
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 of potash and lime, with smaller quantities of soda, magnesia, 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.Th.U., and when air-dried only about 5600 B.Th.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.Th.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 20 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 lb.
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, usually too much ash—and this generally of an objectionable kind. It contains very little available hydrogen, and has a very low calorific power, about 5000 B.Th.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 by far the most 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 it can be economically used or not, 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, 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, etc., 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, etc., 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 afterwards been 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 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

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

patches thinning away to nothing on all sides,"[1] and frequently merging into mere carboniferous shale, and often containing 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 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

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

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 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.

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

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

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. The world's total available coal of all kinds is estimated at 7,300,000 million tons, or about 6000 times the present total annual consumption.

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.

Lignite or Brown Coal.—This variety of coal is of more recent age than the true coal, occurring in rocks of tertiary

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[1] *Coal*, p. 23.

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.

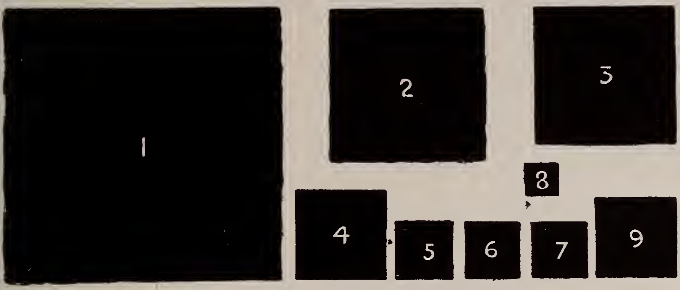

FIG. 3.—Coal available (pre-war) in different Countries.

1. United States	52	per cent.
2. Canada	16½	,,
3. China	13½	,,
4. Germany	5¾	,,
5. Great Britain	2½	,,
6. Siberia	2¼	,,
7. Australia	2¼	,,
8. Russia	¾	,,
9. France, Belgium, etc.	4½	,,
	100	

There are several varieties of lignite.

Bituminous coal 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	50·47	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:

1. **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.

2. **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, etc., 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	78·65	76·12
Hydrogen	4·43	4·65	4·83
Oxygen	4·82	13·66	15·72
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	4·98	5·90	6·35
Oxygen	5·42	17·37	21·97

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 tables give the characters of the different coals :

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

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 lb. 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	·65	·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, 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 20 to 24 per cent, or 11,000 to 13,000 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	25·90	21·12	20·15	23·70	14·2	10·43
Coke	74·10	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	..	..	·88	..	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 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 16,000 cubic feet per ton—of highly illuminating gas, leaving a residue which sometimes consists mostly of ash, and contains but little fixed carbon. Cannel coals were formerly used entirely for gas-making. At the present day there is no demand for rich gas. They give a very high yield of tar oils when distilled at a comparatively low temperature, and fairly successful attempts at recovering these oils for fuel purposes were made during the war.

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	91·7	66·3	4
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. Perhaps the best way to estimate moisture is to dry the powdered sample *in vacuo* over sulphuric acid at the ordinary temperature. Many coals are very hygroscopic, and their moisture content will depend on the humidity of the air.

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, FeS_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, $2FeS_2 + 11O = Fe_2O_3 + 4SO_2$. When such coal is heated without access of air, the pyrites is split up, $FeS_2 = FeS + S$, 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, $CaSO_4$. 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, $CaSO_4 + 4C = CaS + 4CO$.

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, calculated on a basis of phosphoric anhydride, 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 ; 50 per cent remains in the coke ; about 5 per cent is contained in the tar and as hydrocyanic acid ; and the rest (about 30 per cent) is evolved as gas. Splint coals contain on an average about 1·5 per cent of nitrogen, and anthracite coals about ·7 per cent.

Ash of Coal.—All coals leave when burnt 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 from 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. Most coal ashes contain appreciable percentages of alkali which materially affect the fusibility.[1]

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

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[1] Dr. J. T. Dunn, *Journ. Soc. Chem. Ind.*, 1918, 37, p. 171.

Amount of Ash	1. 55·2.	2. 6·94.	3. 2·91.	4. 14·72.
Silica	40·00	28·87	34·21	53·00
Alumina . . . . . Oxide of iron	44·78	56·95	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	100·08	97·82	100·00

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 greater the content of pyrites 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. The fusion point may be as low as 1000° C. or as high as 1500° C.

[Table

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. This is associated with the pyrites present. Its presence is objectionable where food-stuffs are exposed to contamination by the absorption of arsenious oxide fumes—for example, when coke is used in the heating of barley for malting. Many other metals are also to be found in very small quantities, such as copper, lead, zinc, antimony, vanadium, and even silver and gold.

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 above analyses taken from Percy's *Metallurgy*, 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 partially 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 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 there is much "slack" 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 considerably with the temperature and somewhat with the 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.[1]

Valuation of Coals.—The value of a coal 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

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[1] For modern researches see: Fischer and Gluud, *Journ. Gasbeleuchtung*, 1915, 58; P. P. Bedson, *Journ. Soc. Chem. Ind.*, 1902, p. 241, and 1908, p. 147; Burgess and Wheeler, *Journ. Chem. Soc.*, 1911, 99, etc.

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 ·2 × 1000 = 200 units.

4. The nature of the ash—its degree of fusibility.
5. The coking power of the coal.
6. The length of the flame.
7. The amount of sulphur, chlorine, etc., 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.Th.U., or 2220 C. units; but the combustion of pyrites is not a simple combination. The equation $2FeS_2 + 11O = Fe_2O_3 + 4SO_2$ 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 − × 2 = 47600 −
2\. 70500 + × 4 = 282000 +
3\. 196000 + × 1 = 196000 +

=Total heat of reactions, 430400 +

which, divided by 240, the weight of the two molecules of pyrites (FeS_2), gives 1790 as the calorific power of pyrites, and divided by 128 gives 3360 as the calorific power of sulphur when present as pyrites. (In B.Th.U. this = 6050.)

TABLE OF CALORIFIC VALUES

	B.Th.U. per lb. (Dry).	Calories per Kilogramme (Dry).	B.Th.U. per Cubic Foot. 60° F. and 30″ (Moist).	Calories per Cubic Metre. 0° C. and 760 mm. (Dry).
Amorphous carbon to carbon dioxide	14,600	8,110	..	..
Carbon monoxide to carbon dioxide	4,370	2,430	320	3,050
Carbon to carbon monoxide	4,390	2,440	..	..
Hydrogen to water (liquid), gross	61,000	33,900	320	3,050
,, ,, ,, (gaseous), net	51,500	28,600	269	2,570
Methane to $CO_2 + 2H_2O$, gross	23,920	13,290	998	9,530
,, ,, ,, net	21,510	11,950	897	8,560
Ethylene to $2CO_2 + 2H_2O$, gross	21,310	11,840	1,580	15,080
,, ,, ,, net	19,890	11,050	1,475	14,080
Benzene vapour to $6CO_2 + 3H_2O$, gross	18,000	10,000	3,650	34,800
,, ,, ,, ,, net	17,250	9,590	3,500	33,400
Sulphur to sulphur dioxide (SO_2)	4,000	2,220	..	..
Pyrites to $Fe_2O_3 + SO_2$	3,220	1,790	..	..
Sulphuretted hydrogen to $H_2O + SO_2$, gross	7,020	3,900	624	5,940
,, ,, ,, ,, net	6,440	3,580	571	5,450
Naphthalene to $CO_2 + H_2O$, gross	17,750	9,860	5,910	56,400
,, ,, ,, net	17,300	9,630	5,770	55,100

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 25 per cent of the weight of the wood. If finely divided wood, as for instance saw-dust, 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.[1]		Temperature of Ignition.	
3000° F.	1650° C.	2500° F.	1370° C.
2500	1370	1300	700
2000	1090	1100	590
1500	820	900	480
1000	540	800	430
500	260	650	340

Charcoal absorbs gases very readily, and as a rule the lower the temperature at which it is prepared the greater is its

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[1] Thurston, *Materials of Engineering*, vol. i. p. 184.

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 absorptive power of charcoal has been made use of during the war to extract ethylene from coke-oven gas for the manufacture of "mustard gas."

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, ·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 per cent of moisture.

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 heating strongly in a closed platinum crucible.[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. In small bulk it burns with a glow at low temperature, the product being almost entirely carbon dioxide, though a small quantity of carbon monoxide is usually formed and frequently escapes combustion. At high

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[1] According to Desmond, charcoal when heated to redness gave 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

temperature 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 13,700 B.Th.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 per cent of the weight.

For domestic use charcoal is very objectionable, unless burned in a fireplace with a very good draught, on account of the formation of carbon monoxide, which, being odourless and colourless, is not easily detected.

Red Charcoal (Rothkohle).—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.

A plot of dry level ground is selected, as sheltered as possible from the wind, having a slight declination 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 is 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.

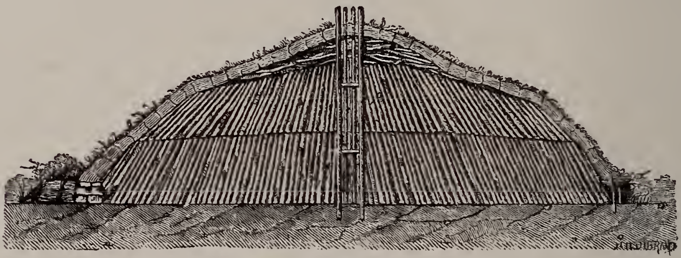

FIG. 4.—Charcoal Burning in Circular Piles.

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 is 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."

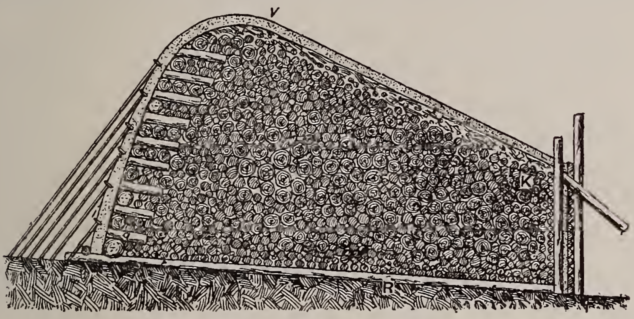

FIG. 5.—Rectangular Pile.

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.

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, etc., 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 beehive 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 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.

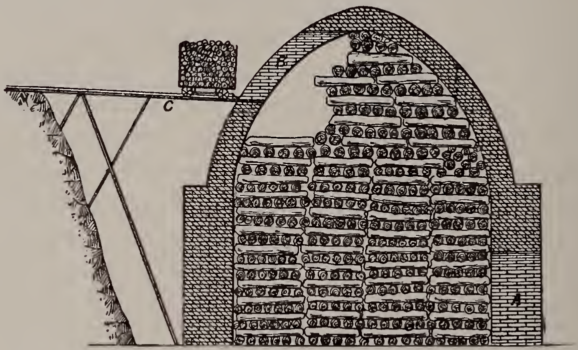

FIG. 6.—American Charcoal Kiln. From Eisler's *Argentiferous Lead.*

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 lb. per bushel, that made from the same wood by the ordinary processes weighing 16 lb. per bushel.

Comparison of Methods of Charcoal Burners.[2]

Method of Coking.	Wood.	Yield.	
		Per Cent Vol.	Per Cent 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

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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.

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 obtained in this way is generally of inferior quality, because the wood used is selected not for its charcoal making quality, but for its yield of pyroligneous acid, etc. 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, and then charring in retorts externally heated, or in a current of 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 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, three varieties of coke are made :

(1) Soft coke, often called smithy char, used for smiths' forges and similar purposes ; (2) gas coke, used for producers, forges, furnaces, and household fires ; and (3) 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.

Gas coke is variable in quality. As obtained from light charges in horizontal retorts and from continuous vertical retorts it is generally of rather small size and of open, porous texture; from heavy charges in horizontal retorts and from intermittent vertical retorts it is larger and denser. Continuous vertical retorts can deliver the coke in a dry state and of a good grey colour. In intermittent systems it is advantageous to quench the coke with water as rapidly as possible to improve the colour and reduce the moisture content. The latter may vary between 1 and 25 per cent.

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-grey colour, with a metallic lustre, and breaks into columnar fragments. That made in Simon-Carvès and similar ovens was formerly black and dull without lustre, and breaks into roughly rhombohedral lumps. Great improvements in carbonizing and particularly in quenching have been made in recent years, and there is now little to choose between beehive and coke-oven coke. 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).

The best metallurgical cokes contain less than 3 per cent of volatile matter and less than 2 per cent of moisture. The volatile matter in general may vary from 20 per cent in low temperature coke to 2 per cent in high temperature coke. 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 lb. per square inch. It is, however, much less at high temperature ; one sample gave 597 lb. in the cold, but at a red heat only 398 lb.

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 approximately the same calorific value as the coal from which it is made when the ash content of the coke is not more than about 7 per cent. When the ash content is very low the coke may have a higher calorific value than the coal, but as a rule there is a drop of about 5 per cent owing to the large increase in the percentage of ash. 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 the relatively lower efficiency 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 objections to it being the difficulty of ignition, the necessity for a deep bed or a good draught, and the bulkiness of the ashes. 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. 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 ironworks it is often assumed that one half of the total sulphur remains in the coke, the other half passing away with the gases. Whether the amount of sulphur which passes into iron depends on the form in which the sulphur is present in the coke is uncertain.

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 escapes mostly as gaseous nitrogen, there being a small percentage which finds its way into the tar.

Coalite.—Some years ago a form of coke was put upon the market and much advertised under the name of Coalite. This is prepared by coking coal at a low temperature, the result being a residue which still contains 10 per cent, or more, volatile matter, and is very porous and therefore ignites very readily. In the manufacture volatile products of considerable value—gas, tar, and ammonia—are given off, and can be recovered. The inventor states that 800° F. (430° C.) is the best temperature for distillation, and in order that the coal may be uniformly heated, retorts of special form are used. With coals which do not cake strongly, D-shaped metal retorts 7 feet long, 5 feet wide, and 16 inches high were recommended, the fuel being spread in a thin layer on the bottom, and the coking lasting eight hours. In the case of strongly caking coals the coal was placed in tapering cylinders 10 or 12 inches long, one end being perforated to allow of the escape of the gas given off. These were completely filled with the coal, and placed either horizontally or vertically in a furnace. After drawing from the retorts the coke was quenched with water. In the more modern Barnsley installation of low temperature carbonizing plant the retorts are vertical ovens, 10 feet long by 10 feet high by 12 inches wide. A central movable iron plate divides the oven in two.

There are many difficulties in obtaining by external heating satisfactory and economical semi-carbonization of caking coals, and furthermore the product is not nearly so strong as high temperature coke and therefore suffers in transport. For these reasons the sale of coalite has not yet made great headway.

The following analysis will indicate the character of Coalite :

	On dry basis. 1.	2.
Fixed carbon	80·0	85·1
Volatile matter	12·0	6·4
Sulphur	1·0	1·8
Ash	7·0	6·7
Moisture		(10·3)

1, Average analysis, Prof. V. B. Lewes. 2, Analysis of sample, Author.

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 does not take place 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 preferably be in a coarse powder. When a coal is not sufficiently good in its coking properties it can often be made quite suitable by the process of disintegrating, wetting (to about 12 per cent moisture) and stamping before charging into the horizontal coke-oven. Most coals are very much improved by washing, the sulphur and ash being greatly reduced.

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 (coke dust), 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.—In this process the coal instead of being coked in an open heap is coked in a space surrounded by walls. The stalls used in Silesia, described by Dr. Percy, were about 60 feet long, 15 feet wide, and 6 feet deep, the walls being built of brick; a number of horizontal passages were left in the wall, each of which communicated with a vertical chimney. Wooden poles were put through the cross openings, so that when they were withdrawn they would leave channels through the coal, and the coal was filled in, each layer being stamped down. The poles were then withdrawn and fires of brushwood lighted in the passages, one end of the passage and the chimney on the opposite side being closed. As soon as combustion was well started the gases from the distilling coal passed downwards and burned on meeting the air, the heat thus produced continuing the distillation. As soon as gas evolution ceased the process had to be stopped to prevent the coke from burning.

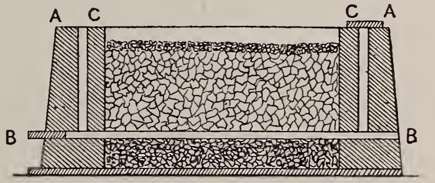

FIG. 7.—Silesian Coke Stall.

Coking in Ovens.—Coke is now usually made in ovens.

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

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.
    - *a.* 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. Waste heat ovens.
          Bauer oven. Simon-Carvès, Otto, Semet-Solvay, Simplex, Coppée, Still, C.G.O.
        - *b.* With regenerators.
          Simon-Carvès oven, Otto-Hoffman oven, Semet-Solvay oven, Otto Hilgenstock oven, Koppers oven, Huessener oven, Coppée, Simplex, Still, and C.G.O. ovens.

Beehive Oven.—The oven until recently in most common use but gradually getting displaced 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.

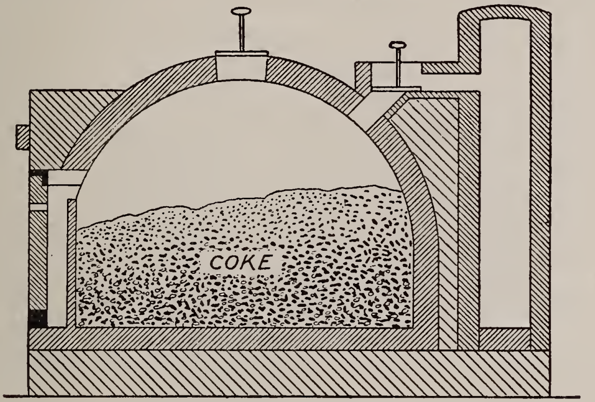

FIG. 8.—Beehive Coke Oven.

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 the form of slack 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.

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 coke 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. When 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 60 per cent; the same coal yielding in the laboratory about 70 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.

FIG. 9.—Discharging Coke Ovens.

Theory of the Process.—This is very simple. The heat of the oven causes distillation to begin, and the resulting gas coming in contact with air burns 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-grey colour. This is said to be due to the thorough escape of the gas, obtained by leaving the damper open some time after all the gas seems to have been driven 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, 10 cwt. ot 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, 48 cwt. of coal yielding about 38 cwt. 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 cwt. per week, and the yield 58 to 60 per cent.

Connellsville Ovens. — At Connellsville, Pennsylvania, the great coke district of the United States, beehive ovens have been used exclusively until recently. 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 4½ 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 sprayed in with a hose to cool the charge, which is then drawn. The yield is about 67 per cent.

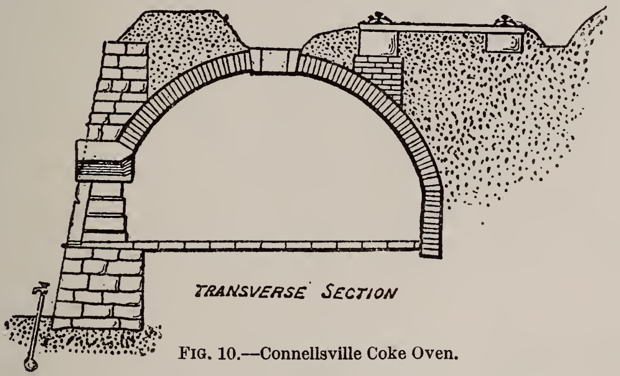

FIG. 10.—Connellsville Coke Oven.

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

Sources of Loss.—The beehive oven, though it yields an

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

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 distillation and partial combustion.

The loss under the first head is very considerable, frequently amounting to 10 or 15 per cent, 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 distillation is at any rate partially used in promoting coking.

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 partial 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 enclosed 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. In this vault rails are fixed so that trucks 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.

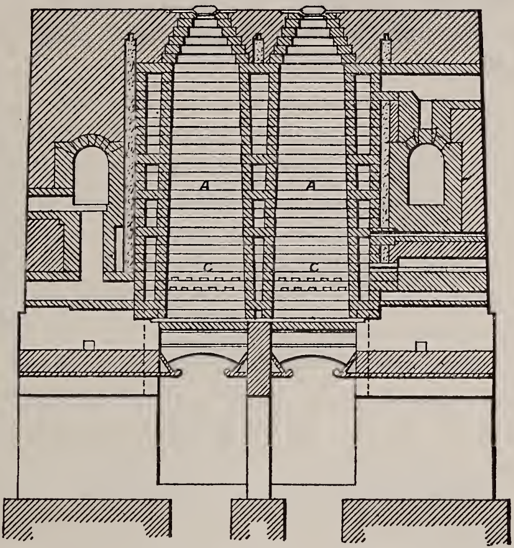


FIG. 11.—Appolt Coke Oven. A, Coking chambers. C, Lower tier of holes.

The retort having only just been discharged, the bottom doors are closed, a charge of about $1\frac{1}{4}$ 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 per cent 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.

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.

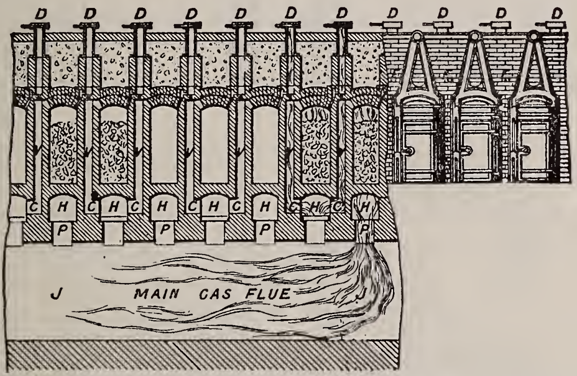


FIG. 12.—Coppée Coke Oven. V, Vertical flues between retorts. H, Horizontal flues. C, Flue connecting contiguous horizontal flues. P, Passage to main gas flue.

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 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 has probably been more largely used than any other.

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 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.

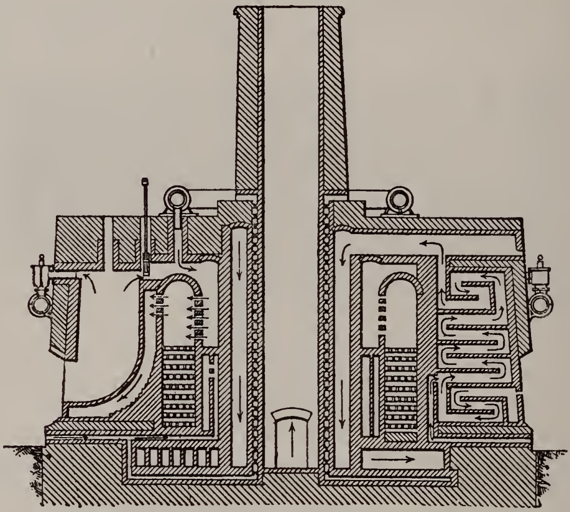


FIG. 13.—Bauer Coke Oven at Dalry. From *Engineering*. Left-hand, section through coking chambers: right-hand, through heating flues.

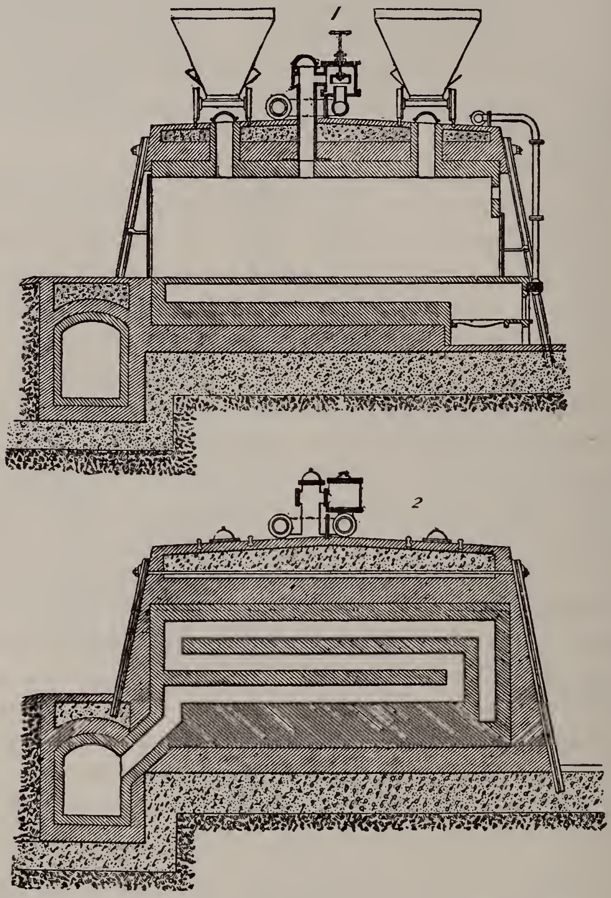
If condensation is not required the gases may be passed at once from the retort to the combustion chamber.

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 a 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 80¾ per cent of coke.

The Simon-Carvès Oven.—Of the different forms of oven arranged for the recovery of the by-products this is one of the most popular 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 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 running on rails behind the oven, and is at once



Figs. 14 and 15.—Simon-Carvès Coke Oven. Section through chamber and through flues.

quenched with water. The coking takes forty-eight hours. The coke is hard and compact, but is not so dense or lustrous as the beehive coke. 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

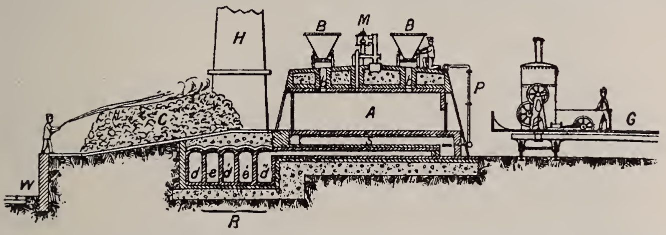


FIG. 16.—Simon-Carvès Coke Oven and Recuperator. A, Coking chamber. B, Charging trucks. M, Gas main. P, Return gas main. S, Combustion chamber. R, Recuperator. *d*, *d′*, *d″*, Air passages. *e*, *e′*, Chimney passages. G, Ram.

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.

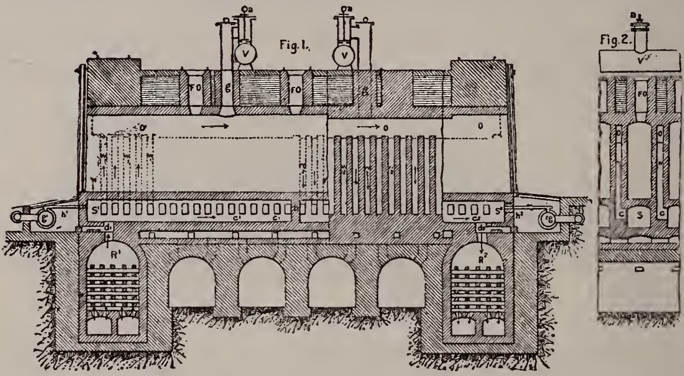


FIG. 17.—Otto-Hoffman Coke Oven. R¹, R², Regenerators. S, Combustion chamber. O, Upper flue. W, Vertical flues connecting O and S′. F O, Charging openings. V, Gas mains. C, Lateral openings from vertical flues. *d*, Hot-air passage from regenerator. *g*, Return gas main.

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°– 930° F.

The charge to the oven is about 5½ tons, and coking is complete in about 40 hours.

The Otto-Hilgenstock Oven.—This is a modification of the original Otto oven, the improvement being mainly in the way in which the gas is burned. The ovens are of the

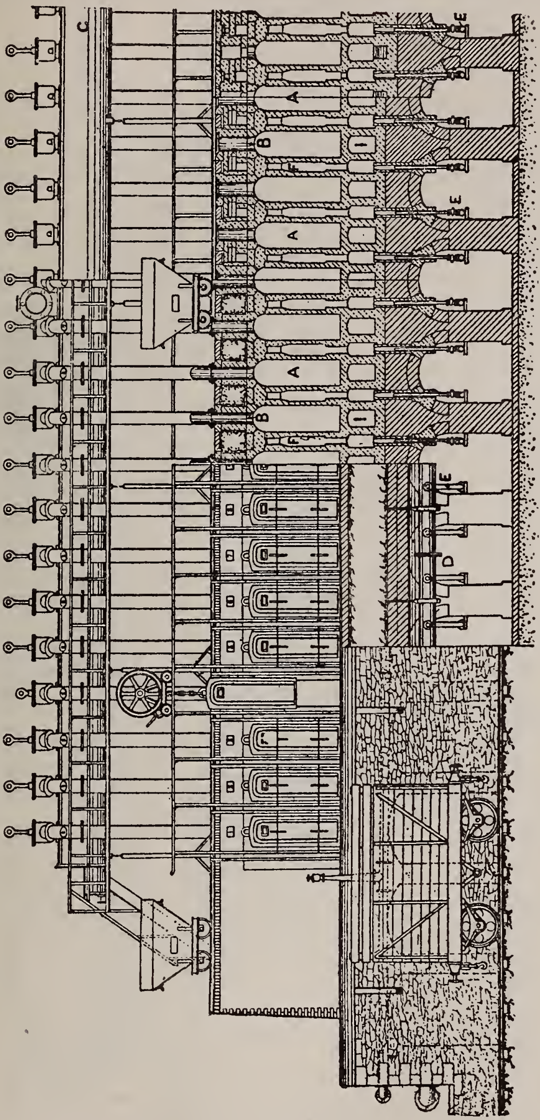


FIG. 18.—Otto-Hilgenstock Coke Oven (Longitudinal Section of Battery).

usual long retort type, about 33 feet long, 20 inches wide in the middle, and 5 feet 11 inches high, each oven usually holding about 5 tons of coal. The gas is carried away to the con-

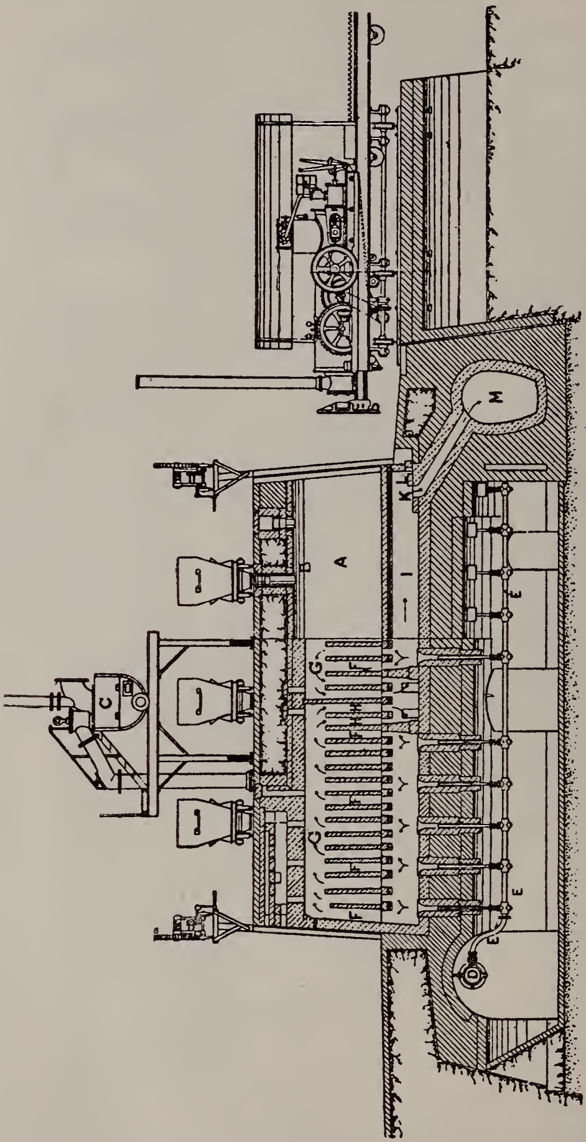


FIG. 19.—Otto-Hilgenstock Coke Oven (Transverse Section).

densing plant, and when freed from condensible substances is brought back by the pipe D to the distributing pipes E, thence by vertical pipes into the larger vertical pipes which open into the horizontal flues beneath the vertical flues in the partition walls between the ovens. These pipes form large Bunsen burners so that air for combustion is drawn in, and combustion takes place in the vertical flues F. The products of combustion pass down by the flues H to the horizontal passage under the ovens and thence by the flue M to the chimney, or they may be passed under boilers for steam raising.

The advantages claimed for this oven are uniform heating, short heating flues, and full utilization of the heating power of the gases, the yield of coke is good, the quality is good, and the oven is very durable. As more gas is produced in the ovens than is required for heating them, the excess can be used for driving gas engines or for any other purpose.

The Koppers Oven.—In this oven the arrangement of the heating is very similar; the gas is burnt by burners under the vertical flues, but the longitudinal connecting flues do not go from end to end but are divided in the middle so that the oven is heated alternately from each end. The air is heated in a regenerative chamber as in the Otto-Hoffman oven. The burners are so arranged that they can be lifted out and replaced from above, and the partition walls are built of "specially moulded fire-bricks, and it is claimed that the rhomboidal shape adopted ensures tight joints and prevents leakage." The oven was originally designed to work with blast-furnace or producer gas, so that the richer coke-oven gas might be used for other purposes.

The Semet-Solvay Oven.—This oven, which has come largely into use, is of similar 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."[1] The ovens are built in batteries, as in the

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

case of other recovery ovens. 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." [1]

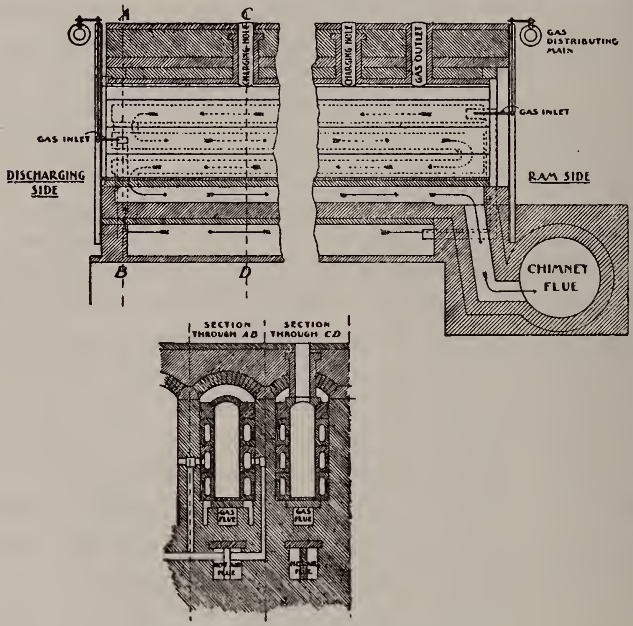


FIG. 20.—The Semet-Solvay Coke Oven.

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. They pass the whole length of the oven, and descend into the next

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

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.

The time of coking is about 24 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.

The Huessener Oven.—This is an oven of a similar type. Part of the gas enters a flue under the oven, passes along the whole length, is carried up and then into a series of horizontal flues in the wall of the oven. In each of these horizontal flues more gas and air are supplied, so as to maintain a high temperature, and the products of combustion are finally carried away by a flue, their sensible heat being used to raise steam. Between each pair of ovens there is a wall of fire-brick which carries the roof of the oven, and the heating flues are arranged on each side of this, so that each coking chamber has an independent series of flues on each side of it.

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.

Coal Compression.—It has long been known that the coke obtained from many coals was greatly improved if the coal was compressed before coking. Many attempts were made to carry out the compression in a rough-and-ready way by loading the coal with heavy weights after it had been charged into the oven, or by forcing the discharging ram against the coal, the discharge door being closed, but such methods were both inconvenient and unsatisfactory. Within the last few years several machines have been devised for compressing the coal before it is put into the oven, the best known of the older types being that of Kuhn, made by Messrs. Kuhn & Co. of Bruch, Westphalia, which may be taken as a type. In this type of machine the coal is compressed into a solid block before it is put into the oven. A machine running on rails on the charging side of the oven is used, forming a carriage which can be drawn along to any oven as required. This carriage carries a strong iron plate about the same size as the bottom of the oven, which can be pushed into the oven, and which serves as a sort of " peeler " on which the block can be pressed and charged into the oven. At one end of the set of ovens is a raised platform along which the trucks carrying the coal can be run ; in front of this is the compressing box, built up of strong iron plates so arranged that when fixed in position they form a box the interior of which is very slightly smaller than the interior of the oven, and the bottom of which is the peel on the carriage already mentioned. Above this box is fixed a stamper worked by a mechanism so that it can be lifted and then pressed down. The coal is run into the stamping box in small portions at a time, each layer being compressed before the next is put in. When the box is full, the sides are turned up, and the block of coal on the peel is moved till it is opposite the oven which is ready to receive it and which has just been discharged, and the peel with its load is pushed into the oven. The door on the charging side is then put in place and fixed, a space being left beneath it for the peel. As soon as the door is fixed the peel is withdrawn and the mass of coal is left in the retort. The time occupied in filling, stamping, and charging is about 20 to 25 minutes, so that one compressor can serve about 60 ovens if the time of coking is over 30 hours. The coal is well moistened so that it may cohere, and 10 to 12 per cent of moisture should be present. The coke produced when a stamper is used is very firm and compact ; the output is not increased because, although the compressed coal occupies less space and the ovens can hold a larger charge, the charge takes much longer to carbonize. The coal is compressed about 25 per cent, but the block must be a little smaller than the oven so that it may be readily inserted.

By-products Recovered.—The by-products recovered are tar and ammonia and benzol. The tar varies in quality according to the temperature of distillation, but is rich in members of the benzene series. It is redistilled and various products are obtained, such as crude naphtha, benzol, light oils, creosote oils, etc., and a residue of pitch is left. The total amount of tar is about 4 per cent of the weight of the coal used. The amount of sulphate of ammonia obtained is about 1 per cent of the weight of coal used, or say 23 lb. per ton. Benzol is extracted from the gas, the amount recovered averaging about 2 gallons per ton of coal.

Comparison of Coke Ovens.—It is not easy to compare the relative merits of coke ovens, because so many points have to be taken into account, and the various types have not 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, to no less than 60,000 tons of ammonium sulphate per annum, 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, probably equivalent at the present time to nearly half a million tons per annum.

All this might be saved by the use of the recovery ovens.

The Coal Conservation Committee of the Ministry of Reconstruction in their final report, 1918, give 14·6 million tons as the amount of coal carbonized in by-product ovens for the year 1916, as against 5·5 million tons from all other types, making a total of 20·1 million tons of coal converted into metallurgical coke. They point to the rapid decline in the number of beehive ovens in recent years :

Year.	Number of Beehive Ovens.
1910	16,037
1911	14,301
1912	13,833
1913	13,167
1914	9,210
1915	7,521
1916	6,892

They supply the information that in November 1917 some 8700 by-product ovens were in operation in Great Britain, of which 8000 were fitted with benzol recovery apparatus ; the following table showing the numbers and total capacities of the different types of ovens in use :

Make of Oven.	Number of Ovens.			Total Rated Carbonizing Capacity. Million tons of coal per annum.
	Built and in operation.	Regenerative type.	With Benzol Plants.	
Otto	2290	553	2234	4·91
Simon Carvès	1876	870	1876	2·75
Koppers	1588	1588	1522	3·50
Semet-Solvay	1417	96	1417	2·88
Simplex	463	93	416	1·00
Coppée	369	60	369	0·74
B.C.O.	65	25	65	0·18
All others	(632)	..	(101)	1·50
Total	8700	..	8000	17·46

Coke experts are agreed there is little to choose between beehive coke and the best by-product oven coke.

Fig. 21 illustrates a modern successful type of coke quencher—the Goodall machine. This consists essentially of a massive rotating table receiving the coke from a Darby quencher. The coke is carefully extinguished so as to minimize the final water content, and a movable plough allows it to pass over a screen direct into the wagon.

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.

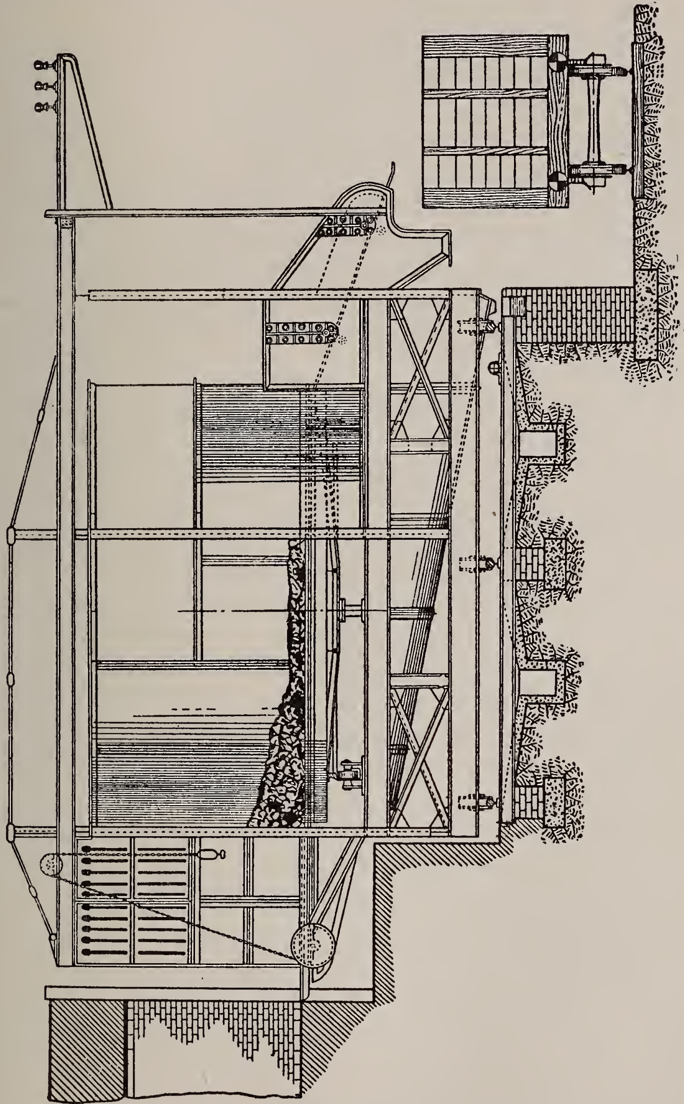

FIG. 21.—The Goodall Coke Quenching, Screening, and Loading Machine.

When hot coke is quenched with water, hydrogen sulphide is sometimes evolved in small quantities 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 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 has, on an ash-free basis, practically the same calorific value as 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 not so suitable as coal; used by itself, it requires forced blast, but, when sandwiched between layers of coal, it burns freely. 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, coke dust, 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 lb., or into small egg-shaped lumps. 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 loaded in bulk, as when delivered 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 lb., the calorific power about 14,000 B.Th.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 and coke-oven 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 lb., but in practice nearly 100 lb. 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 is 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 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.

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

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 9s. 7·5d. per ton, made up as follows :

	s.	d.
Labour	1	0·9
Supplies	0	5·5
Fuel (for boilers, etc.)	0	7·2
Materials for briquettes	7	1·7
Interest and depreciation	0	4·2
	9	7·5

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 usually commands a low price, 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

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

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.

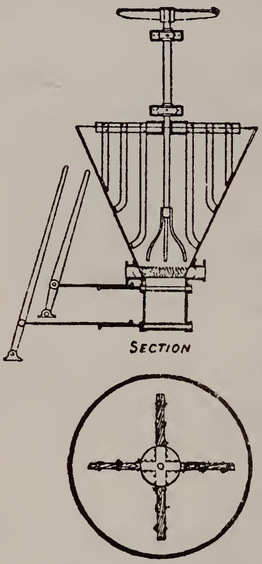

Fig. 21a.—Robinson Coal-washer. From Lock's *Mining Machinery*.

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.

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, etc., 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 whose principle is most 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.

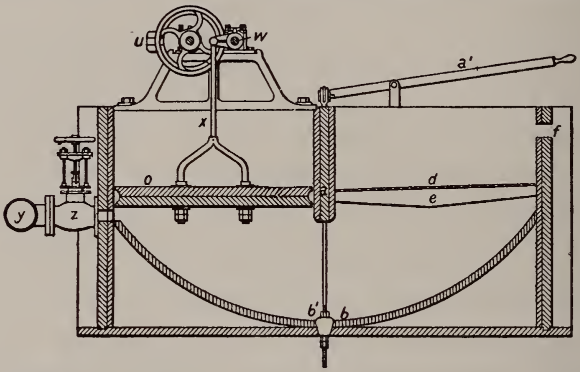

Fig. 22.—Lührig's Coal-washing Jig. From Lock's *Mining Machinery*. *z*, Pipe for supply of water. *o*, Piston. *d*, Screen. *e*, Bars to carry screen. *f*, Opening for escape of coal. *b*, Valve for removal of sludge, worked by lever *a′*.

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.

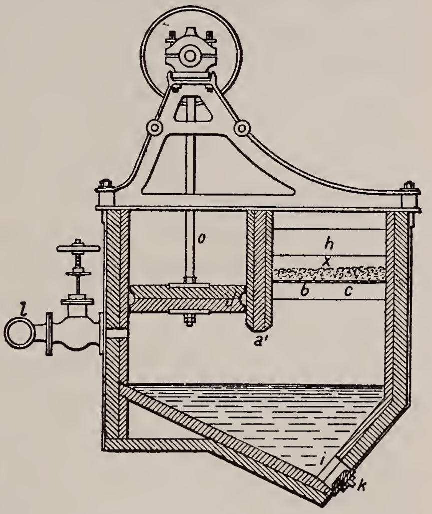

FIG. 23.—Lührig's Fine Coal Jig. From Lock's *Mining Machinery*. *l*, Water pipe. *d*, Piston. *o*, Piston-rod, *b*, *c*, Screen and its supporting bars. *x*, Layer of felspar pebbles. *k*, Trap for removal of sludge. *h*, Overflow of coal.

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.

Other Types of Coal-washing Plant.—Other and more modern systems of coal-washing plant that call for mention—it would lead us too far to describe them—are the Coppée, Baum, the Draper, the Blackett, and the Hoyle systems. The froth flotation process, used very largely in America for the purification of minerals, can also be used with advantage for separating the gangue from very small coal; in this process about a pound of oil per ton of coal is required to assist aeration, and it is necessary to disintegrate the coal so as to allow it to pass through a screen of one-tenth inch mesh.

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 for the manufacture of sulphuric acid. The wetting of the coal is sometimes a disadvantage, for example, for gas-making.

The percentage of ash and sulphur is very much reduced, thus greatly increasing the value of the coal, as the following examples will show:

[Table

Colliery.	Capacity of Plant per day.	Ash.	
		Unwashed.	Washed.
Aston Hall Colliery . . .	1000	21	4¼
Rosehall	800	20	4¼
Bardykes	800	22	4½
Motherwell.	1500	21½	4¼

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, 2·84 per cent.

CHAPTER VI

LIQUID FUELS

Natural Oils.—Natural oils or petroleums are found in many parts of the world and are now a most important source of thermal energy. The principal oil-producing countries are: United States, Russia, Mexico, Dutch East Indies, India, Galicia, Japan, Roumania, Peru, Trinidad, Argentina, Egypt, and Germany.

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	22630	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.

World's Output of Petroleum.—The following table gives a survey of the approximate quantities of crude natural oil produced by the principal oil-bearing fields of the world for the year 1917.

	Million Tons.	Percentage of total.
United States	48	67
Russia	10	14
Mexico	8·0	11
Dutch East Indies	1·9	2·6
India	1·2	1·7
Galicia	0·85	1·2
Japan and Formosa	0·41	0·6
Roumania	0·37	0·5
Peru	0·36	0·5
Trinidad	0·23	0·3
Argentina	0·16	0·2
Egypt	0·14	0·2
Germany	0·14	0·2
Total about	72	100·0

Imports of Petroleum Products.—The following are the approximate quantities of petroleum products imported into the United Kingdom for the years 1913 and 1918 :

	Millions of Gallons.	
	1913.	1918.
Crude Petroleum	1·1	..
Lamp Oil	157	148
Lubricating Oil	68	102
Gas Oil (Solar Oil)	66	41
Fuel Oil	95	842
Motor Spirit	101	193

The figures for fuel oil for 1918 include the enormous quantities used by the Navy.

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-

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[1] Venango County in Pennsylvania.

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 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 from 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 of 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 per cent to 20 per cent, oils 76 per cent to 78 per cent, residue 5 to 9 per cent, and loss, *i.e.* permanent gases, about 5 per cent.

The heavy oil may be used as fuel direct, or it may be subjected 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 per cent of the crude oil, and to use the residue, known as petroleum refuse, as fuel. The results obtained being: light petroleum 5 to 6 per cent, burning oil (1), (kerosene) 27 to 33 per cent, burning oil (2), (solar oil) 5 to 6 per cent, residues 50 to 60 per cent.

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	57·60	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 are washed for recovery of ammonia and light oils before being used as fuel. 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, petroleum naphthas, and paraffin wax. About 4 million tons of oil shale are annually subjected to destructive distillation in the south of Scotland, producing about 400,000 tons or about 100,000,000 gallons of crude oil.

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 30 gallons of tar ; this is distilled in wagon-boiler retorts, or special stills, 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.
8. Reduction of discomfort of loading fuel, clinkering fires, and stoking.

Against these advantages may be set the disadvantages of :

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

The first and second disadvantages are eliminated by a proper choice of the oil whereby a high boiling oil with high flash-point is specified.

Future of Oil Fuel.—In spite of the fact that before the war a therm (100,000 British Thermal Units) cost two or three times as much in the form of oil as it did in the form of coal, and that since then the discrepancy has still further increased, there have been immense developments in the use of oil fuel, more especially for the Navy and Atlantic liners. For the Navy, speed of renewal of fuel, convenience of taking supplies of oil from oil-tankers at sea, increased radius of action, increased speed, and reduction of hands are advantages of paramount importance.

Atlantic liners, too, find it to their advantage to be able to shorten considerably the time required for a double trip, and to increase their passenger accommodation by the reduction of the crew.

When oil engines are used, the increased thermal efficiency of internal combustion may more than counterbalance the additional cost of heat units supplied in liquid form.

As regards light oils, like petrol, gasoline, benzol, and alcohol, the demand for motor vehicles of all kinds, for motor boats, for aeroplanes and airships is ever on the increase, with the result that all possible sources of supply are being sought out, although it is only a few years since oil refiners in the foreign oil-fields were finding that the production of light spirit very much more than satisfied all demands. Of late years vast quantities of motor spirit—as much as 100,000,000 gallons per annum—have been obtained by washing certain grades of natural gas with heavy oil in a similar way to that employed for coke-oven gas. Methylated spirit and mixtures of methylated spirit with benzole have also been brought into use as motor spirit.

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 most 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.Th.U.	Water at 212°
Pennsylvania heavy crude oil . . .	·886	84·9	13·7	1·4	..	20740	21·48
Caucasian light crude oil	·884	86·3	13·6	·1	..	22030	22·79
Caucasian heavy crude oil	·938	86·6	12·3	1·1	..	20850	17·3
Mexican fuel oil . .	·965	81·5	11·2	3·5	3·7	18450	19·1
Petroleum refuse .	·928	87·1	11·7	1·2	..	19830	17·1
Good English coal, average of 98 samples	1·380	80·0	5·0	8·0	1·25	14110	12·16

Essential Qualities in a Fuel Oil.—1. The water content should be as low as possible, certainly not more than 2 per cent. Petroleum is easily obtained in a dehydrated condition, as it is the practice to distil off the light fractions for motor spirit, the middle fractions for lamp and lubricating oil, leaving the fuel oil behind, the water being also distilled off in the process. It sometimes happens that live steam is used to warm the thick oil to make it flow more readily, and there is then a great danger of emulsifying the oil with the condensed steam, and samples may be found containing as much as 25 per cent of water. The chief danger in the presence of water is the extinguishing of the burner flames. The bulk of the water may be separated out in the storage vessels by heating up the emulsion to at least 70° C., and allowing the whole mass to remain hot for a day or two.

Heavy coal-tar, carburetted water-gas tar, and producer-gas tar are particularly troublesome to dehydrate once they have got into the state of emulsion. It is not uncommon to find such tars containing 50 per cent of water, a quantity which naturally detracts greatly from their value. Various types of dehydrating plants are in use, the more convenient designs being continuous in their action. A good coal-tar should contain not more than 4 or 5 per cent of water, before dehydrating, if made and stored under proper conditions.

2. Freedom from solid matter is another essential. Coal-tar generally contains a considerable amount of "free carbon"—solid matter insoluble in benzene or petrol. This is usually for the most part very finely divided, being the result of "cracking" the heavier tar oils in the process of carbonization. The content varies from about 3 per cent in vertical retort tar to 30 per cent in some tars from horizontal retorts and coke ovens. Not only is free carbon present in most tars, but also grit consisting of coal, coke, or ash, and it is this grit that is most objectionable, as it is very liable to choke the fine orifices of the burners unless special filtering arrangements are installed.

3. The flash-point must be sufficiently high so as to avoid as much as possible the risk of the accumulation of vapours which would form an explosive mixture with air.

For safety it should not be less than 140° F. This condition usually necessitates the elimination by distillation of the light fractions.

4. The viscosity should not be too high at ordinary temperatures, otherwise the rate of loading and unloading will be seriously retarded. The British Admiralty (1913) specifies a viscosity of not more than 2000 seconds for an outflow of 50 c.c. at a temperature of 32° F., as determined by Sir Boverton Redwood's Standard Viscometer (Admiralty type for testing fuel oils).

Creosote oil containing naphthalene has a remarkable thinning effect on thick tars and may sometimes be used with advantage.

5. The proportion of sulphur in the oil should not be excessive. It is difficult to define the amount that may be considered excessive. The British Admiralty specifies a limit of 3 per cent, whereas the United States Bureau of Mines would impose a limit of 1 per cent. Where the waste gases remain hot there is little danger of corrosion from sulphur acid gases, and it would seem possible to consume with impunity fuel oils having a high content of sulphur. Pennsylvanian and Russian petroleum contain not more than 1 per cent and Texas petroleum 2 per cent. Mexican fuel oil contains $3\frac{1}{2}$ per cent, and Norfolk shale oils as much as 6 or 7 per cent, of sulphur.

6. It is necessary sometimes to specify freedom from acid, seeing that sulphuric acid is used in the refining of oils. This, according to the British Admiralty specification, should not exceed 0·05 per cent calculated as oleic acid.

7. The specific gravity will of course vary with the nature of the oil fuel, ranging from 0·85 for shale oil to 1·2 for heavy coal-tar, as measured at 60° F.

The coefficient of expansion (ratio of the increase in volume for one degree to the original volume) must be allowed for in determining tonnage by volume measurement. For coal-tar this is 0·00032, for water-gas tar 0·00035, and for petroleum 0·00038 per degree Fahrenheit.

8. The calorific value on the dry basis varies from 16,000 to 22,000 B.Th.U. per lb. It is lowest where there is a large amount of oxygen compounds or much free carbon, as in certain coal-tars, and highest where the oils consist of naphthenes or other unsaturated hydrocarbons and little oxygen.

The above conditions are sufficiently wide to embrace almost all heavy oils and tars that do not contain too much water or grit. In fact the term " fuel oil " is rather misleading, seeing that the material generally supplied as fuel for shipping more nearly resembles thick tar than oil.

Oil Fuel for Internal Combustion Engines.—The oils generally used for engines of the Diesel or semi-Diesel type are the middle oils, too heavy for motor spirit and unnecessarily light for furnace work. There is no definite specification for suitable oils. Moisture and carbon and grit must naturally be excluded as far as possible. The flash-point will be over 72° F. and no special precautions will therefore be necessary in storage and distribution. The sources from which the oil can be drawn are many and wide. Even coal-tar made in vertical retorts and low in free carbon content has been used with success in Diesel engines. Nevertheless, uniformity of quality is essential. Diesel oils have a low vapour tension and can only vaporize sufficiently to form an explosive mixture with air in a hot cylinder. The necessary temperature is attained by high compression of the air used, and the degree of compression will vary with the nature of the oil. Formerly illuminating oils, such as paraffin oil, were chiefly in demand, but there is now a tendency to utilize cheaper heavy oils of all kinds. The consumption is from 0·4 lb. upwards per B.H.P. hour.

Motor Spirit.—For high-speed internal combustion engines, suitable for quick starting, either a combustible gas or a volatile oil readily producing a combustible vapour is employed. The principal light spirits now in use for this purpose are petrol, benzol, and alcohol.

Petrol.—This forms by far the largest bulk of light spirit consumed by motor vehicles. It consists of the more volatile, or low boiling, constituents of natural petroleum or of the heavier vapours occurring in natural gas. It is recovered from petroleum by a process of fractional distillation or from the natural gas by oil washing, stripping, and distillation. It contains principally paraffin hydrocarbons of the general formula, $CnH_2n + 2$, such as

Pentane, C_5H_{12},	sp. gr.	0·64,	boiling at	37° C.
Hexane, C_6H_{14},	,, ,,	0·67	,, ,,	69° ,,
Heptane, C_7H_{16},	,, ,,	0·69	,, ,,	98° ,,
Octane, C_8H_{18},	,, ,,	0·71	,, ,,	125° ,,
Nonane, C_9H_{20},	,, ,,	0·73	,, ,,	150° ,,

also naphthenes of the general formula, CnH_2n, such as hexamethylene, C_6H_{12}, and other methylene hydrocarbons.

Ordinary petrol distils completely over between 60° and 170° C., the bulk of it boiling between 90° and 110°. More reliance is to be placed on petrol which is lighter or has the lower boiling range, especially for aeroplane work where the atmospheric temperatures may be very low.

The specific gravity varies between 0·68 and 0·72. The average composition is roughly 85 per cent of carbon and 15 per cent of hydrogen. The gross calorific value averages about 20,100 and the net value 18,500 B.Th.U. per lb. The sulphur content is so small as to be negligible.

Benzol.—This is known to the chemist in the pure state as benzene, C_6H_6. It is the first member of what is called the aromatic series of hydrocarbons. In commercial benzol it is accompanied by the higher homologues, toluene, C_7H_8, and xylene, C_8H_{10}. Its principal sources are coal-gas, coal-tar, and certain petroleums (Borneo, Rumania).

The specification issued by the Automobile Association (1919) is as follows :

1. Specific gravity, 0·87 – 0·88.
2. Flask distillation, not less than 75 per cent by volume at 100° C., not less than 90 per cent at 120° C., and not less than 100 per cent at 125° C.
3. Sulphur not to exceed 0·4 per cent.
4. Entirely free from water.
5. Colour—water-white.

6. 90 c.c. of the benzol shaken with 10 c.c. of 90 per cent sulphuric acid for five minutes shall not give more than a light brown colour to the acid layer.
7. Entirely free from acids, alkalis, and sulphuretted hydrogen.
8. Shall not freeze at 7° C.

The calorific value is usually about 17,800 B.Th.U. per lb. gross and 17,100 net. Although these values are lower than those of petrol per lb. the specific gravity is so much higher that the net calorific value of a gallon of benzol is about 14 per cent higher than that of a gallon of petrol.

Benzol has the disadvantage of freezing easily. Pure benzene freezes at 6° C. (43° F.). The freezing point, however, is lowered by the addition of small quantities of petrol or alcohol. It does not start the engine so easily as petrol, and requires considerably more air for combustion.

ALCOHOL, C_2H_5OH.—The importance of alcohol as a fuel will necessarily be more and more recognized as the resources of coal and oil become exhausted. It is the only liquid fuel of any account which can be artificially produced from the earth's soil. Potatoes and other foodstuffs containing starch or sugar yield large quantities of alcohol by a process of fermentation and subsequent distillation. Cost of production and Excise restrictions at present limit its extended use.

New processes of manufacture from cheaper materials, such as wood-pulp or even peat, are being developed and give promise of a great future for alcohol as a motor spirit.

Alcohol has a comparatively low calorific value—90 per cent alcohol giving 11,100 gross and 10,100 net per lb.—but it gives a high thermal efficiency owing to the high compressions that may be used without fear of pre-ignition. It is less dangerous than petrol or benzene for storage as its flash-point is higher. It has the advantage of being miscible with benzene. The explosive range is greater than that of benzene vapour or petrol vapour, and as the rate of propagation of the flame is slower there is a greater latitude and also steadier pressure in the working of the engine.

The following comparison of the three spirits in tabular form brings out the chief points of difference :

	Petrol.	Benzol.	Alcohol.
Specific gravity . . .	0·72	0·88	0·82
Boiling points	60° – 170° C.	80° – 125° C.	80° – 110° C.
Freezing point . . .	Below – 100° C.	Below 6° C.	Below – 100° C.
Calorific value—			
B.Th.U. per lb. gross . .	20,100	17,800	11,100 (90%)
B.Th.U. per lb. net . .	18,500	17,100	10,100 ,,
B.Th.U. per gallon gross .	144,700	156,600	91,000 ,,
B.Th.U. per gallon net .	133,200	150,500	82,800 ,,
Theoretical air for combustion cubic feet per gallon . .	1440	1560	940
Explosive range— per cent of vapour . .	1 – 5¼	2¾ – 6¼	4 – 13½
Safe compression— lbs. per square inch . .	Up to 70	Up to 80	Up to 200
Heat of evaporation (calories)	85	93	237
Specific heat	0·46	0·42	0·65
Co-efficient of expansion— per degree C. . . .	0·0008	0·0014	0·0011

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 any one 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 ironworks 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 lb. 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 we may assume an average composition and multiply by the respective calorific values of the constituents (in B.Th.U. (gross) per cubic foot) :

Carbon dioxide	0·006				
Carbon monoxide. . . ,	0·006	×	320	=	1·9
Oxygen	0·008				
Ethylene	0·010	×	1580	=	15·8
Ethane	0·050	×	1650	=	82·5
Methane	0·670	×	998	=	668·7
Hydrogen	0·220	×	321	=	70·6
Nitrogen	0·030				
	1·000				839·5

As 1000 cubic feet of gas of the above composition weigh almost exactly 38 lb., the calorific value per lb. is 22,090 B.Th.U. (gross), a much higher value than the best coal or coke.

The gas is practically free from sulphur. On strong heating it splits up and deposits 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. Its principal uses are for domestic lighting, heating, and cooking. It has a very high calorific power, and is an excellent fuel. It is too expensive for general furnace use, but is employed with success in many minor operations where only a small quantity is required, and its cost is only of secondary importance. In recent years town-gas has been extensively used in industrial centres for metal melting and annealing, for glass-working and various other purposes. Some idea of the extent to which town-gas is now consumed can be gained from the following data published by Dr. C. M. Walter (*Gas Journal*, October 27, 1920): For the year 1912–13 the total volume of gas supplied for industrial heating (that is, apart from household gas-fires and cookers) in the city of Birmingham area was 609,000,000 cubic feet, being the gas yield from 50,000 tons of coal. For the year 1918–19 the gas supplied for industrial heating was 2,522,000,000 cubic feet, the yield from 200,000 tons of coal. In the former case it represented 6·7 per cent of the total output of town-gas, in the latter 21·0 per cent. It is most conveniently supplied in special mains under a pressure of about 12 lb. per square inch, and the furnaces may work directly off high-pressure gas jets inducing their own air supply, or the gas may be used at ordinary pressure with or without air blast. The amount of gas yielded by coal varies from 10,000 to 14,000 cubic feet per ton. The gas to be used for lighting purposes is carefully purified from sulphuretted hydrogen. Formerly carbon dioxide and sulphur compounds were also almost entirely eliminated, but the advent of the incandescent burner rendered this course less necessary. The pre-war cost of gas varied in this country, say, from 1s. to 5s. per 1000 cubic feet, the usual cost being probably about 2s. 6d. 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-, cannel-, and oil-gas :

	1.	2.	3.	4.
Carbon dioxide	0·8	2·5	0·8	0·5
Oxygen	0·7	1	0·7	. .
Unsaturated hydrocarbons . .	4·5	3	15	35[1]
Carbon monoxide	7	8	6·5	0·5
Methane	35	25·5	35	43
Hydrogen	45	46	35	20
Nitrogen	7	14	7	1

1, An average lime-purified coal-gas of year 1900.
2, ,, ,, oxide- ,, ,, ,, ,, 1920.
3, ,, ,, lime- ,, cannel-gas ,, 1900.
4, ,, ,, oil-gas.

We may calculate the gross calorific value of No. 2 as follows, taking the unsaturated hydrocarbons C_mH_n as having a value of 2320 B.Th.U. per cubic foot :—

$$\begin{array}{llcrcr}
C_mH_n & . \quad . \quad . & 0{\cdot}03 & \times \; 2320 & = & 69{\cdot}6 \\
CO & . \quad . \quad . & 0{\cdot}08 & \times \; 320 & = & 25{\cdot}6 \\
CH_4 & . \quad . \quad . & 0{\cdot}255 & \times \; 998 & = & 254{\cdot}5 \\
H & . \quad . \quad . & 0{\cdot}46 & \times \; 321 & = & 147{\cdot}7 \\
\hline
 & & & & & 497{\cdot}4
\end{array}$$

Under the new Gas Regulation Act (August 1920), town-gas is to be sold on a basis of thermal units, gross value, the unit of sale being called the therm, which is standardized as 100,000 B.Th.U., gross. Assuming a gas of 500 B.Th.U. to cost 3s. 4d. per 1000 cubic feet, the price per therm is 8d.

A coal having a calorific value of 12,500 B.Th.U. per lb., and costing 37s. 4d. per ton, represents a cost per therm of 1·6d. or one-fifth of the above figure. In spite of this

[1] Includes Ethane

difference there are many cases where town-gas is able to displace coal.

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.

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.

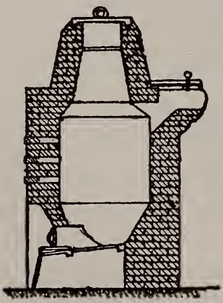

FIG. 24.
Bischof Gas Producer.

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, 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.

"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 $\frac{3}{4}$ caking coal and $\frac{1}{4}$ non-caking coal, is as follows by an analysis dated July 1865 (by volume):

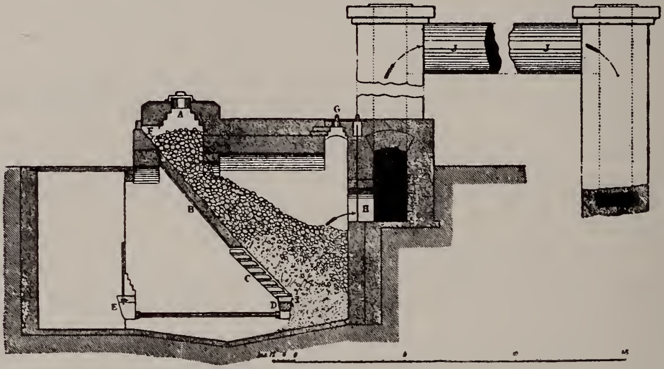

FIG. 25.—Siemens Gas Producer.

Carbonic oxide	23·7	24·2	34·6
Hydrogen	8·0	8·2	
Methane	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]

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

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 lb. 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 indraught 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.

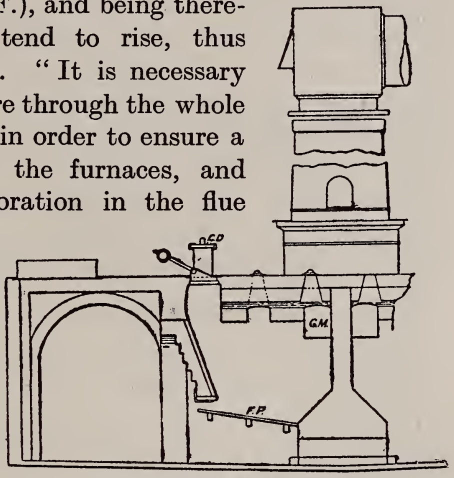

Fig. 26.—Siemens Gas Producer.

"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 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 cubic foot at 1100° F. = ·022 lb.
,, ,, ,, ,, 100° F. = ·061 ,,
Weight of atmosphere per cubic 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 downtake 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 $\frac{\cdot 054}{\cdot 039} \times 10$ feet = 13 feet 10 inches, or say 14 feet."[1]

Siemens further points out that objection has been taken

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

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.

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.

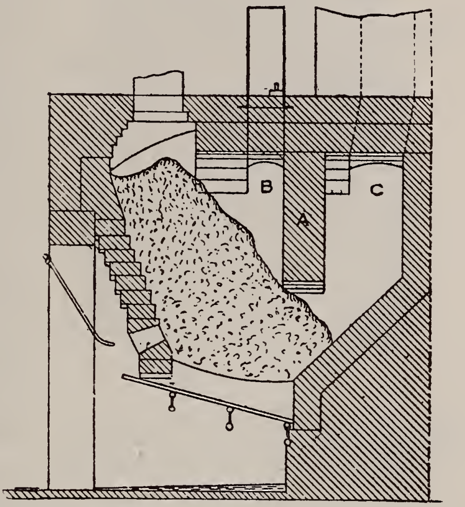

FIG. 27.—Siemens Producer arranged for the Destruction of Tar. A, Descending wall. C, Gas main. B, Cleaning door.

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 in the producer, and permanent gases which will pass away, it 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.

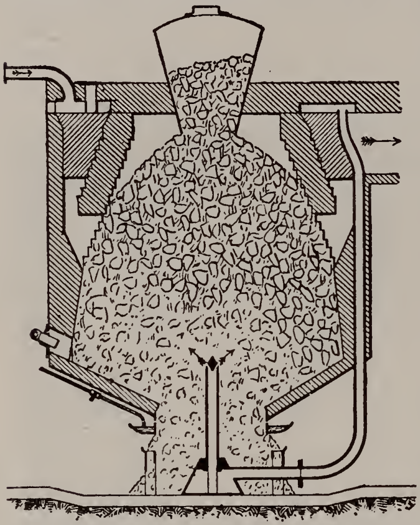

FIG. 28.—Siemens Gas Producer, circular form.

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.

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 may be 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.

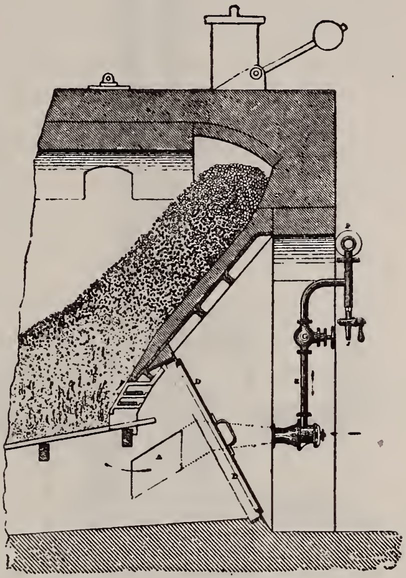

FIG. 29.—Siemens Closed-hearth Producer.

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

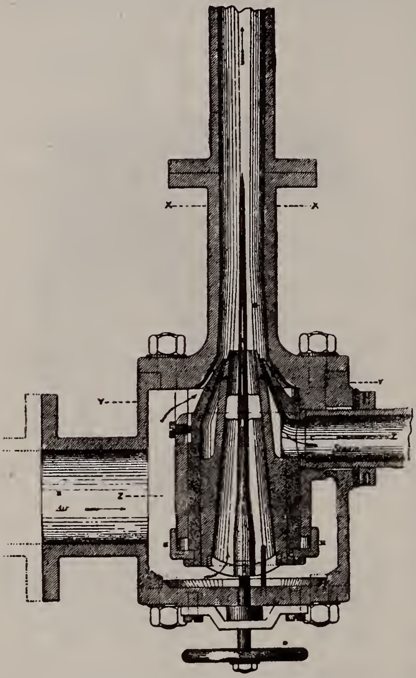

FIG. 30.—Siemens Steam Jet.

"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 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]

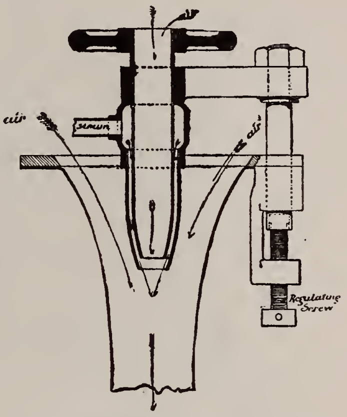

FIG. 31.—The Thwaite Annular Steam Jet. Details of head and adjustable nozzle.

Thwaite Steam Jet.—This is a somewhat simpler form of jet, now largely used. As will be seen, the area of the annular steam jet can be easily reduced or enlarged by

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

lowering or raising the inner tube by means of the regulating screw.

The Thwaite Simplex Producer.—This consists of a circular iron shell lined with fire-brick, with a grate at the bottom, the bars of which are placed slightly sloping ; steam and air are blown into the ash-pit. The gas is drawn off at the side beneath a curtain wall. The air before being used is heated by circulating in a jacket surrounding the casing.

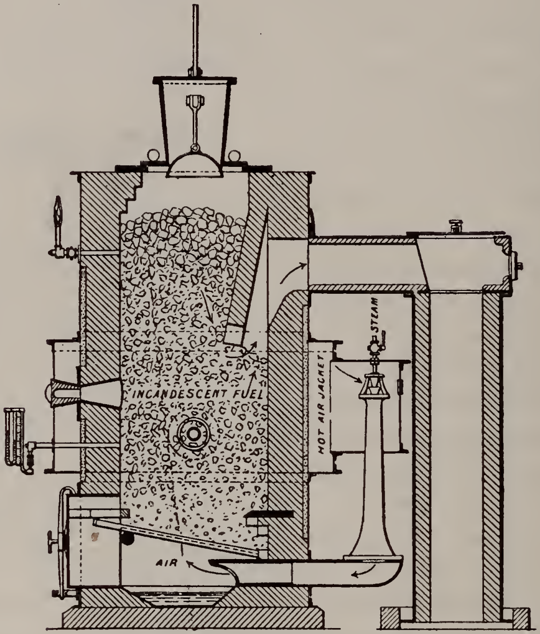

FIG. 32.—Thwaite Simplex Producer.

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.

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.

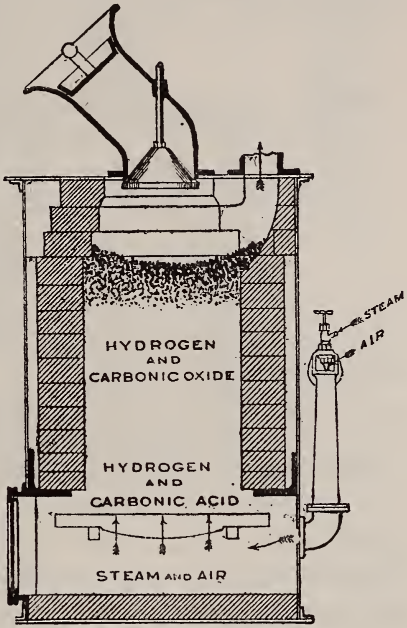

FIG. 33.—Dowson Producer.

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.

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 in traversing the hot coke the 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.

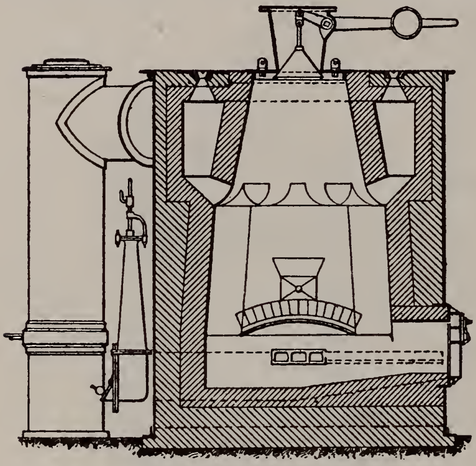

Fig. 34.—Wilson Producer.

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 lb. per square foot of bottom in ordinary cases, but with a good steam supply it may be brought up to 40 lb.

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.

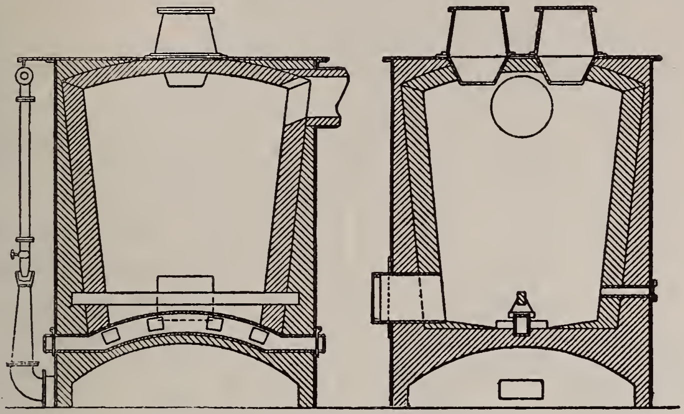

FIG. 35.—Modified Type—Wilson Producer.

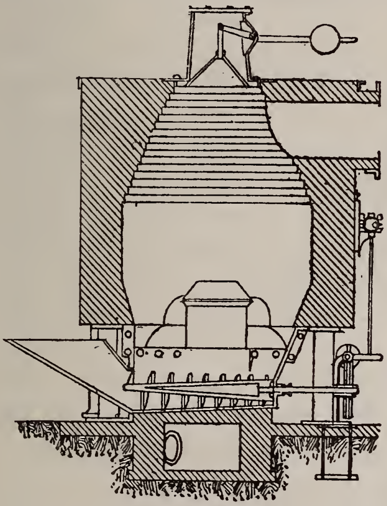

FIG. 36.—Wilson Automatic Gas Producer.

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 cwt. of coal per hour, producing 30,000 cubic feet of gas.

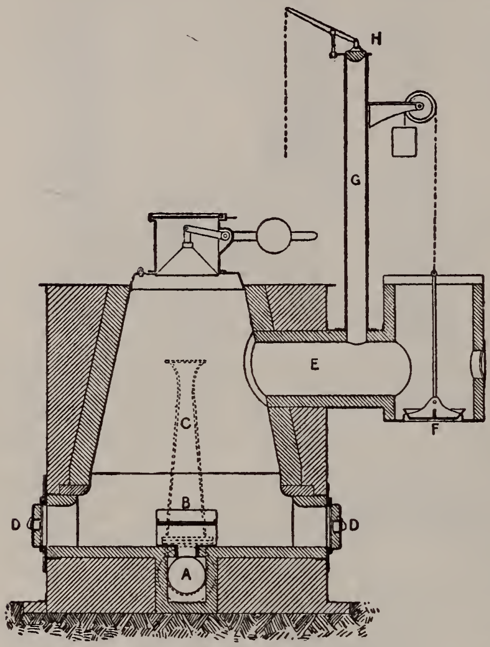

FIG. 37.—Ingham Producer.

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.

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 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.

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.

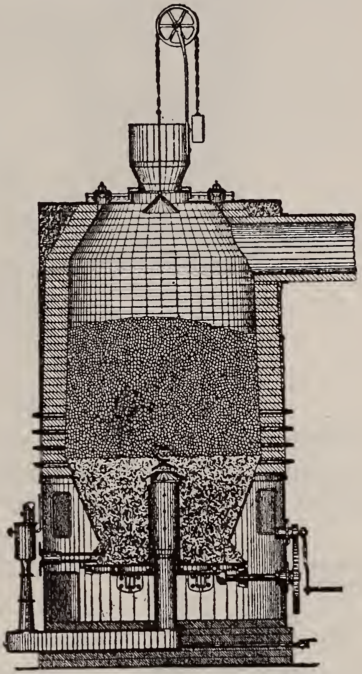

FIG. 38.—The Taylor Revolving-bottom Gas Producer. 9 feet inside diameter.

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 communicating with the gas main. Air and steam are introduced at the bottom 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 is therefore well suited for use in gas-engines.

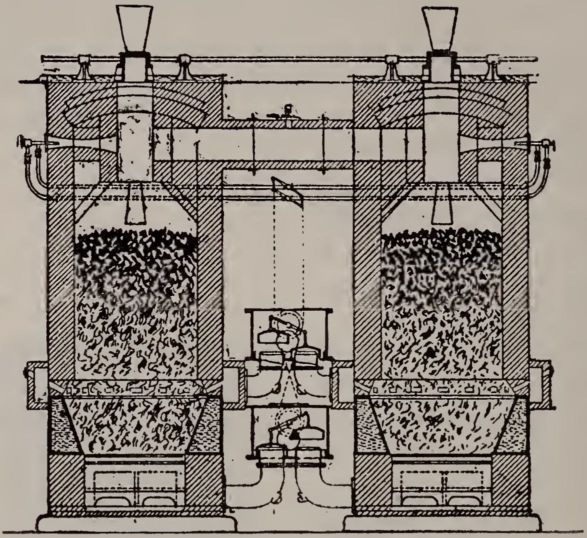

FIG. 39.—Thwaite Duplex Producer.

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.

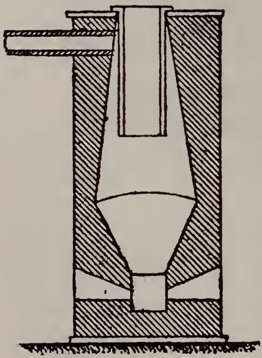

FIG. 40.—Ebelmann's Gas Producer.

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 producer, 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 clinker, 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 blocks are required in the building. A man-hole is placed at any convenient part, the only door

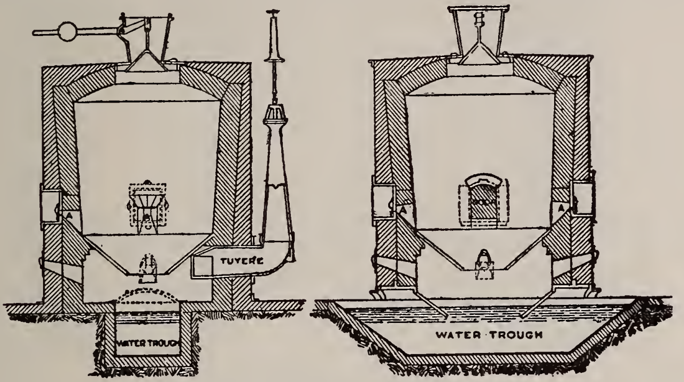

FIG. 41.—Dawson Gas Producer.

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] In a more modern form the cast-iron hopper is dispensed with, and its ashes rest on the bottom of the water trough.

The Duff Producer.—This is one of the most popular producers in use. The casing is circular, but the lining is so arranged that the fuel chamber is rectangular, the casing dips down into the water trough so as to form a water seal, and across the 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 slip off the grates 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.

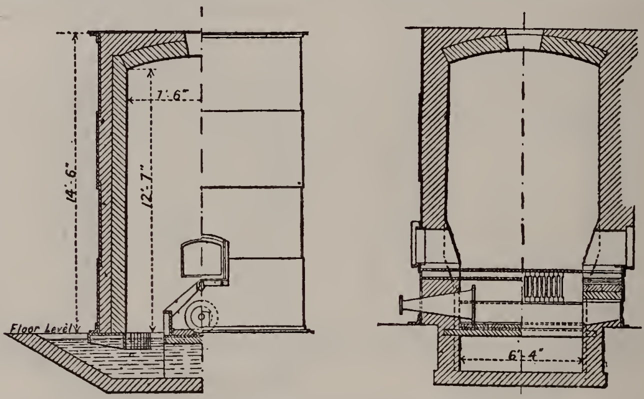

FIG. 42.—Duff Producer. From *Engineering*.

The Thwaite Small-power Gas Generator.—In this generator the fire-grate is formed of a girdle of suspended

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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.

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.

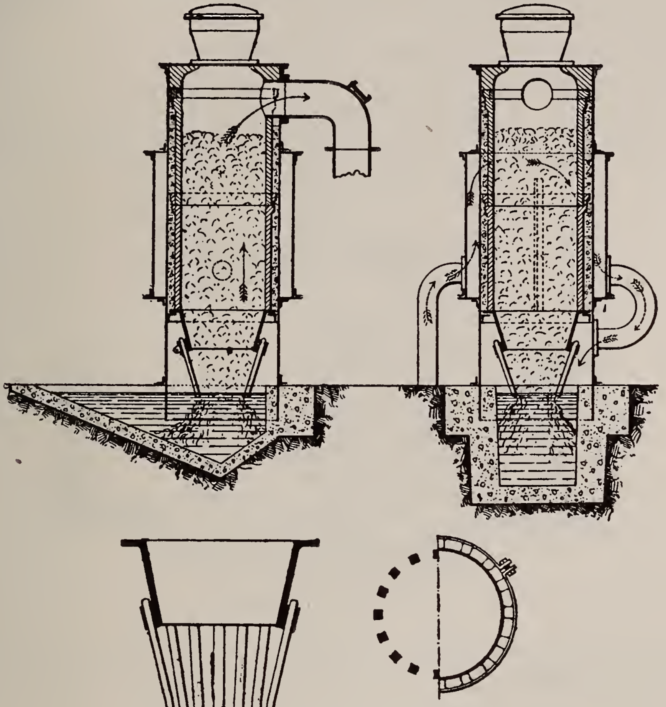

FIG. 43.—Thwaite Small-power Producer.

The clinker and incombustible matter can easily be removed, 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 " hanging " form of grate, the ash does not reduce the grate efficiency, as it does not offer a suitable surface for the repose of either coke or clinker. It is self-cleaning, and there is little chance of the air supply being hindered.

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.

The Smith and Wincott Producer.—Central blowing is in general the most satisfactory, but one of the difficulties with most centre-blown producers is that of keeping the blower clear of clinker. This has been overcome very satisfactorily in this producer. The producer is circular, about 8 feet in diameter inside. The air main enters the bottom of the producer, and then spreads out into the form of an inverted cone about 2 feet 6 inches in diameter and 2 feet high, the periphery of which is perforated with a large number of slits, the main being covered with an iron cap. The air slits sloping inward instead of outwards cannot be blocked by clinker, and the large circumference of the cone ensures a good distribution of air and complete combustion. The shell dips down into a water trough forming a water seal as usual.

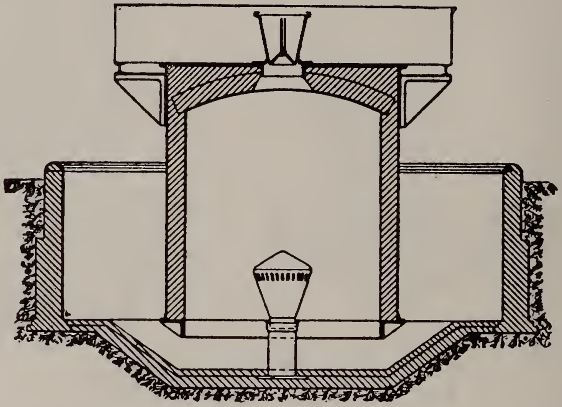

FIG. 44.—The Smith and Wincott Producer.

The Mond Producer.—In connection with the production of Mond gas (see p. 177) Dr. Mond designed a producer which has some special features. The producer is circular and is tapered towards the bottom, the grate is a hanging grate made up of an inverted cone of fire-bars the ends of which are well above the level of the water in the water trough. The producer has a double shell. The inner shell is lined with fire-brick, as usual, and the outer shell is placed so as to leave a space between it and the inner shell through which the air and steam on its way to the producer can pass and thus become heated. The outer shell is carried downwards so as to dip into the water in the trough and form a seal. The fuel is supplied by a long charging hopper round which the gas circulates so as to heat and partially distil the coal before it sinks into the body of the producer.

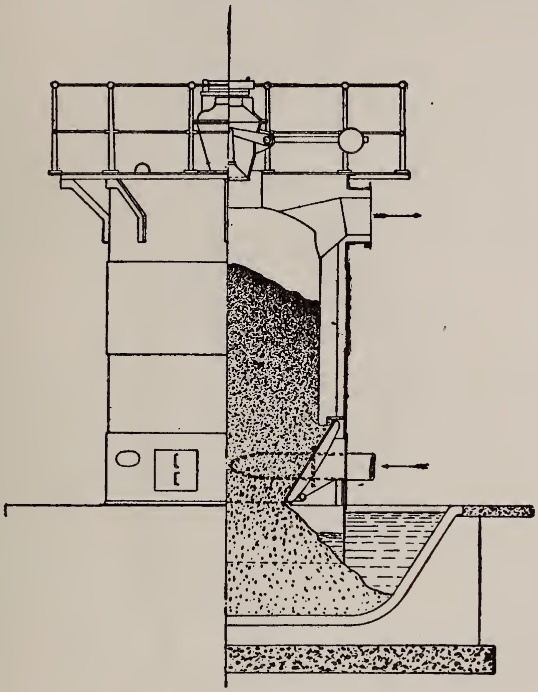

FIG. 44A.—Mond Producer for Non-recovery Plant.

The type of producer now usually supplied for the manufacture of Mond gas is illustrated in Fig. 44A. Under conditions of ammonia recovery the only difference in the producer is the addition of a central bell through which the fuel is charged.

Kerpely Producer. — One of the most successful producers using mechanical grates is the Kerpely illustrated

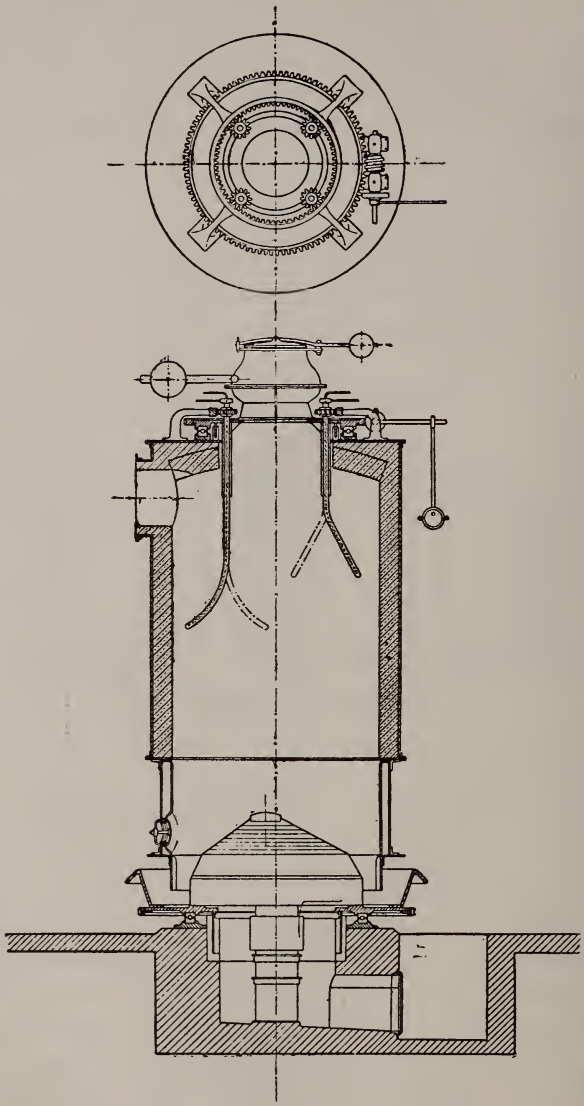

FIG. 45.—Sectional Diagram of Kerpely Producer.

in Fig. 45. This is able to deal with coal containing 40 per cent of ash. The chief features are the eccentric rotating hearth which automatically discharges the ash at one side, and the mechanical rotating pokers which prevent the formation of blow-holes in the fuel bed. In other designs the producer is jacketed with an annular boiler for the production of low-pressure steam and consequent greater fuel efficiency.

Gas for Gas-engines.—When the gas is to be used for gas-engines it must be cleaned by being passed through scrubbers or washers to remove the tar and dust. As the gas production with pressure producer is continuous, a gas holder must be provided to hold the excess gas. The holder also serves a useful purpose in governing the gas pressure.

SUCTION PRODUCERS

When the gas is required only for working gas-engines, the quantity required is usually not very large, and it is inconvenient to provide gas holders to hold the gas, and it is also often inconvenient to provide separate boilers for raising steam. To overcome these difficulties suction producers have been designed. In these the air and steam mixture is drawn into the producer by the suction of the engine, so that gas is only made as it is required, and steam is raised by the waste heat of the gases. A large number of these suction producers are now on the market, but it will be sufficient to describe two or three as types.

The Dowson Producer.—This is a circular producer of the bar-bottom type. The fuel is supplied by means of a cylindrical hopper, and round the top of the producer, descending nearly as low as the bottom of the hopper, is the steam generator, or evaporator, which is in the form of a ring. The hot gases, passing through the space between the coal hopper and the evaporator, heat them both before passing away. The water is supplied from a feeder to a ring which runs round inside the evaporator, and there it is allowed to drop into the boiler and is at once converted into steam. The air enters the steam generator, circulates round it, and passes with the steam to the space beneath the firebars.

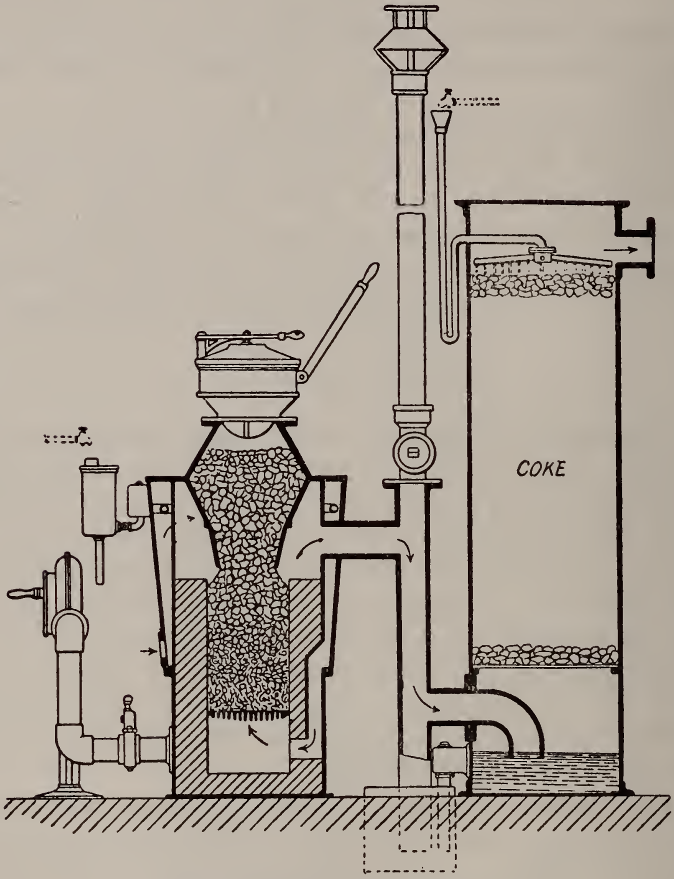

FIG. 45A.—Dowson Suction Producer Plant.

The Campbell Generator.—This generator differs from that of Mr. Dowson mainly in the way in which the steam is raised and supplied. The steam is produced from a boiler placed at the top of the producer, and therefore heated by the gas as it passes away. The air is drawn into the boiler above the water, and thus becoming laden with steam, passes by a pipe to the space beneath the fire-bars, and hot gas is made to circulate round the pipe so that the air and steam become superheated.

The Watt Producer.—This is a cylindrical bar-bottom producer, but differs from those described above in the way the steam is produced and in some other respects. A space of about 1½ inches wide is left round the body of the producer for the passage of the gas to the scrubber, and outside this is another casing so arranged as to leave a second annular space the same width as the first, and the whole is enclosed in a non-conducting casing. The top of the producer is covered with a cone of corrugated iron plate, the corrugations being arranged so as to form a continuous spiral trough. On the outside of the intermediate iron casing a spiral trough continuous with that on the cover is fixed. The whole is covered with an iron cover. The water is supplied near the centre of the conical cover and flows round, being vaporized as it goes, and any that remains flows down the trough in the casing, where it is completely vaporized. Air is admitted to

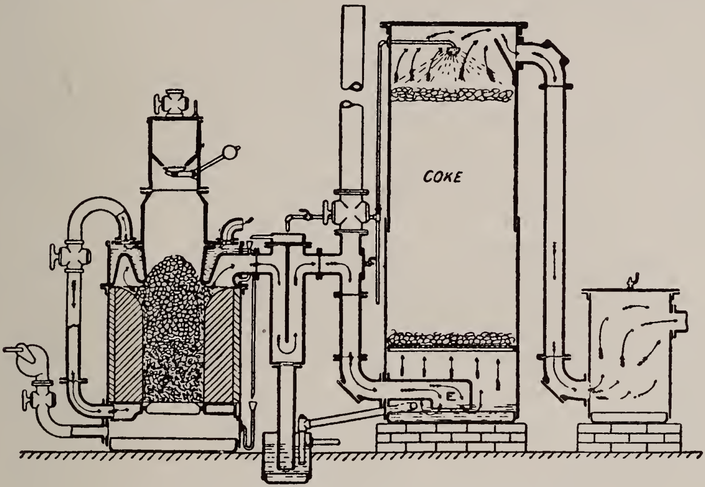

FIG. 46.—Campbell Gas Producer and Cleaning Plant.

the space above the corrugated cover, and, passing down the outer annular space, carries the steam with it to the space beneath the fire-bars. The fire-bars are arranged so that they can each be turned separately and drawn if required.

Starting.—With any of these producers, and indeed with all producers of the suction type, some provision must be made for starting, for the gas is to drive the engine, and no gas can be made until the engine is started and thus draws the air through. To start, a small fan, worked by hand, is usually attached to the converter, and this is worked until the producer is hot enough to begin gas-making, the products of combustion during this time being allowed to burn to waste at an escape pipe. With the Watt producer the fan is sometimes dispensed with, a natural draught being produced first by heating the waste pipe by means of a small fire, and then by combustion of the waste gas at the waste pipe.

Cleaning the Gas.—For gas for gas-engines, charcoal, coke, or anthracite is always used, as if bituminous coal is used it is extremely difficult to remove the last traces of tar. Even blast-furnace gas, purified as described in Chapter VIII., is not free enough from tar for use, but has to be subject to a further purification. This is usually done by passing the gas through a series of small apertures and allowing it to impinge on a flat surface, by which the last traces of tar are removed. The gas made from charcoal, coke, or anthracite also needs purification, but this is much more easily effected, the impurities to be removed being almost entirely dust, carried over mechanically, and traces of tar from bituminous matter left in the coke, and a quantity of water either from moisture in the fuel or from undecomposed steam passing through the producer. To remove these the gas is passed through a scrubber filled with some suitable material down which a rain of water is kept falling, thus at the same time cooling and cleaning the gas. The scrubber consists of an iron cylinder 10 feet or more in height and 2 or 3 feet in diameter, or more according to the quantity of gas passing through, the capacity being about 1·25 times the amount of gas produced per minute, though even larger scrubbers may be used with advantage. A grate is usually fixed across the bottom of the scrubber, and the space above this is filled with some distributing material. Coke broken up into small pieces is often used, and works very well as a dust-catcher. Water is distributed by means of an arrangement of pipes over the top of the coke, and running down meets the ascending current of gas. The amount of water required will be about 1 gallon per hour for each 50 to 75 cubic feet of gas made per hour, but it will vary with the temperature of the gas and other conditions.

To avoid the gas lighting back, the gas, before passing into the scrubber, is always passed through a vessel of water, which forms a water seal, the details of the arrangement varying with the different types of plant.

When there is a small quantity of tar, a saw-dust scrubber is often used. This consists of a rectangular chamber with the inlet on one side and the outlet on the other, and across this are fixed two perforated plates, the space between which is filled with coarse saw-dust which is kept moist, and through which the gas has to pass. If the quantity of tar is large, the gas before entering the scrubber is often passed through a tar extractor, which is usually a closed vessel fitted with a large number of plates against which the gas is directed as it flows. The actual arrangement of the scrubbing plant varies very much, each maker having his own design. The illustration (Fig. 46) shows the arrangement in the Campbell plant.

Cost of Working, &c.—Suction-gas plants are mostly used for making gas for driving small gas-engines which otherwise would be driven by coal-gas derived from the town supply. Which will be the cheaper will depend on various circumstances, but largely, of course, on the price at which coal-gas can be obtained. The cost for fuel in running a suction-gas plant is comparatively small, and may be taken in the case of a good plant as being about 0·3d. per B.H.P.

hour, provided suitable anthracite or coke can be obtained at a low price, say 35s. or so a ton. In addition to this there will of course be the depreciation of the plant, the interest on the cost of plant, the labour at the plant, and other items, which run the actual cost up very considerably, so that the actual cost can only be obtained by a careful consideration of each case on its own merits. As the ratio of the calorific powers of town gas and suction-gas is about $4\frac{1}{2} : 1$, it follows that the cost of the latter per 1000 cubic feet must be reduced to a fifth of that of the former to make the installation of suction-gas a commercial proposition. It must of course be remembered that the fuels necessary for suction producers—anthracite or coke—are much more costly than the dross which can be used for large installations of pressure producers.

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 29,300 + C. units, or 52,700 B.Th.U., whilst the heat value of the reaction $C + 2O = CO_2$ is 97,300 C. units, or 175,100 B.Th.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 utilize 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 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 123,100 + B.Th.U., so that the value of the decomposition will be 123,100 − B.Th.U.

∴ Decomposition of water	123100 −
Formation of carbon monoxide . . .	52700 +
Heat of the double reaction . . .	70400

Every pound of carbon, therefore, which is burnt by means of steam absorbs 5880 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 lb. of carbon must be burnt by air to supply the heat necessary for the combustion of 1 lb. 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 :

$$C + 2O = CO_2 = 175100 + \text{B.Th.U.}$$

$C + H_2O = CO + 2H =$		70400 −
$CO + O = CO_2 =$	122400 +	
$2H + O =$	123100 +	
		245500 +
Difference		174900 +

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 in ordinary producers 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 per cent of steam and 95 per cent 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 per cent 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 per cent
Carbon monoxide from steam	5 ,,	= 4·00
Carbon monoxide from air	39·9 ,,	= 31·90
Nitrogen	75·05 ,,	= 60·10
	124·95 litres	= 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	= 5870 – B.Th.U.
8 lb. of carbon burnt by oxygen = 4390 × 8	= 35120 +
Heat evolved in producer	= 29250 +
Or for 1 lb. of carbon	= 3250 +
Total heat which could be evolved by the combustion of 1 lb. of carbon to carbon dioxide	= 14600 +

Loss per cent = 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 nearly always used for central producers. 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, etc.
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 lb. 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 per cent 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 a very large 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 per cent, 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 very different from ordinary producer-gas by using a very large excess of steam. The producer used is of the water-bottom type, and is described on p. 162, but any other type will do, and the Duff producer is often used. About 2½ 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 130,000 cubic feet of gas, which has the composition on an average:

	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 amount of heat lost in the producer is said to be not more than about 25 per cent of that obtainable from the coal, so that it will be seen that the gas, though very different from ordinary producer-gas, has about the same heating power, and is made with about the same loss of heat.

If the steam be decomposed by carbon, so as to produce carbon monoxide, 1 lb. of carbon would require 1½ lb. of steam. As, however, a considerable portion of the carbon must be burnt by air, it may be said roughly that only about 1 ton of steam can be used for each ton of carbon consumed, so that 1½ tons must pass through undecomposed, and this must be condensed. The plant is arranged by Dr. Mond so as to condense this steam and recover as much as possible of the heat.

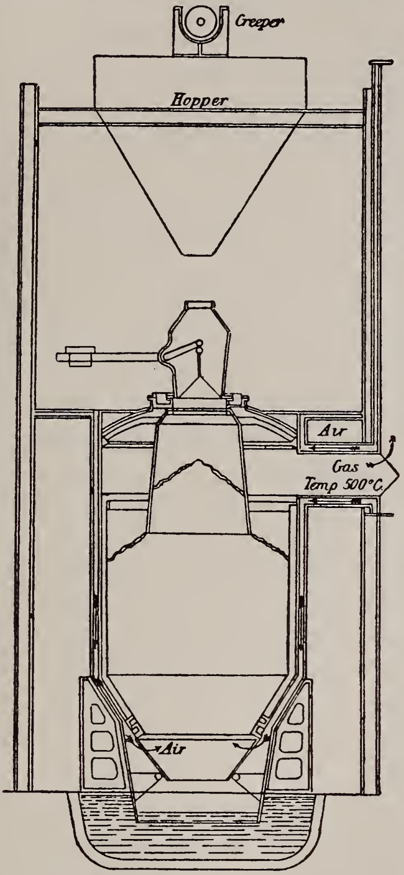

FIG. 47.—Section of Mond Producer.

The gas first passes through a set of "regenerators." These are double, vertical iron tubes. The hot gas passes up the inner tube, and the air and steam on its way to the producer passes down through the annular space between the two tubes. From the regenerator the gas passes to a washer, a horizontal vessel containing water, and fitted with mechanical dashers by which a large quantity of spray is thrown up, through which the gas has to pass. The gas is thus cooled to about 90° C., and a considerable quantity of water is condensed. From the washer the gas passes to the acid tower, a tall tower filled with a chequer-work of acid-brick down which a rain of sulphuric acid is kept falling, the ammonia being thus converted into sulphate and carried down in solution. From the top of this tower the gas, still hot, but deprived of its ammonia, passes to the gas-cooling tower which is packed with wood, or earthenware rings, and down which cold water is kept falling. This still further cools the gas and heats the water, and the gas is passed on to the engines where it is to be used, or to the gas-holders for storage. The hot water may be pumped to the top of another tower, down which it falls and meets the air which is forced in to supply the producer, which thus becomes saturated with moisture and is then carried through the regenerators to the producer, but the more usual procedure is to cool the circulating water by an atmospheric cooling tower.

The ammonia liquor is run into a settler so that any tar can separate, a small portion of the liquor is drawn off, and fresh acid added so as to keep the liquor distinctly acid, and it is then pumped again to the top of the ammonia tower. The ammonia liquor and tar are treated exactly as described in Chapter VIII.

The amount of ammonia recovered varies almost in proportion to the nitrogen content of the coal used, and is usually equivalent to about 65 lb. of sulphate per ton of coal for a content of one per cent, this representing about 60 per cent of the total possible as against 15 per cent in ordinary retort carbonization.

It must be remembered that the nitrogen is not present in the coal as ammonia, but in organic compounds which are broken up by the distillation of the coal, and which in presence of the very large quantity of steam are carried off undecomposed in the form of ammonia.

The first cost of the plant is large, and the cost of raising steam may be considerable, but these are usually more than balanced by the value of the ammonia recovered.

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, $Fe_2O_3 + 3CO = 2Fe + 3CO_2$, 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	. .	1·1
Hydrocarbons	·20	·93	·1	. .

1, Coke, Ebelmann. 2, Charcoal, Ebelmann. 3, Coke, Thwaite. 4, Charcoal, Thwaite.

Owing to the quantity of inert gases present the calorific power of the gas is low. Taking No. 1 as a type, the calorific power can be calculated.

Carbon monoxide . . .	0·2861 × 320 =	91·6 B.Th.U.
Hydrogen	0·0274 × 321 =	8·8
Methane	0·0020 × 998 =	2·0
B.Th.U. per cubic foot . . .		102·4

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 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	52·87
Ammonia	not est.	·13	..	..

No. 1 has a calorific value of 147 B.Th.U. per cubic foot.

It will thus be seen that the gases are quite comparable with those of a gas producer and are better than some, for there are many cases in which producer-gas contains as much carbon dioxide as blast-furnace gas (see table of analyses, p. 192). 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.

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 lb. per square foot of grate area or bottom per hour, reaching a maximum of 40 or 50 lb. in very quick driving.

A blast-furnace is worked at a much higher pressure, 2½ to 7 lb. 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 lb. 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.

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,

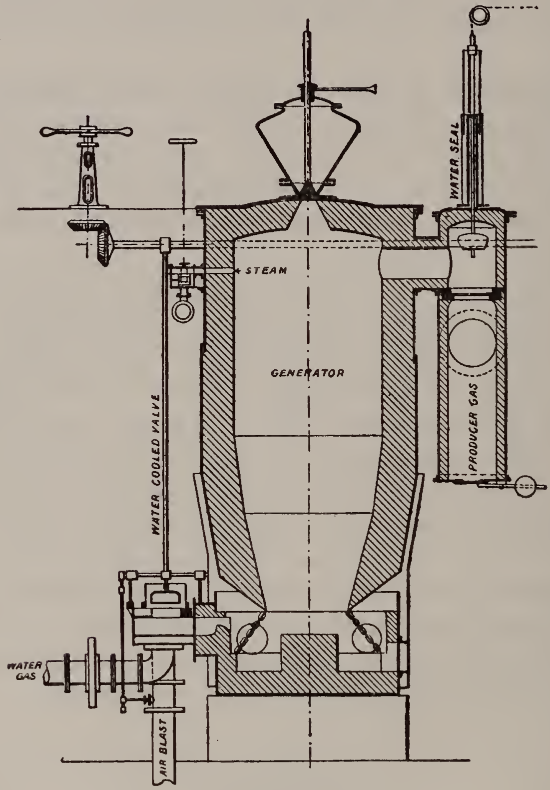

Fig. 48.—Water-gas Plant at Leeds Forge.

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 through till it is again hot enough to produce water-gas. The times at the Leeds forge are 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, and is an improvement of the well-known Lowe system. 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.

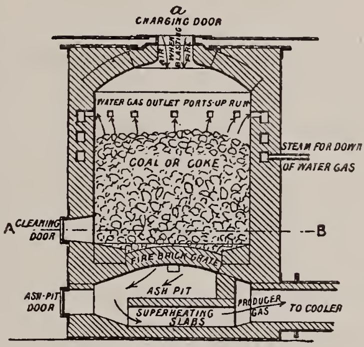

FIG. 49.—Loomis Gas Producer.
From *J.I. and S.I.*

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 gives up its sensible heat 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 is pumped by the ports to the water-gas holder.

Mr. Loomis gives the following estimate as the cost per 1,000,000 cubic feet of gas with coal at $3 per ton :[1]

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	40.00
	75.00
Interest and depreciation	25.00
	100.00

Or cost per 1000 cubic feet, $0.10 = say 5d., or if the producer-gas be lost, $0.14, say 7d.

The Strong Producer.—In this producer, which is largely used in America, the gas is made intermittently in the usual way. The producer-gas is passed into a regenerator—a fire-brick chamber parted with a chequer-work of fire-brick—and is there burnt. When the producer is reversed for water-gas making, the steam is blown through this chamber, and therefore becomes intensely hot before it enters the top of the producer. A stream of coal-dust is also blown into the top of the producer, and the products of distillation pass downwards through the fuel with the hot steam, and are broken up into permanent gases and fixed carbon. As soon as steam passes through undecomposed the process is reversed.

The Dellwik-Fleischer Process.—In all the earlier types of water-gas producer the carbon was only burnt to carbon monoxide, and as this evolves only a small amount of heat, the heating-up stage was very long. During this stage a combustible gas was evolved, but as a rule no use could be made of this. In the process devised by Messrs. Dellwik-Fleischer the fuel during the heating-up stage is burnt to carbon dioxide, so that a large amount of heat is evolved and the heating-up stage is much shortened.

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[1] *J.I. and S.I.*, 1890, vol. ii. p. 280.

Almost any form of producer might be used, but that adopted by Messrs. Dellwik-Fleischer is a simple bar-bottom producer up to 12 feet in diameter and 14 feet high. The only essential is that the layer of fuel must be thin, usually not more than 3 feet thick, and that a large quantity of air must be supplied so as to ensure complete and rapid combustion. To start the producer the fire is lighted, coke is put in from a hopper above, and air is blown in, the products of combustion passing away by a chimney. As soon as the coke is hot enough, the air is turned off and steam is blown in, the gas being led away to a gas-holder. As soon as the temperature is so low that a large quantity of steam is escaping undecomposed, which is determined by means of a test cock, the gas and steam valves are closed and air is again blown in. The heating up occupies only two or three minutes, and gas is made for about eight or ten minutes.

The hot gas on its way to the gas-holder passes through a superheater, so that its sensible heat is partially used in heating the steam, and the plant is so arranged that the steam can be blown in alternately above and below the fuel. About 4 cwt. of coke is added after every second blow. Mr. Dellwik thus describes the theory of the process :[1]

" If we look into the chemical reactions in the formation of water-gas we find that 18 lb. of steam, consisting of 2 lb. of hydrogen and 16 lb. of oxygen, require for their decomposition $2 \times 28780 = 57560$ thermal units. The 16 lb. of oxygen combines with 12 lb. of carbon to form 28 lb. of carbon monoxide, which in mixture with the 2 lb. of hydrogen form 30 lb. $= 753{\cdot}4$ cubic feet of water-gas. The heat developed by the formation of the carbon monoxide is $12 \times 2400 = 28800$ thermal units, thus leaving a balance of $57560 - 28800 = 28760$ thermal units, which must be replaced by the combustion of carbon during the blows. Assuming then, as is approximately the case in practice, that the blow-gas leaves the generator at a temperature of 700° C., we find :

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[1] *J.I. and S.I.*, 1900, vol. i. p. 123.

	Old Method.	New Method.
1 lb. of C requires for combustion .	to CO $\frac{16}{12}$ lb. O.	to CO_2 $\frac{32}{12}$ lb. O.
The O is accompanied by . .	4·32 lb. N.	8·66 lb. N.
And the products of combustion carry with them at 700° C. . .	1136 Th.U.	2092 Th.U.
The heat of combustion of 1 lb. of C is	2400 Th.U.	8080 Th.U.
Balance available for heating is .	2400 – 1136 = 1264 Th.U.	8080 – 2092 = 5988 Th.U.
To fill the before-mentioned balance of 28760 Th.U., in the production of 30 lb. of gas, there must be burnt	$\frac{28760}{1264}$ = 22·75 lb. C.	$\frac{28760}{5988}$ = 4·83 lb. C.
Not counting the heat lost by radiation and other causes, there are required for the production of 30 lb. = 753 cu. ft. of water-gas	12 + 22·75 = 34·75 lb. C.	12 + 4·83 = 16·83 lb. C.
Per lb. of C are obtained . .	21·7 cu. ft. of water-gas	44·7 cu. ft. of water-gas.
As water-gas of the theoretical composition contains 167 Th.U. per cubic foot, there are utilized in the water-gas per 1 lb. of C	3627 Th.U. = 44·8 per cent of the heating value of the C.	7465 Th.U. = 92·5 per cent of the heating value of the C.

In this it is assumed that all the carbon in the heating-up stage is burnt to carbon dioxide. This is very rarely the case, but the products of combustion only contain about 1 per cent of carbon monoxide.

In practice the efficiency has been found to be in some cases as high as 80 per cent.

Fig. 50 illustrates the duplex generator of the Kramer and Aarts (K. & A.) system, and Fig. 51 another modification of the same, showing combined generator and carburettor.

Nature of Water-gas.—Water-gas has a much higher calorific power than producer-gas, as will be seen from the following figures, where we assume an average quality made from gas coke :

	Per cent. By volume.	B.Th.U. per cubic foot.
Carbon dioxide	4	. .
Oxygen	1	. .
Carbon monoxide	38	0·38 × 320 = 121·6
Hydrogen	50	0·50 × 321 = 160·5
Nitrogen	7	. .
	100	282·1

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.

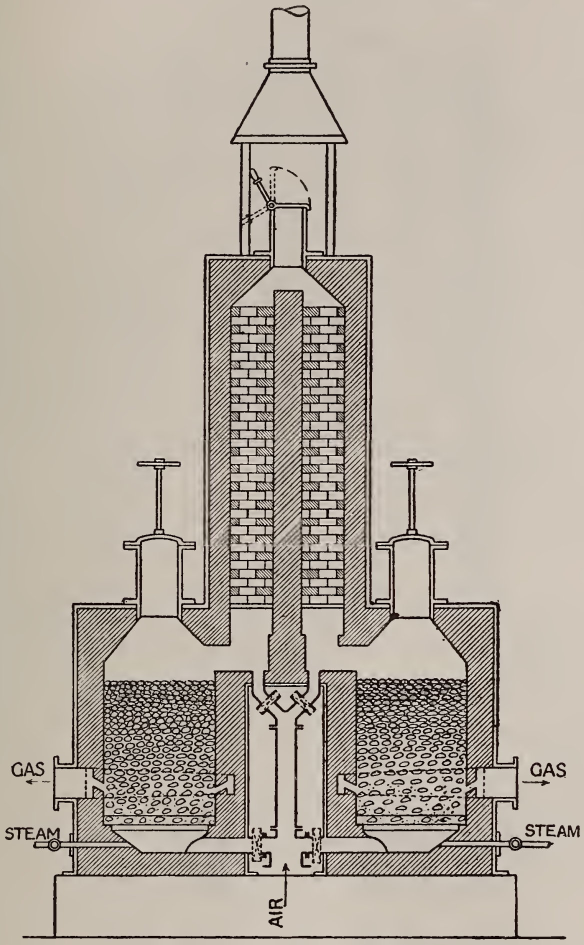

FIG. 50.—K. & A. Water-gas Generator.

As it is comparatively low in content of carbon dioxide and nitrogen, water-gas 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 incandescent lighting, or it may be made luminous by making it take up some volatile hydrocarbon. If acetylene could be

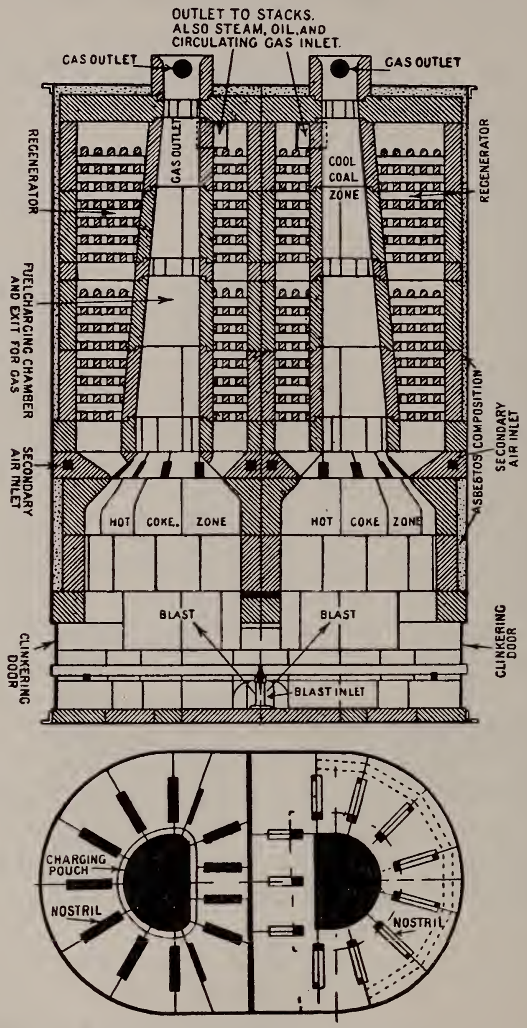

FIG. 51.—Perry Water-gas Generator.

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 sometimes mixed with some strong-smelling volatile body such as carbon disulphide.

The great objection to water-gas is the necessity for making it intermittently, so that gas-holders are necessary.

Carburetted Water-gas.—Very large quantities of carburetted water-gas have been made in this country, and still greater quantities in the United States, to meet the demand for illuminating gas and the enrichment of coal-gas. The water-gas is carburetted by spraying petroleum or heavy paraffin oil on to red-hot brick chequer-work during the "run" in the manufacture of water-gas. The quantity of oil necessary varies from 2 to 4 gallons per thousand cubic feet of total gas made, according to the quality (candle-power and calorific value) required. Over 60,000,000 gallons of oil have been used annually in the United Kingdom for this purpose. Owing, however, to the relegation of the candle-power in town gas to a position of secondary importance, there is now a much lower consumption of oil.

The "Economical" plant used in many gasworks consisted essentially of three chambers, generator, carburettor, and superheater, as in Fig. 52. In the "Humphries and Glasgow" system the superheater is superimposed on the carburettor. In both cases the brickwork of the carburettor and superheater is rendered red-hot partly by the sensible heat of the gases coming from the generator and partly by the combustion of a portion of the producer-gas made in the generator during the "blow," and the temperature is capable of being suitably controlled.

Oil-gas.—This gas is made by the destructive distillation of oil, that is "cracking," 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.

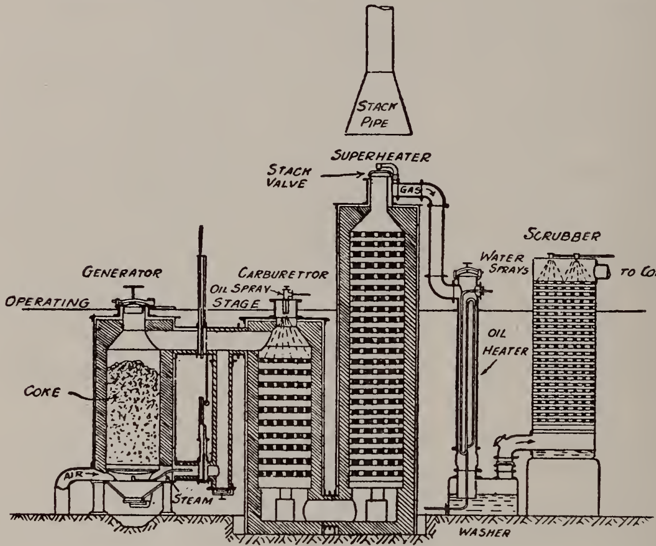

FIG. 52.—Section of Carburetted Water-gas Plant.

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.

An average oil-gas contains 25 per cent by volume of hydrogen, 45 per cent methane, and 30 per cent of heavy hydrocarbons, and possesses a calorific value of about 1050 B.Th.U. per cubic foot, gross.

	Natural Gas.	Coal Gas.	Water Gas.	Carburetted Water Gas. (Rich.)	Ordinary Producer Gas. (Coke.)	Semi-Water Gas. (No ammonia.) (Coal.)	Semi-Water Gas. (Ammonia.) (Coal.)	Blast Furnace Gas. (Coke.)
Carbon Dioxide, CO_2 . . .	..	3	4	3	6	5	16	9
Heavy Hydrocarbons, $C_m H_n$	..	3	..	9	..	..	..	..
Oxygen, O	..	1	1	1	..	..	..	..
Carbon Monoxide, CO . . .	1	9	40	30	25	25	12	28
Hydrogen, H	..	43	48	40	..	15	26	2
Methane, CH_4	96	27	$\frac{1}{2}$	12	..	3	3	1
Nitrogen, N	3	14	$6\frac{1}{2}$	5	69	52	43	60

Composition of Various Gases.—The analyses on p. 192 will give a good idea of the nature of the gases used as fuels.[1]

The approximate composition of the more important industrial gases is given in the above table.

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 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, etc., 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

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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.

Producer.	Source of Analysis.	Per Cent Total Combustibles.	Per Cent of Hydrogen.	Per Cent of Methane, etc.	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

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

BY-PRODUCTS AND LOW-TEMPERATURE CARBONIZATION

Recovery of By-products.—It has now become general practice to aim at recovering tar, ammonia, and crude benzole from the gas made in coke-ovens, producers, and blast-furnaces wherever possible.

In many cases it has not been profitable in the past to carry out the whole recovery process owing to various difficulties.

While all coke-oven plants and gasworks can, and for the most part do, quite readily recover tar and ammonia very completely in a readily utilizable condition, the tar made by producers is accompanied, as a rule, by so much steam and is so constituted that it condenses in a partly emulsified condition containing on an average, say, 40 per cent of water, which is difficult to remove, and whose removal is absolutely necessary to make it fit for the ordinary purposes of tar.

Again, gas producers, as a rule, do not yield anything but the merest trace of ammonia. In order to recover ammonia it is necessary to at least double the proportion of steam fed to the producer along with the air-blast. For example, the Mond producers generally require 1 lb. of steam per lb. of coal gasified when working under non-recovery (no ammonia) conditions, whereas 2½ lb. of steam are required when it is desired to cause the evolution of ammonia in profitable quantities.

The question as to whether it will be a paying proposition to make the ammonia at the expense of the steam is one that can only be settled by considering the particular circumstances of each individual case. Fortunately the pressure of steam required is only 2 or 3 lb. per square inch, and exhaust steam can therefore be utilized.

If, therefore, there is a large available supply of exhaust steam going to waste in connection with steam-engines already installed in a works, such as those driving exhausters, pumps, electric generators, air compressors, etc., the problem is simplified and the probability will be a saving of about four shillings, on a pre-war basis, per ton of coal gasified after allowing for all charges.

In such a case, or designedly so, the steam is used for a double purpose—to drive the engines at high pressure under non-condensing conditions and afterwards to supply the producers. The engines act like so many reducing valves or governors.

When, however, we are considering an entirely new industry or plant we cannot in fairness present free steam to the producer plant, but must take into account the probably well-recognized fact that in a modern works, especially having regard to present high prices of fuel, it would be most wasteful to instal non-condensing engines of any kind if there were no producer plant to consider. The price of steam to be charged to the producer plant is in this case determined by the difference in steam consumption between condensing conditions on the one hand and non-condensing conditions on the other. As 12 lb. and 36 lb. may be taken as representing the consumption of steam per brake-horse-power hour for condensing and non-condensing engines respectively, we may assume a fair charge for steam supplied to the producers would be between 60 and 70 per cent of the actual cost as delivered from the boilers.

The cost of sulphuric acid and the market price of sulphate of ammonia are the other principal factors that govern a decision of this question. The recovery of 90 lb. of sulphate of ammonia, worth about 14s. per ton of coal, would appear to be a most attractive proposition, and from a national point of view a very desirable one, and it is a duty to give it fair consideration in every case, even though it does entail very considerable additional capital outlay.

While the extraction of crude benzole from coke-oven gas is very general and profitable, there are not very many gasworks which now take the trouble to wash out the light spirit from coal-gas, although a large number of the larger works were obliged to do so to augment the supplies of benzene and toluene for high explosives manufacture during the war. Whether it is profitable to do so or not depends chiefly on the relative values of the therm (100,000 B.Th.U.) and motor spirit. At the end of the year 1920 the therm in London gas costs about 10d.; in petrol at 4s. per gallon it costs about 33d. There is in this case a good margin of profit, but with petrol at 2s. per gallon there would cease to be sufficient margin in most cases.

Coke-oven gas, though differing in no essential feature from ordinary town gas, cannot be sold at the same price per therm as town gas, because there is no outlet for it except in certain favoured places like Middlesbrough and Sheffield, where it is purified from sulphuretted hydrogen and sold as town gas. It is therefore worth little more than its heating value compared with coal, which at 30s. per ton represents a cost of not more than 1½d. per therm. Assuming a moderate yield of benzole—a minimum of, say, one gallon per ton of coal—it would probably be still profitable to recover benzole from coke-oven gas even if motor spirit dropped in price to 1s. 3d. per gallon, coal remaining at 30s.

Tar.—The yield of tar from the ordinary carbonization of coal varies from 8 to 15 gallons per ton according to the nature of the coal and the system of carbonization. It is greatest with vertical retorts where steaming of the charge is practised, and least with horizontal retorts having only one ascension pipe working at the highest possible temperatures. In the latter case the tar is particularly well cracked, with the result that the gas yield is increased but the tar is diminished and contains a large amount of free carbon. Bituminous coals, high in volatile matter, give the best yields. Probably the richest Yorkshire coals take the lead in this respect, though, of course, they are greatly surpassed by the various cannels, which, as a rule, yield at least 20 gallons of tar per ton.

Not only does the production vary with different coals and systems of retorting, but also the composition or quality shows marked variations. While coke-ovens, horizontal and inclined retorts, and chamber ovens are pretty much alike in the content of middle and heavy oils, naphthalene and pitch, vertical retorts give a much larger proportion of middle and heavy oils, much less naphthalene and pitch, this pitch containing only a small percentage of free carbon.

The proportion of light oils, distilling up to 170° C., to be found in different tars is subject to very great variation, even when the same system of retorting, the same temperature of carbonization, and the same coal are considered. The difference may be due entirely to the conditions of condensation which allow more or less light oils to be retained in the gas according to whether the cooling is sudden or gradual, or whether the tar is circulated in contact with the gas or not. It is worthy of special note that coal-gas made from a ton of coal retains in the cold state, after removal of all the tar, from ten to forty times as much benzene as is to be found in the tar made from the same quantity of coal. Generally speaking, when the yield of gas is comparatively large the percentage of light oil left in the tar will be low.

The amount of water or ammoniacal liquor to be found in tar is seldom less than 2 per cent, and may, in emulsions, be as high as 80 per cent, when the problem of separation becomes a serious one.

Ordinary coal-tar made in gasworks and coke-oven works gives very little trouble as a rule with regard to the water content, a long period of settlement, preferably in a warm state in underground wells, being sufficient to enable the water to rise to the top and any sediment to sink to the bottom. But cases are known where, owing to its rapid circulation in the hydraulic mains of coke-oven installations —necessary in order to keep down pitch deposits—the tar partly emulsifies and may contain 40 or 50 per cent of water. The difficulty and cost of removal of the water makes the tar almost worthless to the ordinary tar distiller.

The worst cases of tar emulsion are, however, to be found in the manufacture of carburetted water-gas and producer-gas, and special means have to be sought to dehydrate or distil the product, even if there be no balance of profit in the operation, because, as a rule, it is impossible to dispose of the emulsion into a river, canal, or pit.

The plant required for the collection and removal of tar made from the distillation of coal is simple and the cost is low. In general, the hot gases enter a cooling main pipe, hydraulic main or foul main, in which tar or ammoniacal liquor is circulated; then follow atmospheric condensers, water-cooled condensers, and a final tar extractor of some kind. The Pelouze and Audouin tar extractor, the Livesey washer, Cyclone extractors and centrifugal fan extractors are the principal apparatus in use for this purpose. The tar recovered hot is naturally heavier in specific gravity and higher in boiling-point than the tar obtained from the final extractor.

The removal of tar from producer-gas is a much more difficult problem. In many cases it has been found more profitable to allow the gas to carry most of the tar in the hot state direct to the furnaces, not only because of the difficulty of tar removal, but also because of the increased calorific value of the supply.

It has sometimes been found, in steelworks especially, that a tarless gas does not effect a sufficiently high temperature.

In cases where there is ammonia recovery and the gas is necessarily cooled, the bulk of the tar is thrown down and has to be dealt with. Tar mist in producer-gas is, however, very persistent and travels many miles when the velocity is high. Washers, centrifugal fans, and woodwool or sawdust purifier boxes have to be brought into requisition to make the gas suitable for furnace work, such as firing coke-ovens and for gas-engines. The tar collected is very viscous and difficult to handle unless kept hot by closed steam-pipes. It usually contains about 40 per cent of water and must be dehydrated or distilled *in situ.*

It is dehydrated by agitation at a temperature of about 95° maintained by closed steam coils for two days, or it may be distilled *in vacuo.* By the former method there is a slight loss of creosote and the only product is an inferior pitch. By the latter a good yield of creosote and a good hard dry pitch are obtained.

Producer-gas contains not more than 0·1 per cent of benzene vapour or its equivalent as against about 1 per cent in ordinary coal-gas. It is thus able to retain all the light spirit made in the producer. In a similar way it carries middle oils which would have condensed with the heavy tars were their vapours not so diluted by the large volume of gas.

It is not easy to obtain reliable data of the composition of different varieties of coal-gas tar, but an average analysis on first distillation is as follows :

Distilling Temperature. ° C.	Sp. Gr.	Fraction.	Per Cent.	Commercial Products.
0°-170°	0.94	Light oils (crude naphtha)	3	Benzole for motor spirit, dyes, and other chemicals, solvent and burning naphtha.
170°-230°	0·98	Middle oils (carbolic oil)	17	Naphthalene, carbolic acid, creosote.
230°-270°	1·04	Heavy oils (creosote oil)	10	Creosote, lubricating oil, wash oil, fuel oil.
270°-350°	1·08	Anthracene oil	15	Anthracene, wash oil, fuel oil, lubricating oil.
Above 350°	..	Pitch	55	For briquetting, varnishes, cements, asphalt, road-spraying, and fuel.
			100	

The ultimate products when purified are approximately :

	Per Cent.
Benzene	1
Toluene	¼
Xylene	½
Phenol (carbolic acid)	½
Cresylic acid	1½
Naphthalene	8
Pyridine	¼
Anthracene	2
Middle and heavy oils	31
Pitch	55
	100

Ammonia.—In ordinary gasworks or coke-oven practice half the ammonia collects in the condensate along with the tar, and half is obtained by washing the gas in specially designed apparatus.

The former is usually called the virgin liquor and contains nearly all the fixed ammonia salts—chloride and sulphate principally. It separates out readily from the heavier tar. With ordinary dry coal the virgin liquor amounts to about 15 gallons per ton, but when water is added to the coal to aid compressing this figure may be doubled.

The ammonia retained by the cooled gas is generally removed by two washers or sets of washers or scrubbers. For example, a washer with a very efficient bubbling action like the Livesey washer may be used to serve the double purpose of removing tar and ammonia, while the final apparatus, which has the more difficult work of removing the last traces of ammonia, is of special design, and is fed with a minimum quantity of cold wash water, a minimum quantity being used so as not to reduce the strength of the ammoniacal liquor and make the subsequent distillation of the ammonia more costly. As the final type of washer, tower scrubbers filled with coke or wooden boards set on edge were formerly very largely used, but are being replaced more and more by mechanical appliances, such as the Holmes horizontal brush washer or vertical centrifugal spraying machines, where the extraction is carried out very efficiently by systematic stage washing.

Many coke-oven plants use the system of direct recovery of ammonia. The gas is deprived as completely as possible of its tar while still hot, and is then subjected to washing with sulphuric acid in lead-lined vessels, solid sulphate of ammonia being obtained directly. In the Otto-Hilgenstock process there is an ingenious system of tar removal from the hot gas by means of tar jets.

The ammonia in producer-gas is accompanied by so much steam that any process of recovery as ammoniacal liquor (aqueous solution) must fail owing to the low concentration possible. In this case it is quite necessary to employ the direct recovery method. The Power Gas Corporation, who supply Mond gas plants, have made use of tower scrubbers, and mechanical dash washers either in cast iron or lead, for this purpose.

Benzole.—About 30,000,000 gallons of benzole are recovered annually by the by-product coke-ovens of the United Kingdom. The crude benzole at first obtained is subjected to fractional distillation. The portion distilling below 100° C., forming the great bulk of the product, is usually washed with concentrated sulphuric acid for removal of thiophene and unsaturated hydrocarbons, thereby reducing the sulphur content and otherwise purifying the spirit. On again distilling pure benzene may be obtained. Only a small proportion of the benzene contained in the crude benzole is required in this country for chemical purposes, such as the manufacture of nitrobenzene, aniline, and dyestuffs; Germany is said to consume annually about 30,000,000 gallons in this way. The chief outlet for this valuable light oil is as motor spirit. A small proportion—about 15 per cent—of the total consists of toluene, which is usually sold in what is known as 90's benzole, but was carefully separated by fractionation during the war for the manufacture of the high explosive trinitrotoluene (T.N.T.), as was also benzene itself for making synthetic phenol and hence picric acid (lyddite). Toluene is also used fairly largely in the dyestuffs industry.

The higher fractions consist principally of xylene, and find their principal use as solvent and burning naphtha.

The process of benzole extraction consists in washing the gas with a suitable heavy oil—creosote or anthracene oil—at the rate of about 100 gallons of wash oil per ton of coal carbonized. The benzolized oil thus obtained generally contains about 2½ per cent of benzole. It is preheated and run down through a "stripping" still, where it meets live steam, which disengages almost the whole of the light spirit from the heavy oil. The vapours of steam and light spirit passing away together are condensed to water and liquid benzole respectively, and continuously separated. The stripped oil is cooled and returned to the washers for further use. It can be used over and over again almost indefinitely so long as it is freed from accumulations of naphthalene or heavy tar or water, which interfere with its efficiency. The washing efficiency is considered satisfactory at 90 per cent. It is essential to cool both gas and oil to a temperature of not more than about 70° F. to obtain the best results.

There is probably quite as much light spirit produced from a ton of coal when gasified in a gas producer as there is when the coal is carbonized. But it is useless to attempt to wash it out with heavy oil, because the vapours of the light spirit are diluted ten times and must therefore escape recovery, the washing process being a purely physical one depending on solubility and vapour tension, and not on chemical affinity.

The same type of plant is used for oil washing as for ammonia extraction by means of water, and here, too, the old-fashioned cumbersome tower scrubbers are giving way to the more efficient, compact, mechanical washers, particularly those of the vertical centrifugal type.

Coke-ovens, horizontal and inclined retorts, and chamber ovens give the highest yield of benzole. Vertical retorts give a smaller yield of light spirit, and a considerable proportion of it is "paraffinoid" and not of the "aromatic" series of hydrocarbons (benzene series).

Ethylene and Alcohol from Coke-oven Gas. — Mr. Ernest Bury of the Skinningrove Iron Company has during the war opened up the question of extracting the 2 per cent by volume of ethylene (C_2H_4) to be found in coke-oven gas. This can be absorbed as such by charcoal, but probably not in an economic way, and the method proposed and actually worked on a small scale is to wash the gas, purified from sulphuretted hydrogen and dried, with concentrated sulphuric acid at 60-70° C., and subject the resulting ethylhydrogen sulphate (sulphovinic acid) to hydrolysis and distillation in a current of steam with the production of weak alcohol, which is further purified by redistillation.

It would be possible to produce about 30,000,000 gallons of pure alcohol annually from the coke-ovens now engaged in benzole recovery and thus make an important contribution to the supply of motor spirit, of which about 150,000,000 gallons are required every year by this country alone.

It is, however, not yet clear that the process will be a commercial success.

Potash Salts from Blast-furnace Gas. — It has long been known that the dust contained in blast-furnace gas contains a large proportion—in the neighbourhood of 20 per cent—of potassium compounds, chiefly chloride. Potassium in its various forms is a valuable manure, and is also required in the glass industry. Certain quantities have been recovered by washing with water at some works. A large plant has been erected at Skinningrove by the Lodge Fume Deposit Company, on the principle of electrostatic precipitation of the dust from the hot gas, the very high voltage of about 50,000 being employed for the purpose with an efficiency of deposition of over 80 per cent.

Low-temperature Carbonization.—Much has been said and written on the subject of the distillation of coal at low temperatures during the last twenty years. It is largely due to the company promoter, however, that the man in the street owes his knowledge of smokeless fuel, the value of which has been extolled to the skies. There is nothing to find fault with in regard to the advocacy of replacing raw coal by fuel that will not produce the direct nuisance of smoke and the secondary one of fog, evils that owe their origin very largely to the burning of coal in fire-grates both in the house and in the factory. It was no doubt the fancy price which it was hoped would be obtained for a smokeless solid fuel that acted as chief incentive to the pioneers of these processes in the first instance. Latterly the question of tar oils has loomed largely into view, and at the present time probably claims the place of greatest importance.

About forty years ago it was general practice to employ cast-iron retorts for coal-gas manufacture. With these it was not advisable to exceed a temperature of 1650° F., otherwise the retort had too short a life to be economical. Retorts in those days all worked intermittently—a charge of coal was thrown into the retort and withdrawn at the end of, say, six hours, by which time it attained throughout its mass a temperature of 1600°. The gas yield was comparatively small, but the quality was good. The gas was rich in heavy hydrocarbons, such as ethylene and benzene. To these constituents it owed its high candle-power. It contained a high percentage—at least 35 per cent—of methane, and to this it owed the largest proportion of its heating value. The yield of tar was considerably greater than is now usual in carbonizing practice, and the quality of the same was superior to the present-day product in that it was thinner, contained more light spirit, less naphthalene, less pitch, and much less free carbon. The yield of ammonia at 1650° F. was very good though not the best possible, this being at a maximum, probably at a carbonizing temperature of 1750° F., but it was distinctly better than can be obtained at the modern temperatures of 1900°-2000° F., vertical retorts excepted. There was an increase in the content of sulphuretted hydrogen and carbon dioxide in the gas, but a large reduction in organic sulphur compounds (carbon disulphide principally). A further feature of the conditions of gas manufacture and supply forty years ago was the almost total absence of naphthalene trouble, the main cause of stoppages in the gas services.

In the early days of " Coalite " the advocates of the process based their calculations and hopes on the selling of coalite at a high figure which could only be realized by the conversion of a multitude of consumers to the religion of smoke abatement and abhorrence of the use of raw coal. There was probably a miscalculation in estimating that the whole of the coke would be available for sale at a high price ; allowance was not made for the friable nature of coalite, and the large amount of breeze produced in handling and breaking up, such breeze commanding a very poor market. On account of these circumstances and unforeseen difficulties in carbonization, and lack of assistance by experienced gas engineers, the early efforts to make the coalite process a commercial success signally failed.

At the present time when fuel of all kinds fetches high prices, and oils especially are at a premium, there is certainly a better field for the activities of low-temperature carbonization.

As a commercial proposition much depends in the first place on the prices to be obtained for the tar oils and motor spirit, and, in the second place, on the cost of carbonization, that is, the capital charges, wages, and fuel costs incidental to the process. Given a high return for specially valuable oils and a very large through-put per retort and per man, there is great hope that low temperature may be successfully adopted to recover the bulk of the volatile matter contained in our bituminous and semi-bituminous coals, now going in large measure to waste. One of the great difficulties in making coalite is to effect uniform carbonization. When made in the ordinary type of horizontal retort in layers 7 or 8 inches thick, the portions of the coal coming in contact with the retort and also the upper surfaces exposed to the radiant heat from the crown and upper sides of the retort are carbonized in much greater degree than the centre portions. The thicker the charge the poorer the result, owing to the very slow transmission of heat at low temperatures, and if very thin charges are used the output per retort is much reduced. When the convenient arrangements of vertical retorts are taken advantage of, " sticking " becomes a bugbear, and a careful selection of coals and a suitable special design of retort are then rendered essential. The difficulty is almost entirely one of retorting, and many designs and processes have been devised and patented to overcome this.

The history of the process as gleaned from the technical literature written on the subject is briefly as follows : As early as 1681 a patent was taken out by Becker and Serle for carbonizing coal to produce pitch, tar, and smokeless fuel, and in 1781 the Earl of Dundonald brought out an improvement on this. As one of the first of modern efforts in this direction the English Patent, 67, 1890, by Parker, is noteworthy. In this process it was proposed to produce smokeless fuel by distilling the coal in a current of steam, water-gas, or coal-gas superheated to a temperature of 600° to 650° C.

In 1906 the principal Coalite patent was taken out by Parker (Eng. Pat. 14,365 ; 1906). This consisted in distilling coal in the presence of steam at a temperature not exceeding 800° F. (427° C.). At first horizontal ⌓-shaped retorts, 5 feet wide, 7 feet long, and 16 inches high, were employed, the layer of coal being not more than 6 inches thick. Tapering cylindrical retorts and tubes of 6 inches diameter were subsequently used with only partial success. Narrow vertical retorts of oblong cross-section were afterwards brought into use, and these in turn gave place to bunches of vertical tubes, 4 to 6 inches in diameter. Slots between the different tubes to relieve gas pressure were one of the more novel features. These arrangements were the subject of different patents. Internal heating by means of hot gases does not seem to have been developed to any extent by the Coalite company and its immediate successors. No definite carbonizing results have been published. The chief features of the process of " The Premier Tarless Fuel Ltd." are the very high vacuum and the special design of retort (Tozer).

As high a vacuum as 20 to 27 inches of mercury (Simpson's process) is said to be capable of maintenance on a working scale and of producing improved yields of by-products. From the published description of the plant erected at Battersea one learns that their most recent design of vertical retort is cylindrical, 9 feet 5 inches long by 1 foot 8 inches in diameter, with an annular space divided by a central partition so as to give two carbonizing rings each containing four sections through the divisions created by vertical heat-transmitting ribs. The thickness of the charge of coal in each annulus is 2½ inches. The central space of the retort is empty, or rather contains hot air. Carbonization is conducted at 900° to 1000° F., the heating being external. The duration of charge is 3½ to 4 hours. The bottom discharge doors are fitted with asbestos rings and are interlocking. The top mouthpieces are not partitioned ; when charging is in progress the central channel of each retort is sealed by a stopper. A bed consists of six retorts which take a combined charge of 2700 lb. of slack, equivalent to 50 tons per week. The retorts are encircled by firebrick and not exposed to direct gas heating, which is done by producer-gas at first and afterwards by a portion of the stripped gas made.

The bed is divided into two chambers, three retorts in each. The gas goes to three condensing separators in series. These run off three different grades of tar, the pipes leading to the collecting tanks being at least 32 feet high to prevent condensate being drawn up and out by the high vacuum. A P. and A. tar extractor, constructed without seal and to stand a high vacuum, removes heavy tar oils.

Next come the ammonia-washers, followed by the oil-washers for stripping the gas. The exhaust pump comes at the tail end. Before being sent to a holder the gas is compressed to 70 lb. per square inch and again suddenly expanded. On expansion a light spirit of a peculiar nature is said to separate out. Sample results from Yorkshire coals have been published as follows :

	1.	2.	3.
Tarless fuel, per cent	73	73	78
Tar (water-free), gallons per ton of coal .	19·2	17·2	22
Sulphate of ammonia, lb. per ton of coal	11·7	11·5	10·5

The gas yield is given as about 5800 cubic feet of a quality of 750 B.Th.U. (gross) before stripping, and 150 to 200 after. This remarkable drop in heating value, if correct, is difficult to account for. Quoting from Dr. C. Young's report published by the company, we learn that at a carbonizing temperature of 900° to 1000° F., and a vacuum of 20 to 25 inches of mercury, the yields from a cannel and a bituminous coal were :

	Cannel.	Bituminous Coal.	(For Comparison.) Best Yorkshire Coal at High Temperature.
Tarless Fuel, cwt. per ton .	14	14	(13)
Gas stripped to 300 B.Th.U. cubic feet per ton . .	5000	5000	(13,000)
Sulphate, lb. per ton . .	25·3	23·8	(30)
Tar (water-free), gals. per ton	44	22	(15)
Light Spirit, gals. per ton by compressing and stripping gas	8·7	2·2	(3)
Light Spirit in Tar (to 170° C.), gals. per ton	2·9	1·3	(½)
Total Light Spirit, gals. per ton	11·6	3·5	(3½)
Total Tar Oils, gals. per ton	55·6	25·5	(18½)
Pitch in above, lb. per ton .	191	90	(90)

The coke obtained therefrom is described as dense but porous, not readily friable, easily ignited, giving a clear hot fire with good flame, but without smoke or soot. The tar oils produced had a specific gravity intermediate between shale oils and ordinary coal-tar. They are more closely allied to the former as they consist of paraffinoid compounds and unsaturated hydrocarbons. Benzenoid hydrocarbons, such as naphthalene and anthracene, are entirely absent. The light oils are said to yield, in about equal quantities, solvent naphtha and a motor spirit resembling petrol rather than benzole, with a specific gravity of about 0·80. The middle oils, when fractionated, produce varying amounts of solar and fuel oils. The heavy oil is obtained as a crude lubricant, and the residue, amounting to 30 or 40 per cent, is a good hard pitch containing very little free carbon.

An important point of difference from ordinary coal-tar is the large content (about 10 per cent) of tar acids, which consist almost entirely of cresylic acid and its homologues, and little or no phenol.

Whether there are outstanding advantages in the use of a high vacuum is, to the writer's mind, rather doubtful. Heavy tars formed during the destructive distillation of the coal will certainly not be allowed to condense to the same extent on the cold coal as in other processes, and sticking will no doubt be thereby reduced. But we doubt if there is a greater yield of gas, tar, or oils than in other processes working at the same carbonizing temperature. There are the obvious disadvantages of increased costs of working and greater capital outlay, and danger of severe leakage and the attendant risk of explosive gas mixture. The process has yet to prove itself on a large scale.

In the system adopted by the Barnsley Low-temperature Carbonization Company, fireclay takes the place of cast-iron. (Fireclay retorts would, of course, be quite out of the question in the Premier Tarless Company's process, on account of their porosity.) The retorts are vertical ovens, 10 feet high by 10 feet long by 12 inches wide. According to the Eng. Pat. 108,200, there are four zones of heat, starting with the base of the retort at 450° C., the next 500°, the next 550°, and the free space at the top of the charge 900° to 1200°. The purpose of the high temperature at the top of the charge is to crack the tars, and this action is facilitated by suspending in the free space a grid of suitable shape and material. This kind of device was also adopted in the Woodall-Duckham high-temperature retort, but it probably has not a great deal of utility. The Barnsley method has also apparently followed that of the Woodall-Duckham company in having the highest temperature zone at the top of the retort.

Definite results of the system have not been published.

The carbonizing temperature is stated to be 600° C., the volatile matter left in the coke about 10 per cent, the yield of gas 6000 cubic feet, light spirit about 4 gallons, and tar about 18 gallons per ton of good gas coal. The ammonia yield is equivalent to about 15 lb. of sulphate per ton.

Still another system of recent origin is that known as "Carbocoal" (Smith's patents), now working on a commercial scale in the United States. The process is a combination of low and high temperature carbonization. The finely crushed coal is first carbonized at 480° C. in horizontal retorts, where it is agitated by two slowly rotating paddles. The low-temperature coke automatically delivered as a spongy mass is briquetted with 8 to 10 per cent of pitch and then carbonized at 1090° C. in secondary retorts, which are of the inclined type. It is claimed that the yields of gas, tar, spirit, and ammonia are in excess of those obtained by other systems, while the resulting coke briquettes are hard, easily transported, and perfectly smokeless in burning.

The Summers process, also of American origin (Eng. Pat. 2069 and 10,284 of 1914), of compressing the coal while in a hot, semi-plastic state does not appear to have made much headway as yet.

Various systems of internal heating have also been tried, with good prospects of ultimate success. The great drawback to external heating is the small throughput and the consequent high capital outlay for retort plant. With a suitable method of intimate heat exchange between the mass of coal and a heating medium, one would imagine that the rate of distillation at a given temperature would be greatly speeded up; and this is found to be the case in practice. In the McLaurin process (*J.S.C.I.*, 1917, 620) the coal is carbonized in a current of hot producer gas. Some rather remarkable results of this process have been published. Coking coals are said to distil without showing any signs of intumescing.

This is thought by Evans to be due to the oxygen present, although in small quantity, in the producer gas. McLaurin suggests that the rate of heating is the chief factor, and if it is too fast caking will ensue. In this process difficulties in passing the gas through are encountered, if the coal is very fine.

The tars produced are remarkable in character, being readily separated into a resinous portion and tar oils by mixing them either with paraffin or weak sulphuric acid. (See McLaurin's patents 24,426, 1913, etc.)

In the Chiswick (Del Monte) system we have an example of a continuous low-temperature process.

In this case an Archimedean screw, revolving in a horizontal retort of circular section, keeps the fuel in motion and carries it along to the discharging end.

In one modification of this system the screw was mounted on a hollow shaft, which could be heated internally by a row of gas jets, and a graduated temperature, instead of a uniform one, was maintained in the retort. This retort, however, is said to be unsuitable for caking coals, and can only be used for wood, shale, lignite, peat, cannel and non-caking coals.

In the system of Pringle and Richards the coal is carried through a retort at about 500° C. by an endless conveyor, which is subdivided into compartments, each carrying its quota of coal.

So far, the system has been tried only on a small scale, we understand, but it is said to offer prospects of ultimate success, the coke possessing superior qualities as a domestic fuel, being very porous and easily ignited.

One of the most recent proposals is that of Swinburne, in which the inventor designs the retort for internal heating to a temperature of 350° C. by electric conductors.

Another is to cause the powdered coal to fall in a shower down the inside of a retort heated with superheated steam or other inert gas.

The process of Merz & M'Lellan, Michie & Weeks (Eng. Pat. 117,290, 118,777, 136,868, and 149,733), consists in the use of a vertical retort of large section, and the passage of a large volume of superheated steam upward through the charge of coal, which is preheated and fed continuously into the top of the retort. The coke is discharged continuously, as hot as possible, direct to the automatic stokers feeding the boilers. The coke is small, soft, and friable. The latent heat of the steam is recovered by heat-interchange with the boiler-feed water. The tar oils are separated from the condensate, and utilized partly for fuel, partly for special purposes, for which they command a high price. The gas is washed in the usual way for the recovery of light spirit, etc. Owing to the very large throughput attained, the low capital cost, and the low labour charges, it is not necessary to depend for commercial success on the problematic sale at a high figure of a household smokeless fuel. The process must be regarded as a distinct advance in the campaign against the use of raw coal as fuel.

The advantages claimed for smokeless fuel over coal by Low Temperature Carbonization Ltd. are as follows :

1. It radiates more heat into the room, the difference being very remarkable in large fires.
2. It burns absolutely without smoke.
3. It lights easily and burns up brightly at once, so that the fire is cheerful and efficient from the beginning.
4. It keeps a clear glowing fire for many hours without attention.
5. It can be burnt down into a very small fire without going out.
6. It heats a room more cheaply than the best coal.
7. It can be used in any form of grate or stove.
8. Chimney and kitchen flues will not require sweeping.

The validity of No. 6 will naturally depend on the respective prices of coalite and coal.

There are, to the writer's mind, two essentials other than a suitable price necessary to the full success of a smokeless fuel in replacing coal in British grates. One is the proper sizing of the material, which should be uniformly of the size of a hen's egg. The other is the reduction of the ash content of the coal carbonized by some system of coal-washing. With these conditions observed even ordinary gas coke would be a welcome substitute for coal in household grates.

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 mixed with the fuel, but is in contact 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 black-band iron-stones, 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. 53 and 54, and no further description is necessary.

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, etc., 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, etc., which by the removal of a damper can be placed in communication with a central chimney, and each space has also a door BB 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

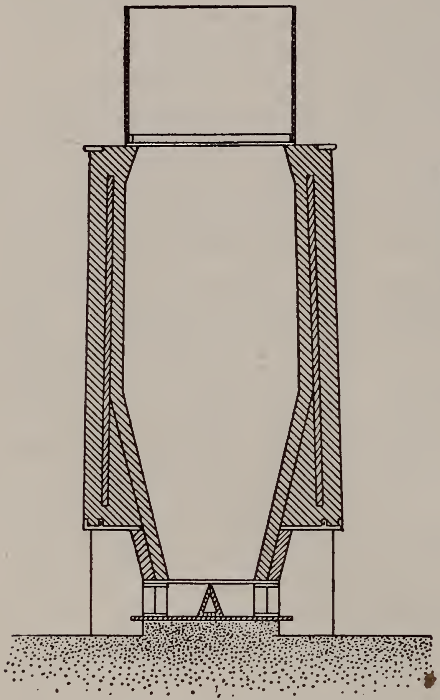
FIG. 53.—Scotch Iron-ore Kiln.

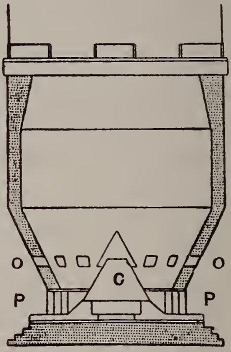

FIG. 54—Gjers Kiln.
C, Cone. P, P, Pillars.
O, O, Lateral openings.

pp shown in Fig. 55. The 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

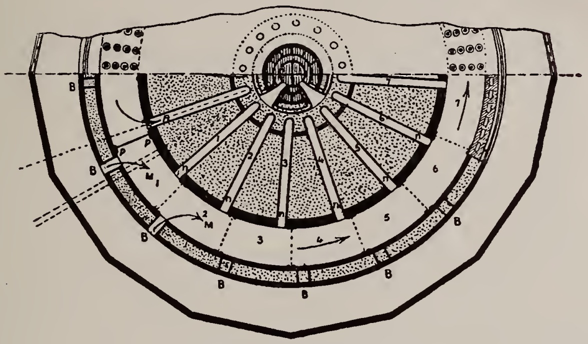

FIG. 55.—Otto Hoffman Kiln.

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 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.

The charge is introduced at the top, which is now

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[1] Roberts-Austen, *Introduction to the Study of Metallurgy.*

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 tuyères 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.

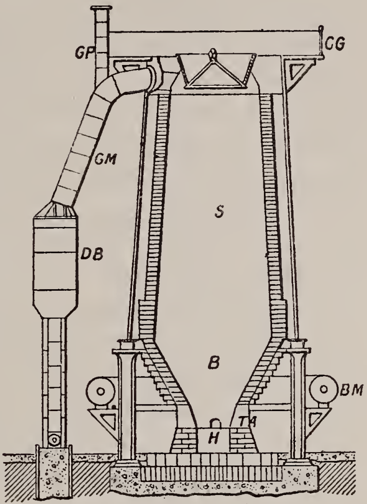

FIG. 56.—Typical Blast-furnace. S, Shaft. B, Bosh. H, Hearth. TA, Tuyère opening. BM, Blast main. CG, Charging gallery. GM, Gas main. DB, Dust box. GP, Waste-gas pipe.

The chemical action which takes place in the blast-furnace is in the main simple. The oxygen of the air coming in contact with the fuel at a high temperature is at once converted into carbon monoxide. 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 moderate 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 one-third 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 per cent 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.

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, $CO_2 + C = 2CO$, thus consuming more coke without doing any good. The temperature at which this 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.

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	61·53	38·47	284	114	3·50	1·500
W. Virginia	52·54	81·56	64·33	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	58·96	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

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,

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[1] Fulton, *Transactions American Institution of Mining Engineers*, vol. xii. pp. 212-223.

in the region of the tuyères, 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 lb. of iron produced :

	Centigrade units.	B.Th.U.
Evaporation of water in coke	313	563
Reduction of oxide of iron	33108	59595
Carbon impregnation	1440	2592
Expulsion of CO_2 from limestone	4070	7326
Decomposition of CO_2 from limestone	4224	7603
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	15356	27641
Heat usefully employed	70311	126560
Carried off in gases	7900	14220
Otherwise lost	8789	15820
Total	87000	156600

giving an efficiency of about 80 per cent of the heat evolved by the fuel consumed, only about 9 per cent being carried off as sensible heat in the gases.

The amount of fuel actually consumed in smelting iron ores is about 18 to 21 cwt. of coke, or 30 to 36 cwt. of coal per ton of iron produced.

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

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[1] *Principles of the Manufacture of Iron and Steel*, p. 95.

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 tuyères, 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.

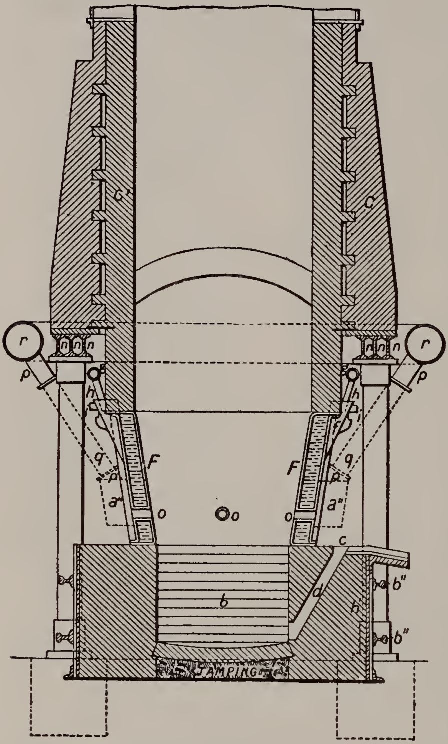

FIG. 57.—Blast-furnace for smelting Lead. From Hoffman's *Lead*. *o*, Tuyères. F, Water-jacket. *d*, Siphon tap. *r*, Blast main.

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 tuyères, 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; 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.

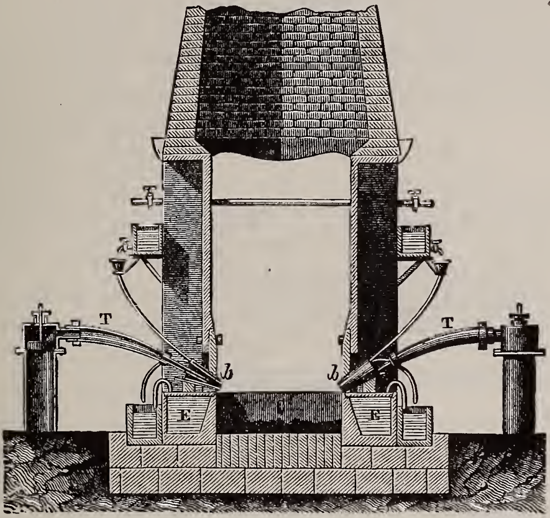

FIG. 58.—Refinery Hearth.
C, The hearth. E E, Hollow water-jacketed walls. T T, Blast-pipes. *b b*, Tuyères.

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.

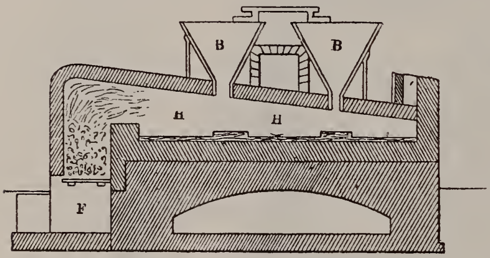

FIG. 59.—Reverberatory Furnace for calcining Copper Ores. H H, Hearth. F, Fireplace. B B, Hoppers.

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. 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 fire-brick 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 farthest from the fire-place, 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 following table gives the details of a few typical furnaces:

	Puddling Furnace.	Reheating Furnace (Major Cubillo's).	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	..	..

The height of the bridge above the hearth is about 1 foot to 1 foot 9 inches, and all details may vary very much, 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 $\frac{3}{4}$ 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 $1\frac{1}{4}$ to $1\frac{1}{2}$ inch square bars of iron resting on bearers. The bars should be cast from grey 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 $\frac{3}{4}$ 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 lb. per square foot per hour should be burnt ; if less caking, from 14 to 16 lb. ; and if non-bituminous, from

16 to 20 lb. may be used." Rankine gives the rate of combustion in various grates:

	Lb. 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—

	Lb. 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

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[1] Schmackhöfer and Browne, *Fuel and Water*, p. 96.

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 : [1]

General Balance of the Reverberatory Furnace.

Heat produced.			Heat consumed.		
	Calories.	Per Cent.		Calories.	Per Cent.
Heat of fuel . . .	163960	98·12	Fusion of the iron .	26210	15·60
Heat of substances oxidized during the process . . .	3106	1·88	Fusion of the slags .	2246	1·34
			Vaporization of water in the fuel . .	2133	1·27
			Heat carried off by gases	128900	77·13
			Heat lost in ashes .	1990	1·13
			Loss by radiation, etc.	5618	3·35
	167066	100·00		167097	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 [2] has worked out the thermal values of

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[1] *Proc. S. Staff. Institute of Iron and Steel Works Managers*, 1893–1894, p. 13.

[2] *J. I. and S. I.*, 1892, vol. i. pp. 245 *et seq.*

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. 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	197·8	22·70
Combustion of 135·73 CO and 6·72 H[1] . .	521·0	59·80
Heat introduced by air	86·7	9·96
Oxidation of silicon	26·1	2·90
,, manganese	2·0	·22
,, carbon	29·8	3·45
,, phosphorus	·2	·02
,, sulphur	·2	·02
,, iron	6·3	·72
	870·1	99·79

Heat consumed :

	Calories.	Per Cent.
Latent heat of fusion	5·2	2·90
Heat of blooms	20·1	
Heat of fusion of cinder	22·1	2·64
Vaporization of water in ore	5·4	·60
Lost up stack	366·7	42·14
Vaporization of water in gas	7·6	·87
Reduction of Fe_2O_3 to FeO	14·1	1·61
Reduction of Mn_2O_3 to MnO	3·3	·38
Heat of ash	9·6	1·11
Radiation	415·0	47·70
	870·1	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

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[1] Per 100 kilogrammes of blooms.

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.

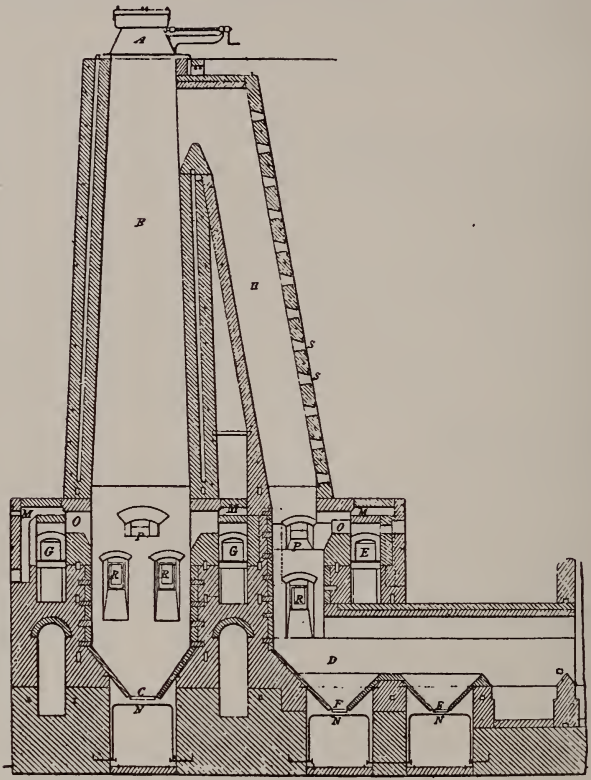


FIG. 60.—The Stetefeldt Furnace.

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.

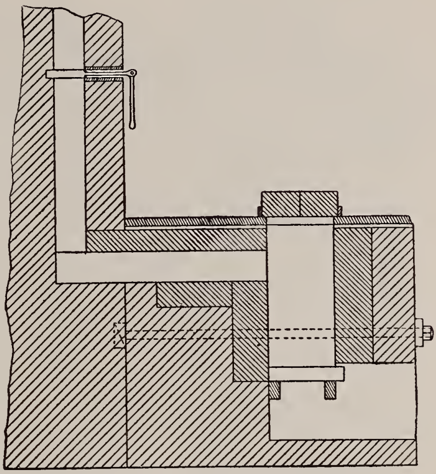


FIG. 61.—Crucible Furnace.

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.

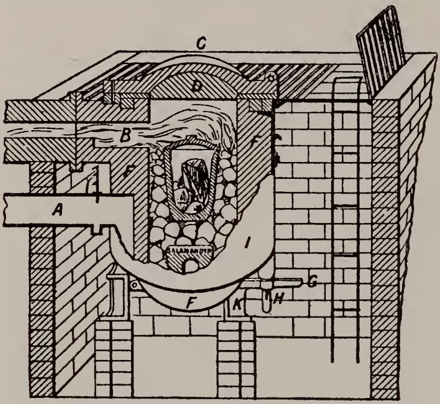
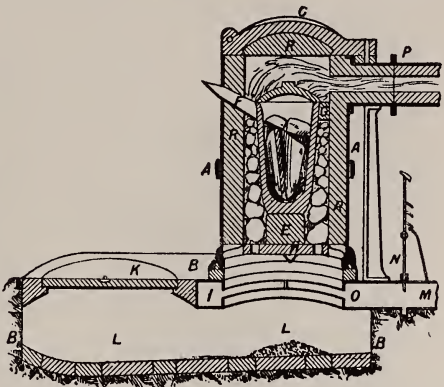


Fig. 62.—Fletcher's Patent Furnace.
A, Air tube. I, Iron casing of furnace. F, Fire-brick lining. B, Flue. C, Cover with fire-brick lining D.

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 Morgan's Tilting Furnace. The furnace is an octagonal steel 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 is fixed by means of blocks into the casing, and the casing is so fixed that it can be rotated in such a way that the spout is the centre of rotation. When the charge is to be poured, the blast is turned off, the chimney disconnected, the furnace body turned by means of a screw gear, and the molten metal poured out of the spout into the moulds. In another form of the furnace the body is carried on trunnions, and is so arranged that it can be lifted away bodily by means of a crane and carried to the moulds.

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.



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. 63.—Piat's Oscillating Furnace.

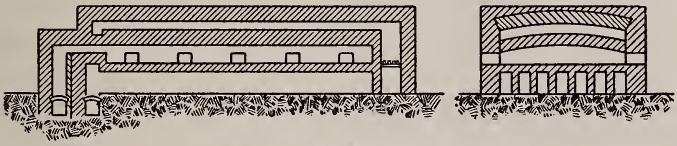


FIG. 64.—Muffle Furnace.

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.

Boiler Furnaces.—Fuel is very largely used for steam raising, and the feeding of boiler furnaces is a matter of extreme importance. If the boilers are badly fired the fuel is very wastefully used, and a large quantity of smoke is often produced.

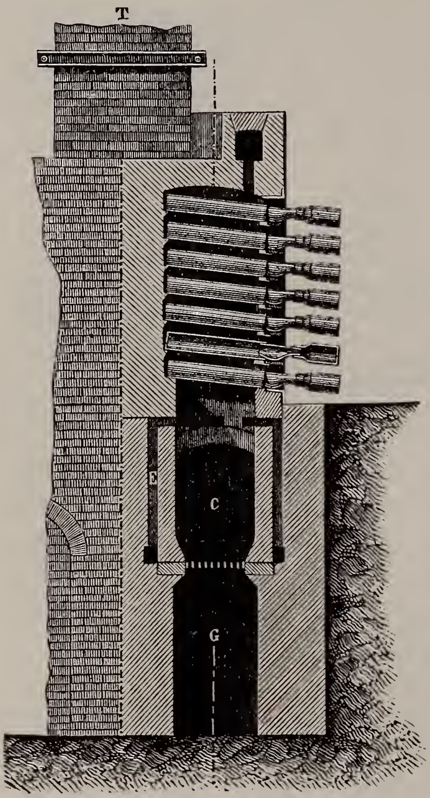


FIG. 65.—Retort Furnace for distilling Zinc. C, Fireplace. G, Ash-pit. E, Air passages. T, Chimney.

The fuel is supplied to a fire grate, and the air may be supplied either by chimney draught or under pressure. The chief air supply is always below the bars, but an additional air supply is sometimes arranged above the bars. If smoke is to be prevented it is essential that air be supplied in such a way that it will mix with the hydrocarbon gases before their temperature has fallen below ignition point, and thus complete the combustion.

Ordinary hand firing is as a rule very unsatisfactory. The coal is supplied in comparatively large portions at a time, and the conditions are much the same as those already described for a domestic fire. When the doors are open for firing, cold air rushes in and cools the gases, and very often every time coal is added dense black smoke escapes from the chimney. It is almost impossible to make hand firing satisfactory, but the smaller the quantity of fuel added at a time the better it will be.

To overcome the difficulties of hand firing, mechanical stokers, in which the fuel is added continuously or in small portions at a time, are now largely used. These are of two kinds.

Coking Stokers.—As an example of this type Messrs. Meldrum's " Koker " Stoker may be taken. The principle of all the coking stokers is that the fuel is fed on to a " dead " plate, *i.e.* a plate through which air cannot pass; there it is coked by the heat of the furnace, and the volatile products of distillation pass over the hot burning fuel, and are raised to a high temperature and burnt.

In the Meldrum furnace the coal is supplied to a hopper in front of the furnace, and beneath this is an oscillating casting B, which rocks backwards and forwards. When it comes under the hopper it is filled with coal, and as it rocks forwards it empties its contents on to the coking plate D, whence it is pushed forward at each oscillation of the rocker. By the time it has reached the end of the coking plate, the volatile matter has been expelled, and the coke is pushed on to the bars. The fire-bars are corrugated and are moved backwards and forwards by means of a cam. They all move forward together, and so carry the coke forward, but are drawn back singly, so as not to take it back with them. In some cases perforated coking plate is used, and air is supplied just above it. Forced draught may be used.

The combustion is very rapid and very complete and is almost smokeless.

Closely allied to the coker stokers are the chain-grate stokers, in which the solid bars are replaced by chains which are moved slowly forward, carrying with them the fuel, so that the fuel is always received at the end farthest from the flue and is there distilled.

Sprinkling Stokers.—In these stokers the fuel is sprinkled in small quantities at a time on the surface of the fuel, the action thus resembling in some respects good hand firing, but differing from it in that the additions are very

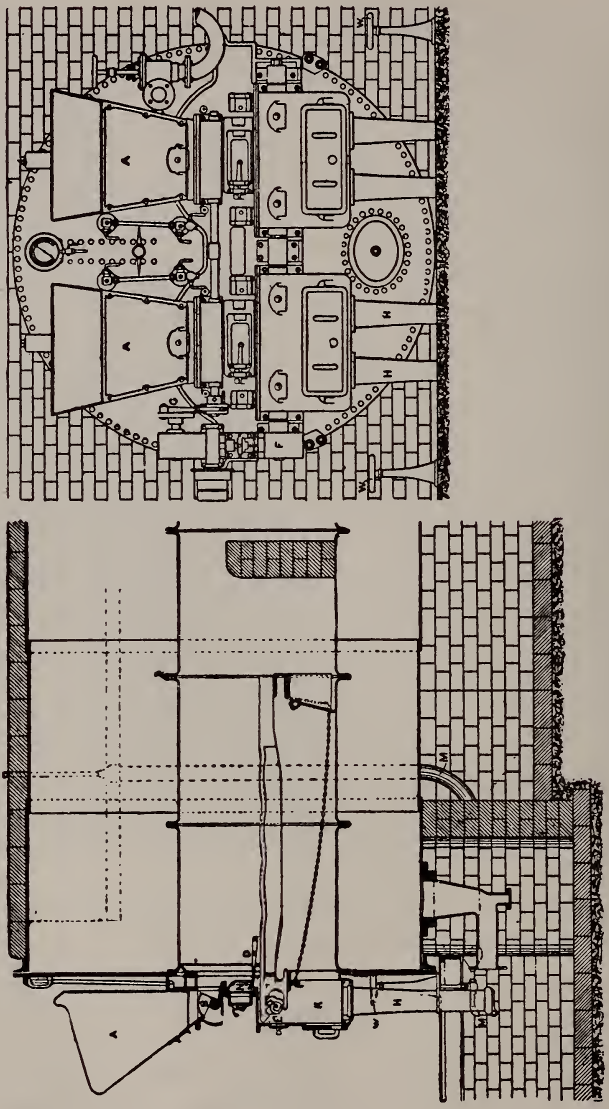


Fig. 66.—Meldrum's "Koker" Stoker.

frequent and very small, and that the fire doors are not opened. As an example the Proctor Stoker may be taken.

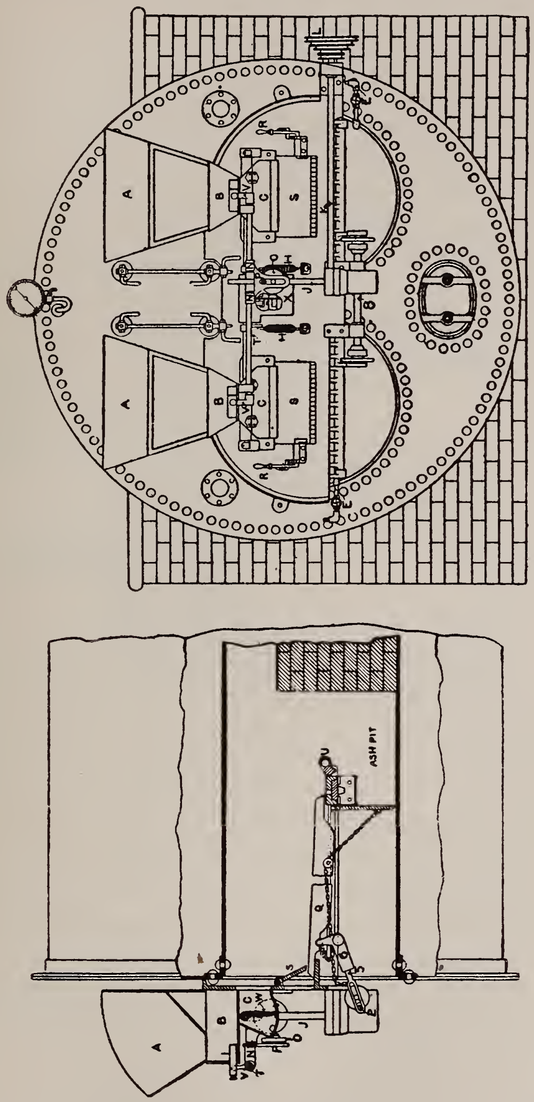


Fig. 67.—Proctor's Sprinkling Stoker.

The fuel is fed into a hopper, from which it falls into an iron box, fitted with a ram which moves backwards and forwards, As it goes backwards coal falls into the box, as it goes forward it pushes the coal into the sprinkler box. The shovel is drawn back by a cam, and as it recedes the coal falls in front of it. As soon as it reaches the back of the box it is released and is brought rapidly forward by the spring H, so that the coal is shot out into the fire, this action being repeated at any required speed.

The bars are supported on bearers, the bearer farthest from the fire door being kept cool by the circulation of steam, and each alternate bar is made to reciprocate so as to break up the clinker and ultimately deliver it over the ends of the bars to the ash-pit.

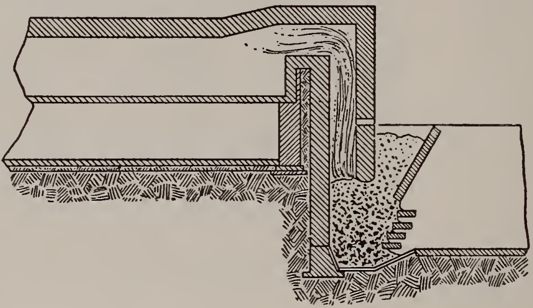


FIG. 68.—Mond's Gas-fire.

Underfeed Stokers.—These stokers are of recent origin and have been designed to work with a thick bed of fuel, the feed being obtained by Archimedean screw or chain grate. Fuels having a low percentage of volatile matter, such as anthracite and coke breeze, and others of as high ash content as 50 per cent, can be burned with advantage over other types of stokers.

Almost all automatic stokers must be fed with slack or coarsely powdered fuel, and they all use some steam to drive the necessary mechanism.

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.

Boetius Furnace.—This furnace was patented in 1865. 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

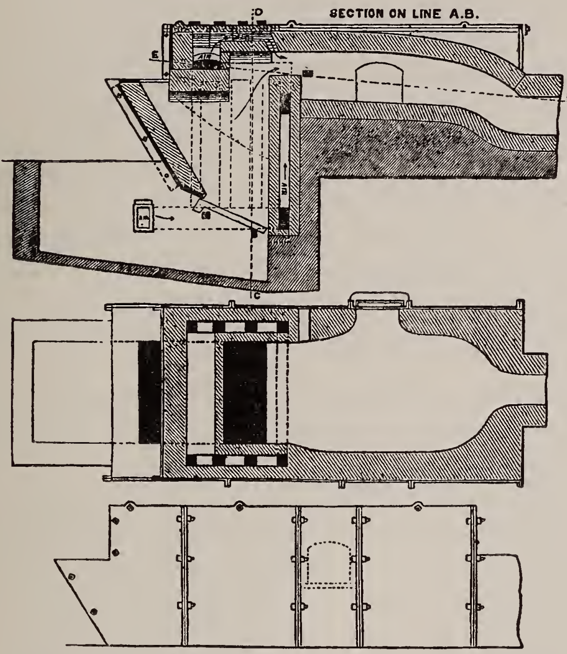


FIG. 69.—Boetius Heating Furnace. From D. K. Clark's *Fuel.*

become heated before passing to the furnace, where it mixes with the combustible gases just as they enter.

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.

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 firebrick. The air and gas are supplied at one end of the furnace, burn, and 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 half-hour, 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.

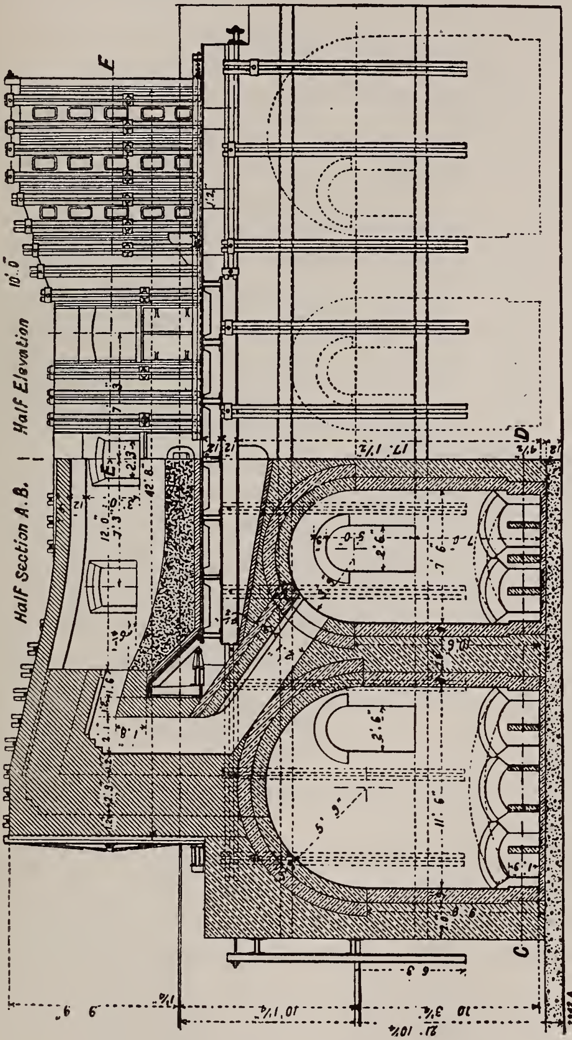


FIG. 70.—Steel Furnace at Wishaw Steel Works. From *Engineering*.

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 lb. of fire-brick and (in reversing every hour) 17 lb. 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]

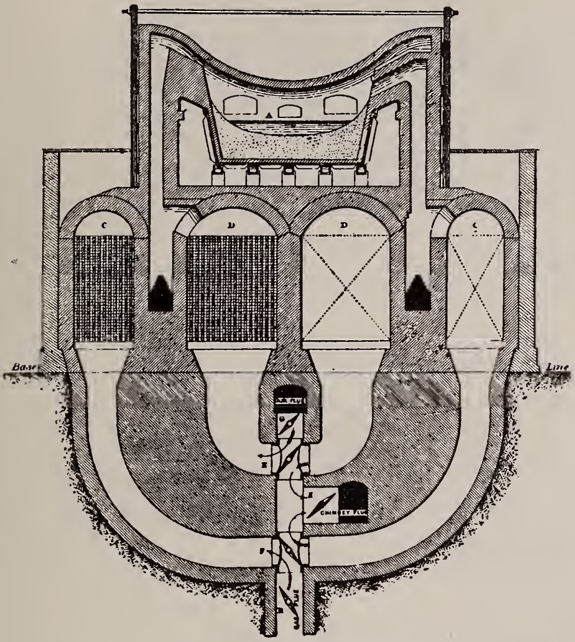


FIG. 71.—Section of Siemens' Steel Melting Furnace, with Valves.

Roberts-Austen gives 14 to 15 square feet of regenerator brick surface as being necessary for each 2 lb. 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. 71. The butterfly valve is the commonest

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[1] *Collected Works*, vol. i. pp. 227, 228.

[2] *Introduction to the Study of Metallurgy*, p. 261.

form, but many other forms have been suggested for the purpose, and have been described in the technical journals.

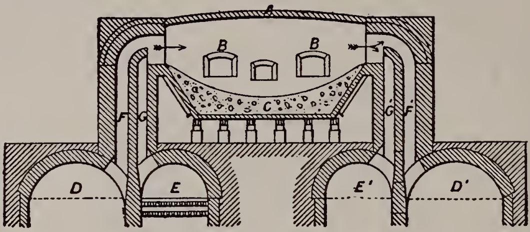


FIG. 72.—F. Siemens' Furnace.
B, Working doors. E, Gas regenerators. D, Air regenerators. G, Gas port. F, Air port. A, Roof.

The regenerative furnace has many advantages. Though the temperature in the furnace itself is very high the gases 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.

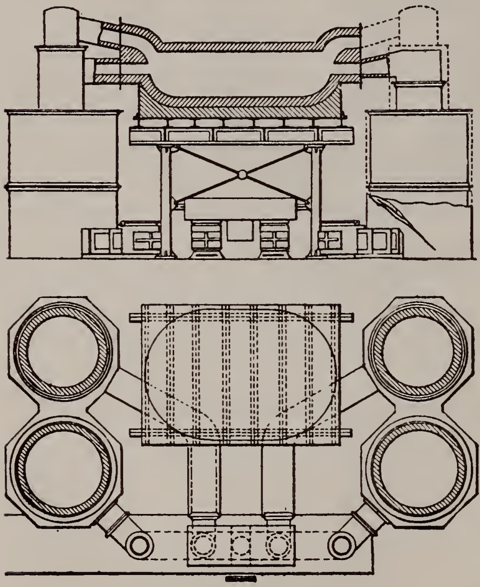


FIG. 73.—Batho Furnace.

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.

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.

Gas from the producer B passes through the flue C′ and valve A′ to the gas port, thence into the combustion chamber *h′ g′*. Air for combustion passes through the regenerator A′, by an air flue, the air 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.

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."

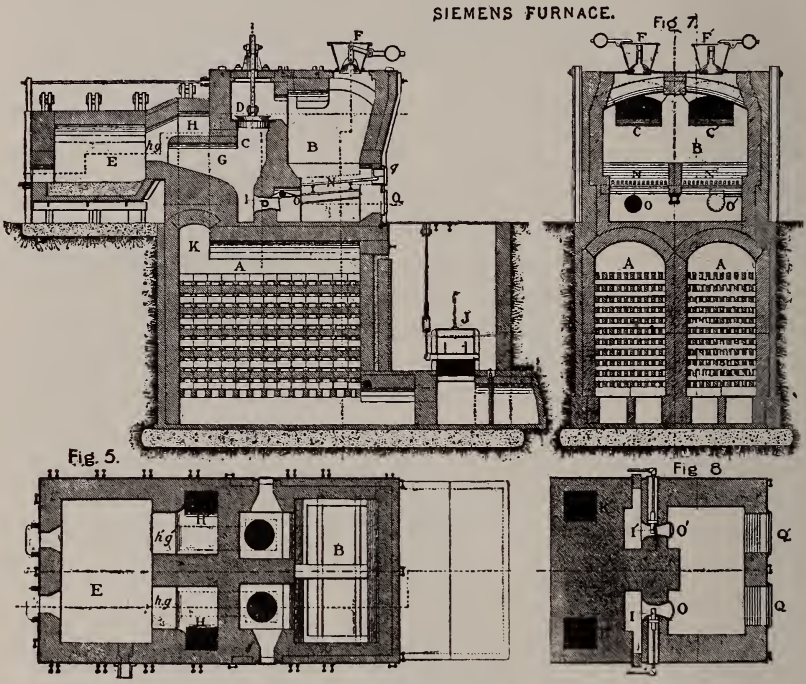


FIG. 74.—New Form of Siemens' Regenerative Furnace. From *J. I. and S. I.*

It has only been used for reheating and has not yet been applied to steel making.

The Ideal Furnace.—Another type of furnace 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,

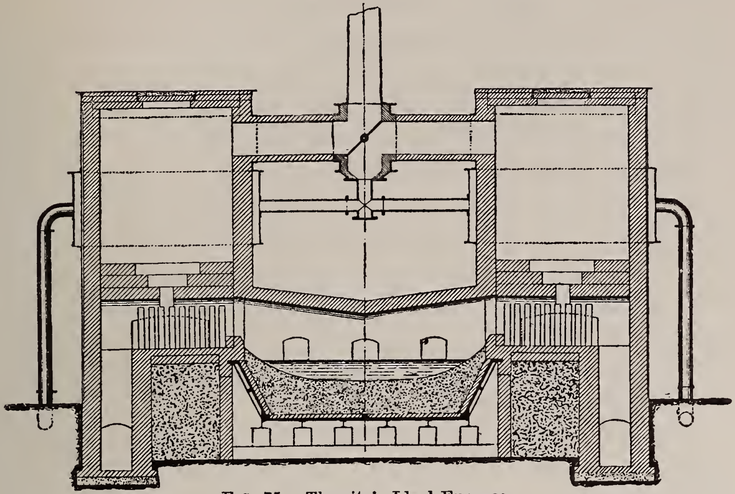


FIG. 75.—Thwaite's Ideal Furnace.

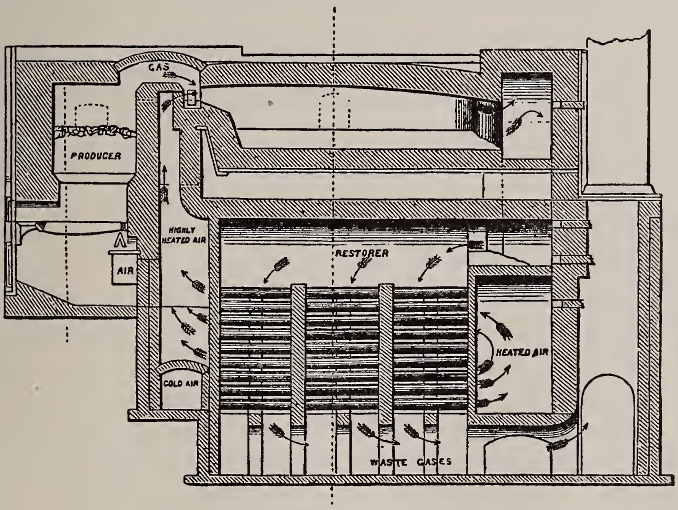


FIG. 76.—Gorman's Heat-restoring Gas Furnace. From D. K. Clark's *Fuel*.

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 ironworks for reheating.

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 lb. of coal was:

Carbon monoxide	155·9
Carbon dioxide	42·4
Hydrocarbons	8·0
Hydrogen	3·7
Nitrogen	392·2
	602·2

whilst 3·97 lb. 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	155·9 × ·2479 = 38·66
Carbon dioxide	42·4 × ·2164 = 9·17
Hydrocarbons	8·0 × ·5929 = 4·75
Hydrogen	3·7 × 3·4046 = 12·73
Nitrogen	392·2 × ·2440 = 95·69
	602·2 × ·2673 = 161·00

The formation of the gas in the producer evolved

66·800 lb. C to carbon monoxide	= 300600 B.Th.U.
11·560 ,, C to carbon dioxide	168100 ,,
	468700 ,,

The total heat of combustion of the coal for 100 lb. would be:

84·38 lb. C to carbon dioxide	1226900 B.Th.U.
5·2 ,, H to water	319900 ,,
	1546800 ,,

Therefore $\frac{468700}{1546800} \times 100$ or 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, 1078100 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	309·4 lb.
Water	47·2 ,,
Nitrogen	999·5 ,,
Oxygen	30·2 ,,
	1386·3 ,,

of which the capacity for heat can readily be ascertained.

	Units.
Carbon dioxide	309·4 × ·2164 = 67·0
Water	47·2 × ·4750 = 22·4
Nitrogen	999·5 × ·2440 = 243·9
Oxygen	30·2 × ·2182 = 6·6
	1386·3 × ·2452 = 339·9

That is to say, the products of combustion absorb 339·9 units of heat for each degree rise of temperature.

Distribution of Heat.—M. Krause analysed the work of a heating furnace at Soughland ironworks. The furnace heated about 18,000 lb. of iron in twenty-four hours, and the quantity of coal used was 4000 lb., or at the rate of about 4·44 cwt. per ton of iron heated.

The coal contained 10 per cent of ash, so that the 4000 lb. was equivalent to 3600 lb. of combustible matter. The valves were reversed every half-hour, so that between each reversal 75 lb. of combustible was burned, developing 1160100 units of heat.

Losses by the Chimney.—Suppose the gases to leave the chimney at 392° F., they would carry with them 339·9 × ·75 × 360 = 91760 units of heat.

Losses by Transmission through Walls of Regenerator.—This M. Krause calculated, assuming the gases to leave the furnace at 2910° F., to be 27750 calories, or 110100 B.Th.U.

Heat absorbed by Iron.—To heat 18,000 lb. of iron to 2910° F. from 32° in twenty-four hours, or 375 lb. each half-hour, its specific heat being ·185, would absorb 375 × 2880 × ·185 = 199800 units.

Summary of heat evolution for each 75 lb. of coal :

	Units.	Per Cent.
Conversion into gas and loss in cooling-tubes	382800	33·0
Loss by chimney	91800	7·9
Loss by transmission through walls of regenerator	110100	9·5
Taken up by the iron	199800	17·2
Lodged in furnace and loss through walls .	375600	32·4
	1160100	100·0

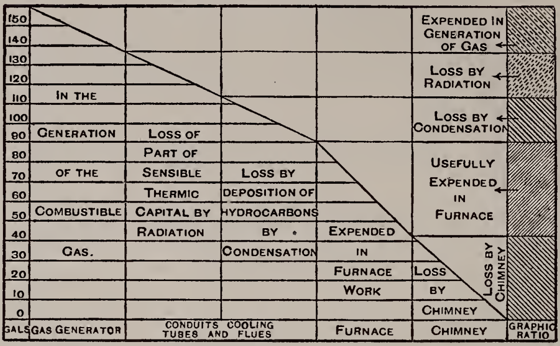
Heat intercepted by Regenerators.—The products of combustion leave the furnace at 2910° F., and carry off 2880 × 254·9 = 734000 units in half an hour ; of these the chimney takes off 91680, and the walls of the regenerators take up 110100, and the remainder 532200 is available for heating up the gas and air, so that if the regenerators are of equal size there would be 266100 stored up in each. The quantity of gas produced from 75 lb. of coal is 451·6 lb., of which the capacity for heat is 120·8 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 per cent excess for the 75 lb. of coal, would be 588·2 lb., 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.

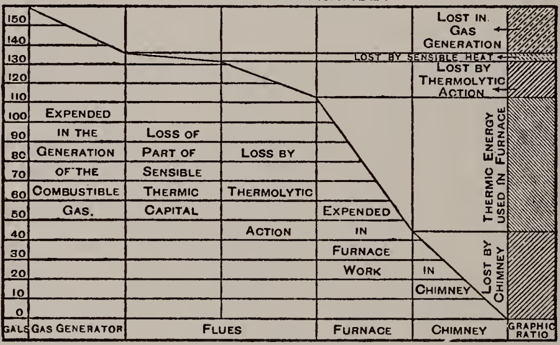
As it is desirable that the air and gas should be at as nearly as possible the same temperature, the air regenerator is preferably made larger, so as to give a larger heating surface. The heat carried forward by the gases is of course added to that obtained by the above combustion.

The above calculations cannot pretend to be accurate, on account of the uncertainty of our knowledge of the true

COLD GAS FURNACE.



HOT GAS FURNACE.



IDEAL FURNACE.

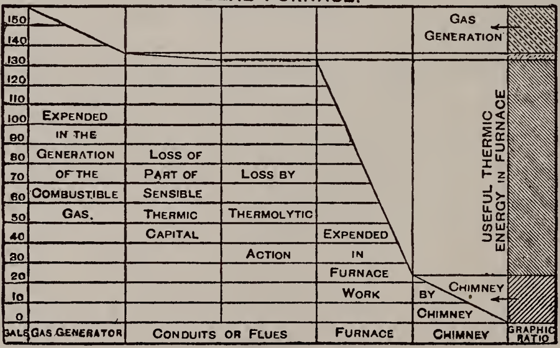


FIG. 77.—Thwaite's Diagrams.

specific heats of gases at high temperatures. They are useful, however, in indicating the method of arriving at a heat balance.

Mr. Thwaite's Calculations.[1]—Mr. Thwaite has 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. 77. 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.

Surface Combustion Furnaces.—In using a high temperature gas-fired furnace one observes that the velocity of combustion increases as the temperature of the fire-brick rises. The flames, which at first may protrude from the portholes of the furnace, recede when the temperatures approach a bright orange heat, showing that more gas can be burned in a given time when the contact surface is very hot. Some surfaces have a greater power than others in inducing or accelerating combustion.

Some years ago Professor W. A. Bone took up this subject, and in collaboration with Messrs. M'Court, Wilson, and others elaborated a system of "surface combustion," as it has been called, whereby high calorific intensity is developed, the refractory material used being maintained at a very high temperature, and thus producing a greatly increased radiation effect.

In simple forms of surface combustion burners the air and gas are supplied under considerable pressure, the air being only slightly in excess of the quantity required for complete combustion. The mixture passes from a mixing chamber through a flat porous diaphragm made of fire-clay granules held lightly together by a flux. A short time after ignition the flame disappears, combustion taking place just inside the outer surface of the diaphragm, which attains, with gases low in inerts, a bright orange or nearly white heat.

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[1] See *Journal S. Staff. Institute*, vol. vi.

In a muffle furnace (Fig. 78) the muffle is surrounded with granulated carborundum or other very refractory material, and for the highest temperatures the air may be reheated. The air-gas mixture must have sufficient velocity to avoid back-firing.

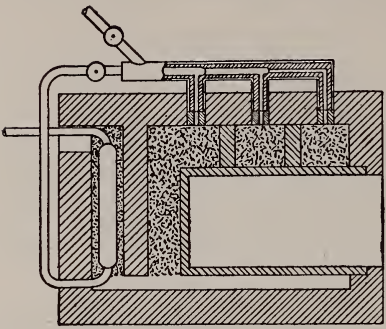

Fig. 78.—Bone and M'Court's Surface Combustion Muffle Furnace with Preheated Air.

Surface combustion gas-firing has been applied to boilers of the marine type, and efficiencies as high as 90 per cent have been attained with recuperation. The boiler tubes are fitted with specially designed blocks of granulated refractory material. The heat transference is very rapid. The development of the gas-fired boiler is limited by the comparatively high cost of the therm in the gaseous form.

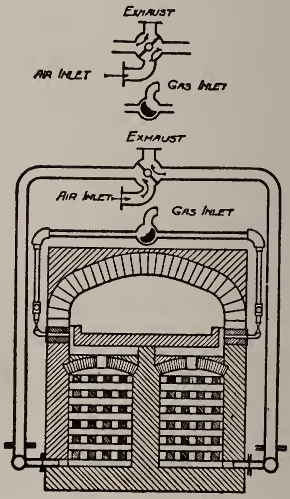

Fig. 79.—Section of the "Revergen" Gas Furnace.

Furnaces using Town Gas.—In recent years there have been great developments in the use of town gas or coke-oven gas for industrial purposes. The furnaces employed are generally of the most simple kind, and only in exceptional cases is there any attempt at recuperation. Temperatures of 1000° C. are attainable without the use of any aid to the ordinary Bunsen burner. When higher temperatures are required, either air blast or compressed gas (or both) or some system of recuperation is used. Fig. 79 shows a modern reversing gas furnace. Fig. 80 indicates a good working arrangement for the firing of water-tube boilers by coke-oven gas.

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 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.

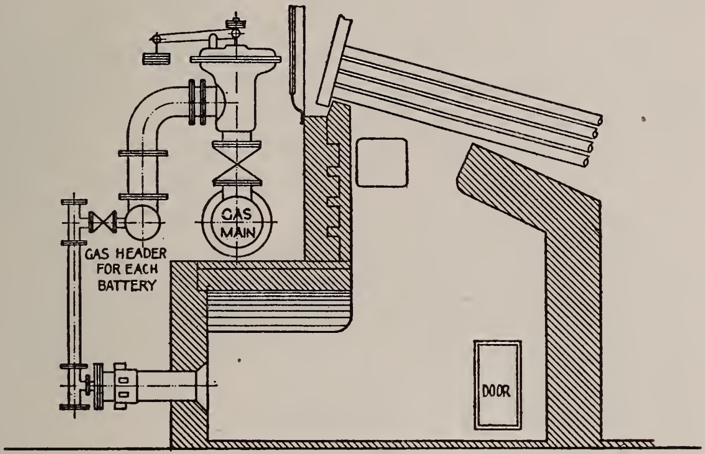

Fig. 80.—Gas Firing of Boilers.

2. The oil in the liquid form is injected by pressure through a jet into the combustion chamber in the form of a very fine spray, or is atomised by compressed air or steam by means of specially designed burners. 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. 81 and 82.

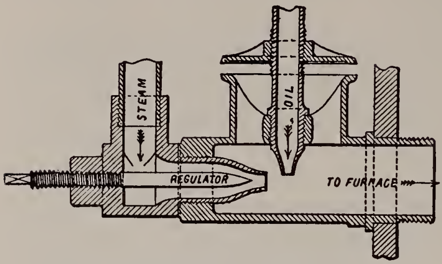

Fig. 81.—Aydon's Type of Injector as used at Messrs. Field's.

Fig. 83 illustrates one of these modern rather elaborate contrivances used for atomising heavy oils or tar. The oil, air, and steam enter at O, A, and S respectively.

Liquid fuel has been very successfully used for firing boilers, stationary, locomotive and marine, by means of these injector burners, but the use of liquid fuel has not made the progress for these purposes that many of its advocates expected until quite recently.

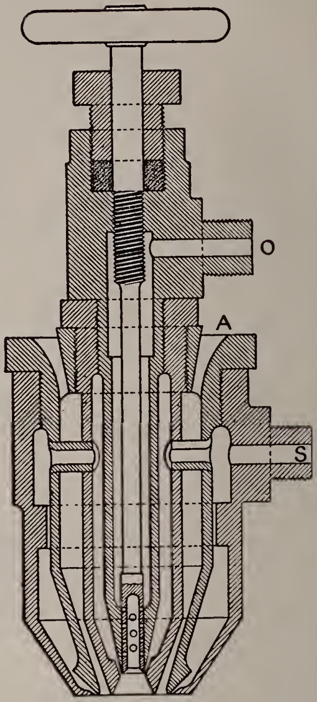

Fig. 83.—Field-Kirby Automiser.

Liquid fuel has, however, come largely into use for small furnaces, for metal melting and other purposes. These are of two types, reverberatory furnaces and crucible furnaces.

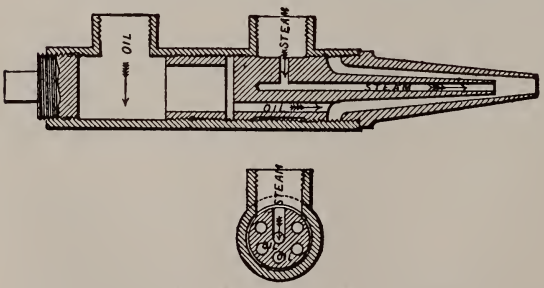

Fig. 82.—Aydon's Type of Injector as used at Woolwich.

Rockwell Furnace. — Of the reverberatory furnace type the Rockwell Furnace is perhaps the best known, although there are now several other forms on the market. This furnace consists of an iron cylinder lined with very refractory material, and narrowed at the two ends. At the one end air is blown in, and the other serves for the escape of the products of combustion. A charging opening is provided in the middle of the cylinder. When the furnace is in use this is held firmly in place by catches, and there is a hole in the centre through which the metal can be poured. Very frequently these furnaces are built double, the oil being supplied alternately at the two ends, and each furnace being capable of independent rotation. The usual capacity of these furnaces is about 1000 lb. of metal, though they may be built either larger or smaller.

In 1905 Mr. Quigley read a paper before the Pittsburg Foundrymen's Association in which he described some experiments he had made with furnaces of this type, and he gave the following figures :

Metal charged	7000 lb.
Oil used, including that used in heating up .	93 gals.
Oil used for 100 lb. of metal melted . .	1·3 gals.
Time required to heat up furnace starting cold	27 mins.
Oil consumed in heating up . . .	8 gals.
Actual time furnace was in blast, including heating up	7 hours 58 mins.
Time per 100 lb. of metal melted . .	6·8 mins.
Weight of metal per minute . . .	14·6 lb.
Average time per head of 500 lb. . .	34 mins.

The Steele - Harvey Furnace.—This is a crucible furnace fed with oil, and it may be built fixed (in which case the crucible is lifted out), or tilting, so that the crucible is poured without removing, the latter being in every way the best arrangement. The tilting furnace consists of a cylindrical steel shell lined with refractory fire-brick carried on trunnions so that it can be tilted, or in some cases it is arranged so that it may be lifted away bodily by a crane. The crucible rests on a block of refractory material, and is wedged in position by side blocks. The mixture of oil and air is blown into the bottom by means of a suitable burner, and burns in the space round the crucible. The furnaces are made with a capacity up to 750 lb. of metal. The lining stands about 500 heats, the crucible about 30 or more. The air is supplied at a pressure of about 40 lb.

Mr. J. W. Krause, in a paper read before the Pittsburg Foundrymen's Association in 1905, gave the details of some experiments made with these furnaces at the works of the Maryland Steel Co. On a four days' test the figures were :

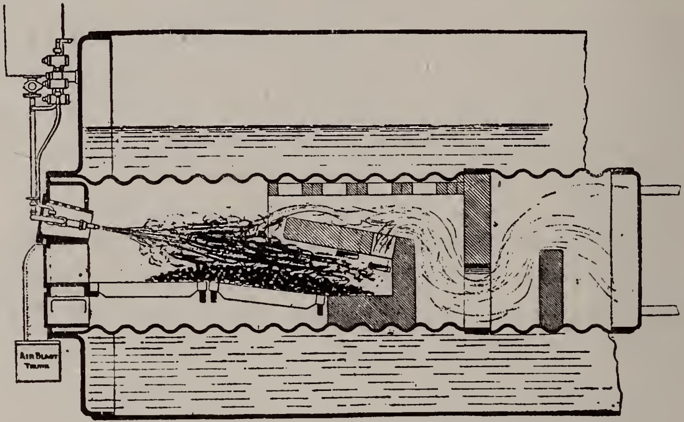

FIG. 84.—Oil Furnace as applied to a Steam Boiler.

	Metal lb.	Oil gals.	Cost.	Loss of Metal per Cent.
1st day . .	1488	32	$0·80	1·06
2nd ,, . .	2252	56	1·40	1·19
3rd ,, . .	2579½	65	1·62	1·96
4th ,, . .	2534	62	1·55	1·03
	8853½	215	5·37	1·06 average per c.

The cost of melting 100 lb., including oil and proportional cost of crucible, was 13·4 cents.

Fig. 85 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).

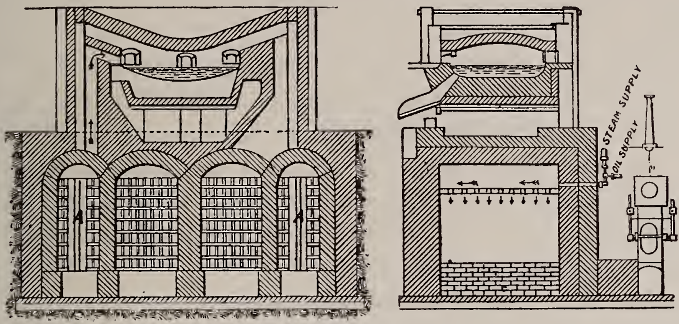

FIG. 85.—Oil-fired Steel Furnace.

In the United States there are now in existence boiler and other furnaces where a mixture of powdered coal and oil is sprayed in as the fuel.

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 lb. of air will be required to burn 1 lb. of coal, assuming the excess of air to be equal to that actually required, so that the products of combustion from 1 lb. of coal will weigh about 25 lb., 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 lb. 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, 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

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[1] See Kent, *Trans. A.S.M.E.*, vol. vi.

to take place, amounting in some modern marine boilers to 150 lb. 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 largely 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 or rate of flow, 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, etc. . . .	14·3	3·3–5·2	4·4	3·9
Hydrogen	..	..	..	..
Sulphuric acid	4·33	..	..	..
Sulphur.	..	..	4·8	3·2
Mineral matter, etc. . . .	36·67	8–9·7	22·3	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 per cent	60·0 per cent
In cinder	13·71 „	28·12 „
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, or washing the coal to free it from pyrites, which is the chief sulphur-bearing impurity.

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 practical but also 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 29·92 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 lb. 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 lb. of water at 0°, the result will be 100 lb. 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 refer 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 lb. 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.
8. Radiation of heat.

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.

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[1] *Memoirs U.S. Geological Survey.*

If a sufficient number of determinations be plotted suitably, and a curve be drawn through them, intermediate points may 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 $L(1+at)$ at t°, where a 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 a remained constant at all temperatures, whereas in fact it 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.

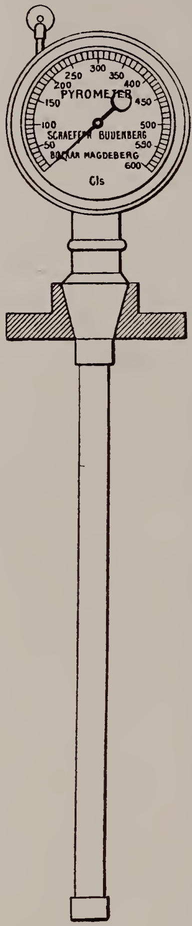

Fig. 86.
Schäffer and Budenberg's Pyrometer.

Many attempts have been made to devise a practical pyrometer based on the expansion of solids. The instruments as a rule are very slow in their indications, and are not to be trusted except for very rough determinations. One of the best-known instruments of this type is that of Messrs. Schäffer and Budenberg (Fig. 86), which is based on the differential expansion of iron and copper. It consists of an outer tube of iron and an inner rod of copper attached to the bottom of it. The expansion of the copper being greater than that of the iron, the length which the copper rod projects will increase with rise of temperature, and this increase, which is of course very small, can be magnified by a system of levers and indicated by a pointer on a dial.

As usually made the instrument indicates on the dial from 212° F. to 720° F. The tube is about 2 feet 6 inches long, and when placed in heating flues, or other positions where the atmosphere is oxidizing, should be protected by a layer of clay.

Expansion of Liquids.—This is the most common means of measuring temperature, but is not often available for very high temperatures.

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 29·92 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 −38·9° C. (−38·0° F.), and boils at 357° C. (674·6° F.). These temperatures mark the extreme limits between which, under ordinary conditions, 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. Nitrogen-filled glass thermometers are made to register up to 540° C., but these do not stand prolonged heating owing to the softening and bending of the glass. Thermometers made of transparent silica instead of glass are not open to this objection, however.

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 utilising 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 nearly ·003665 per C.°, but varies slightly for different gases. 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 enclosing vessel, and the observed expansion will therefore always be the difference between the expansion of the gas and that of the enclosing 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, etc., 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 enclosed 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, etc.

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. One source of error which it is impossible to overcome is the diffusion of gas through the bulb ; and for this and other reasons these methods are of little practical value.

The methods as described can only be used up to the temperature at which hard potash 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 metal, on account of its infusibility, might at first sight appear suitable, but it occludes gases, and also at high temperatures is porous to some furnace gases. Callander suggests[1] the use of bulbs

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[1] *J.I.S.I* , 1892, vol. ii. p. 165.

made of pure silica; and these are now obtainable commercially. Borosilicate glass has also been suggested, but has not a sufficiently high melting-point.

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 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.	232° C.
Bismuth	,,	267° ,,
Lead	,,	328° ,,
Zinc	,,	420° ,,
Antimony	,,	632° ,,
Silver	,,	961° ,,
Gold	,,	1064° ,,
Copper	,,	1084° ,,

And by means of suitable alloys, the melting-points of which are known, other points can be obtained.

One objection to this method is that the alloy can only be used once.

Seger Cones.—For the determination of high temperature a similar principle has been used, clay mixtures which melt at high temperatures being used in place of alloys. Seger cones are small pyramids, about 3 inches high, standing on a base $\frac{5}{8}$ inch wide (a smaller size is also in use), and the fusibility of these is graduated, so that at the temperature marked on them the point of the pyramid bends over and touches, or nearly touches, the surface on which it stands.

These and similar appliances are largely used in the pottery industry, bars of the clay mixture carried on supports being sometimes used in place of the cones. Seger cones are most useful as danger signals for high temperatures. The new scale of cone numbers and corresponding melting-points is as follows :

Softening Points of Seger Cones

Cone No.	Cent.	Fahr.	Cone No.	Cent.	Fahr.
017	730	1346	11	1320	2408
016	750	1382	12	1350	2462
015*a*	790	1454	13	1380	2516
014*a*	815	1499	14	1410	2570
013*a*	835	1535	15	1435	2615
012*a*	855	1571	16	1460	2660
011*a*	880	1616	17	1480	2696
010*a*	900	1652	18	1500	2732
09*a*	920	1688	19	1520	2768
08*a*	940	1724	20	1530	2786
07*a*	960	1760	26	1580	2876
06*a*	980	1796	27	1610	2930
05*a*	1000	1832	28	1630	2966
04*a*	1020	1868	29	1650	3002
03*a*	1040	1904	30	1670	3038
02*a*	1060	1940	31	1690	3074
01*a*	1080	1976	32	1710	3110
1*a*	1100	2012	33	1730	3146
2*a*	1120	2048	34	1750	3182
3*a*	1140	2084	35	1770	3218
4*a*	1160	2120	36	1790	3254
5*a*	1180	2156	37	1825	3317
6*a*	1200	2192	38	1850	3362
7	1230	2246	39	1880	3416
8	1250	2282	40	1920	3488
9	1280	2336	41	1960	3560
10	1300	2372	42	2000	3632

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 $WS(T - t') = W'(t' - t)$; therefore, $T = \frac{W'(t' - t) + t'}{WS}$, whence T can be calculated, since all the other values are known.

These formulæ are of little value for high temperatures, because the specific heat of metals varies, and S can only be the mean specific heats between the temperatures, and this is not known till T is known. By the use of tables calculated for various temperatures this difficulty can be overcome.

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. 87, 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.

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 this takes some time, but does not require great skill in conducting it. 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.

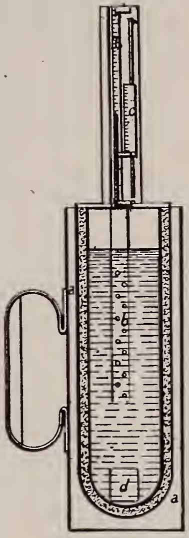

FIG. 87.
Siemens' Pyrometer.

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 PG, and rushes through the nozzle F, drawing in cold air through the

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[1] Von Bergen, *Journal Iron and Steel Institute*, 1886, vol. i. p. 207.

pipe P, the temperature of the inflowing air being registered by the thermometer T. The mixture of hot and cold air escapes

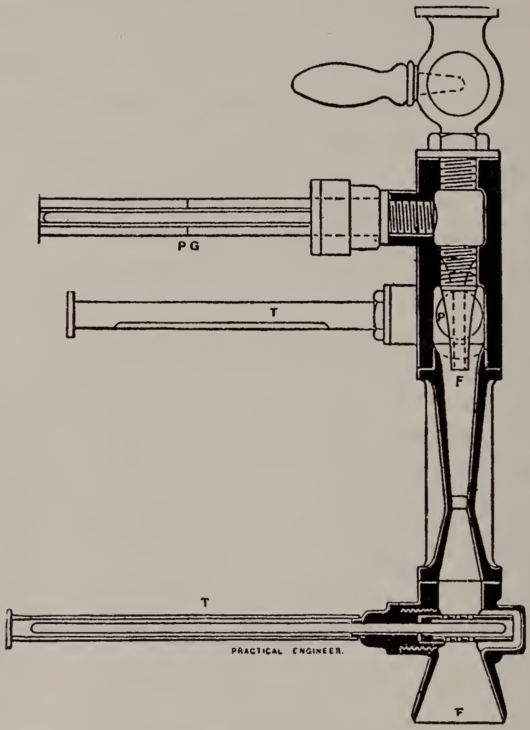

FIG. 88.—Krupp's Pyrometer.

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.

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.

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. Such methods are not capable of giving accurate determinations.

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. 89) 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.

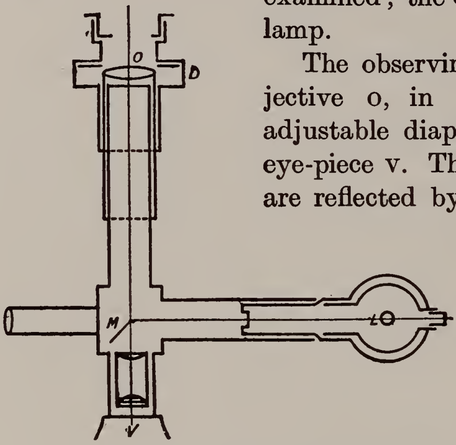

FIG. 89.—Cornu-le-Chatelier Pyrometer.

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 top. 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.

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.

A modified form of this apparatus is now made under the name of the Féry absorption pyrometer. The principle is exactly the same, but absorption wedges which can be moved by screws are used to reduce the light to an equality with the standard lamp. The instrument is mainly useful for

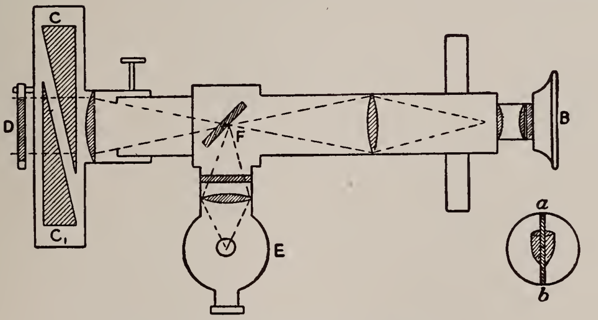

FIG. 90.—Féry Absorption Pyrometer.

taking the temperature of small objects, such as incandescent filaments, for which the other pyrometers are unsuitable.

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.

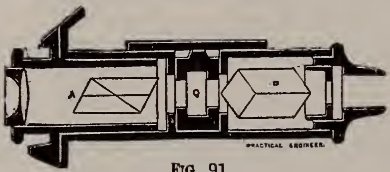

Fig. 91.
Mesure and Noel's Pyrometer.

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 is available below a red heat, and therefore they cannot be directly compared with the mercury thermometer.

The Wanner Pyrometer. — "In this instrument the light emitted by the heated body, the temperature of which is being measured, is broken up by a train of prisms, and the spectrum is screened off so that only the red portion corresponding to the Fraunhofer C line is visible. The intensity of this is compared with that of the red radiation from a small 6-volt electric lamp. The pyrometer has the external appearance of a telescope about a foot long; at the end which is directed towards the furnace there are two slits, one of which is covered by the small electric lamp. When the instrument is directed towards the furnace, the field, as viewed through the eye-piece, is seen to be composed of two semicircles; one of these is illuminated by the lamp, and the other by the light from the furnace. The two halves of the field can be adjusted to equal intensity by rotating the analyser, which forms the eye-piece of the instrument; and, from the angle through which the eye-piece has been turned to produce equality of colour, the temperature is ascertained by reference to a table.

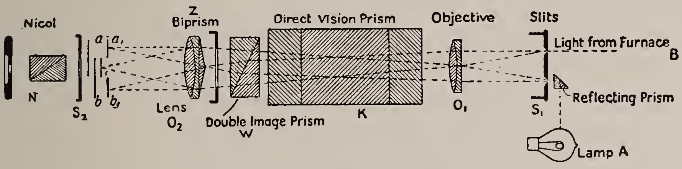

FIG. 92.—Wanner Pyrometer.

“ Fig. 92 shows a vertical section through the instrument. The light which is emanating from the two sources A and B (lamp and furnace) passes through the slits S, S_1, which lie in the focus of the lens O_1; it is broken up into its constituent colours by the train of prisms K, and is subsequently polarized by the Nicol's prism W; the rays then pass through a double prism Z, and are afterwards brought to a focus by the lens O_2. Two images of A, due to the ordinary and extraordinary rays, and two of B are thus formed, but the prism Z is so constructed that the image of A, due to the ordinary rays, coincides, in front of the eye-piece slit S_2, with that of B, due to the extraordinary rays. On looking through the eye-piece the upper half of the field is seen illuminated by rays from A, and the lower half by those from B, as the sets of rays are polarized in planes at right angles to each other, rotation of the analyser N has the effect of intensifying one half of the field and weakening the other.

"The electric lamp must be adjusted periodically by comparison with the flame of a lamp burning amyl acetate. For this purpose it is placed on a horizontal stand with the uncovered slit directed to the flame of the amyl acetate. The analyser is set at zero, and the resistance in circuit with the lamp is adjusted so that the upper half of the field, illuminated by the electric lamp, has the same intensity as that of the lower half, lit by the amyl acetate flame. The instrument is then ready for use. The standard is the flame of amyl acetate, but as it would be impossible to apply it practically, on account of the flickering caused by draughts of air, an electric lamp is adjusted to this standard and used in its place.

"Two forms of this instrument are made — one for measuring temperatures from 900° to 2000° C., and the other for the range 900° to 4000° C. The adjustment to equality of illumination can be easily and quickly made; the error is approximately half a degree of rotation, which corresponds in the first of these instruments to about 5° at 1300° C., and 14° at 1600° C."[1]

Electric Pyrometers.—Two of these are in use, depending on quite different electric principles.

The Siemens Pyrometers.—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.

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[1] Prof. T. Gray, *J.S.L.I.*, 1904, p. 1195.

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 enclosed in a porcelain tube instead of an iron one.

The apparatus for measuring the resistance is the most complex part of the instrument for accurate work. 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. In other forms direct-reading apparatus, such as the Whipple Indicator made by the Cambridge Scientific Instrument Company, have been used, and recording apparatus can also easily be applied.

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 $\frac{1}{10}$° 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 Professor 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 junctions, 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 hot junction.

As the current to be measured is a feeble one, delicate apparatus is essential, a galvanometer of the reflecting type being always used where accuracy is required. The junction of the wires, which are either fused 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 Professor Roberts-Austen has done with it. He states that he is satisfied that it is accurate to 1° at temperature over 1000° C., and that it can be made to indicate $\frac{1}{10}$° at 1000° C.

The instrument is calibrated by determining the currents at known temperatures. The following may be taken as being fixed points sufficiently accurately known for the purpose :

Boiling-point of water	100° C.
Melting-point of tin	232 „
„ „ lead	328 „
Boiling-point of mercury	357 „
Melting-point of zinc	419 „
Boiling-point of sulphur	445 „
Melting-point of aluminium	657 „
Boiling-point of selenium	690 „
Melting-point of silver	962 „
„ „ gold	1064 „
„ „ copper	1084 „
„ „ nickel	1452 „
„ „ platinum	1750 „

Whilst the principle on which this instrument is based is thus simple, the actual construction of the instrument itself, especially the indicating portion, is capable of very great variation. The light-spot method is unsuitable for many purposes, and several forms of direct-reading apparatus are on the market. In Messrs. Baird & Tatlock's pyrometer, for instance, the indicator is a " portable form of high-resistance dead-beat D'Arsonval galvanometer, the coil of which carries a long pointer over a graduated scale reading in degrees Centigrade and Fahrenheit."

" The moving part is a rectangular coil delicately suspended between the poles of a powerful permanent magnet."

Direct-reading instruments are also made by other makers.

Several recording forms are also in use. In the Thread

Recorder of the Cambridge Scientific Instrument Company (Fig. 93) the paper to carry the record is stretched over a cylinder C which is made to rotate by clockwork as usual, and over this is an inked thread G. The boom of the galvanometer A is depressed every minute or half-minute, and, pressing the thread against the paper, leaves a mark. Fig. 94 shows the record obtained of the recalescence of eutectoid steel.

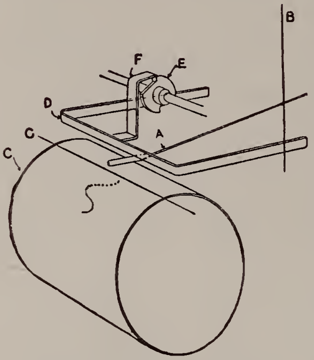

Fig. 93.—Thread Recorder.

In ribbon recorders the boom of the galvanometer is made to depress a point on to a ribbon, and in photographic recorders the needle casts a shadow on a slit behind which a band of sensitized paper is passing.

Couples of iron, nickel, copper and alloys may be used, but they are not as durable as the platinum or platinum-rhodium couples, though they may produce a higher voltage.

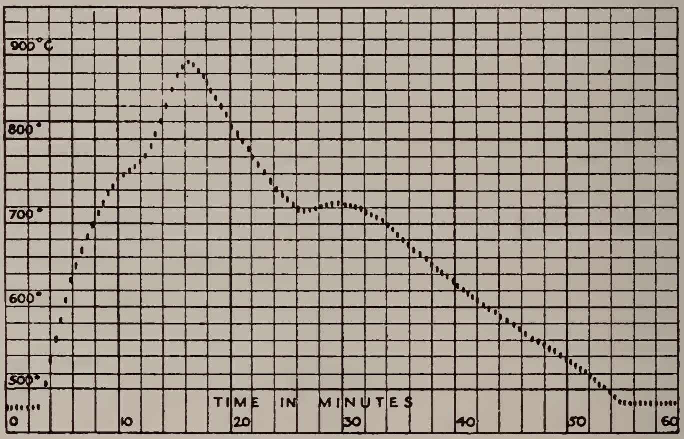

Fig. 94.—Heating and Cooling Curve of 0·9 per cent Carbon Steel.

The couples require standardizing from time to time, and the platinum and platinum-rhodium couple should never be exposed to furnace gases, as they attack the metals.

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. The most useful instrument is one having two scales for a dead-beat reflecting galvanometer, the lower scale reading to about 600° C., and employed with a base metal (copper constantan, for example) couple, and the higher scale reading to 1700° C. for use with a platinum platinum-rhodium couple.

The Féry Radiation Pyrometer. — In the forms of apparatus described above the couple must be placed in the furnace the temperature of which is to be taken, and must itself become heated to that temperature. The Féry Pyrometer is a modification of the thermo-couple pyrometer in which this is not necessary. It can be used for any temperatures above 600° C.

The radiation which emanates from the hot body falls upon a concave mirror, and is thus brought to a focus. In this focus is a thermo-electric couple, the temperature of which is thus raised, and the increase of temperature is measured by the current generated. As the couple is never raised to a high temperature it is not liable to be destroyed or injured, and within wide limits the reading is independent of the distance which the instrument is placed from the source of heat. " It has been found, for example, that the reading obtained for the temperature of a stream of molten steel was precisely the same—1200° C.—whether the instrument was set up 3 feet or 60 feet away."

The apparatus is quite portable, and consists of the tube containing the couple, which is fitted with a telescope through which the object the temperature of which is to be taken can be observed, so as to get the instrument in the right position, and a galvanometer for indicating the temperature.

An adjustable diaphragm is fitted at the front of the telescope so that the amount of radiation falling on the couple can be regulated. Either a direct-reading galvanometer or a recorder may be used. The instrument has a very wide range of applicability. The temperature of the sun was determined by Professor Féry as being 2800° C., and the temperature produced by the iron "Thermit" reaction as being 2500° C.

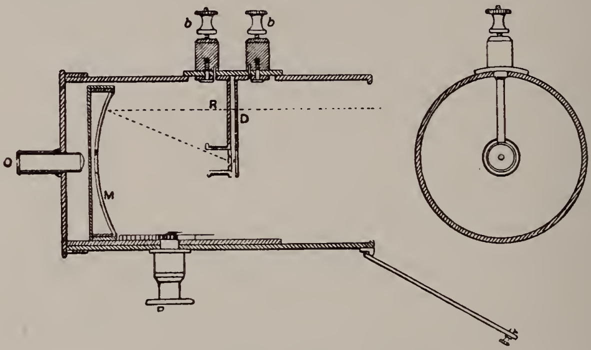

FIG. 95.—Féry Radiation Pyrometer.

Féry Spiral Pyrometer. — This is the simplest commercial instrument yet invented for measuring quickly and easily the temperature of any body above a dull red heat. It is only necessary to sight the instrument on the hot body, focus its image, and in a few seconds read the temperature indicated by the pointer on the dial. The instrument is completely self-contained, and although focused optically, it works on the purely mechanical principle of the difference in expansion of two metals. The heat rays are reflected by a mirror on to a spiral, built up of two dissimilar metals fixed together at one end, rolled flat together and very thin, and coiled into very small compass. The recording is done by a pointer attached to the free end of the spiral, which uncoils on being heated by the rays from the hot body. Extreme accuracy is not claimed for the instrument, but it is quite serviceable for most commercial purposes, since by careful calibration an error of 1 to 2 per cent at 1000° C. is seldom exceeded. The chief limitation to its use is the inability to obtain a continuous record, and the reading is always low unless when sighted upon a " black-cold " body, such as charcoal. Its great advantages of easy manipulation and low first cost and upkeep render it highly useful in many instances of furnace management.

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

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[1] *Traité des Essais*, 1828, as quoted by Percy, *Fuel*, p. 166.

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 sawdust 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."

This process is quite useless, and does not give results of any value whatever. It is only mentioned because it has been so often recommended.

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 was formerly used in research 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.

Thompson's Calorimeter.—This instrument is intended for technical work, for which purpose it is well adapted, and it has now come into general use. Its accuracy, however, is questionable. The fuel is not burned in oxygen, but in a mixture of potassium chlorate and nitrate which readily gives up its oxygen.

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, 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.Th.U. absorbed by the water.

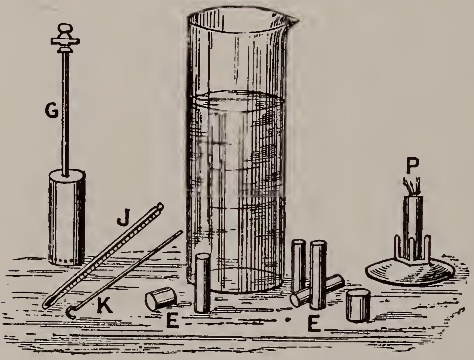

FIG. 96.—Thompson's Calorimeter.

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

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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.

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. For example,

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."

Parr Calorimeter, Wild Calorimeter, etc.—In this type the fuel is mixed with sodium peroxide, Na_2O_2, and fired by a hot wire. In course of the reaction sodium carbonate is formed. From the total heat 27 per cent has to be deducted for this and other chemical reactions. The results are probably not of a high degree of accuracy.

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

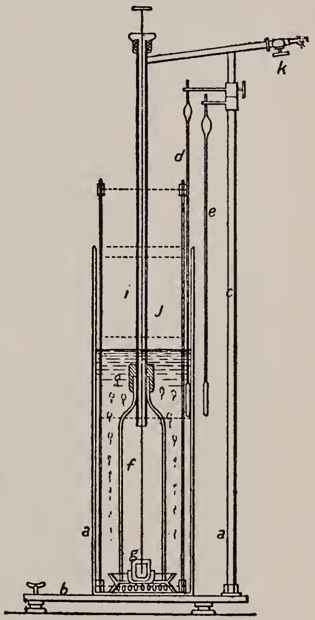

FIG. 97.
W. Thomson's Calorimeter.

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.

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 $\frac{2000}{11} = 182$ 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 1 to 1·5 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 1 gramme of fuel were taken, and the rise of temperature of the water was to be ·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

$$\frac{\cdot 9 \times 2182}{1} = 1964.$$

This apparatus gives fairly good results.

Several modified forms of this apparatus with improvements are now on the market, the best known being those of Rosenhain and Darling. In any case the oxygen used should be cooled to the atmospheric temperature before being passed into the combustion chamber.

The Berthelot-Mahler Calorimeter.—This is a form of bomb calorimeter which is the only really satisfactory form of calorimeter for solid fuels. It is a modification of the bomb used by Berthelot in his classic researches on the heat of combustion of different substances.

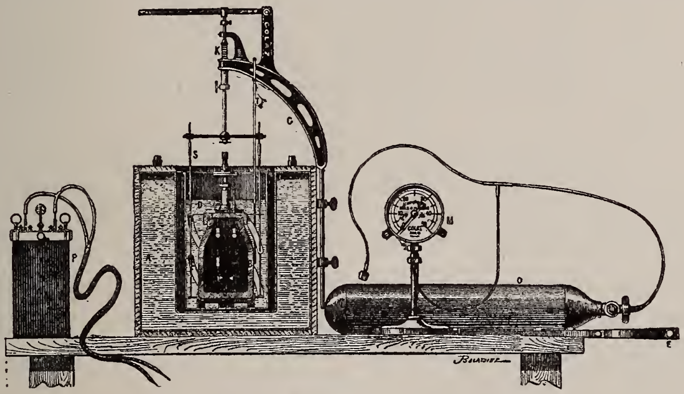

FIG. 98.—The Berthelot-Mahler Calorimeter.

The combustion chamber B is of mild steel. It is 8 mm. thick, and has a capacity of about 600 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 or, better, platinum can be heated to ignite the fuel, which is contained in a platinum or silica 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 in the crucible, which is then fixed in position; 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 at intervals of 1 min. for 5 mins., an electric current is passed from the battery P, and combustion takes place instantly. The temperature of the water is taken at intervals of half a minute until the maximum is reached, then observations are continued at intervals of a minute for another 5 mins., the stirrer being kept going all the time.

After the observations are completed the combustion vessel or "bomb" is washed out, and any nitric acid present may be determined volumetrically if great accuracy is required.

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 or falls before firing and falls after firing. The addition to be made to the observed rise is generally not more than 2 per cent, and can be calculated exactly from the periodical thermometer readings. The thermometer should be a very sensitive one, preferably a differential (Beckmann) thermometer, readable to 0·001° C.

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,

·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,
$$x = \Delta(W + W') - (0{\cdot}23\,n + 1{\cdot}6f).$$

Fig. 99 shows the Mahler-Cooke bomb which embodies certain mechanical improvements.

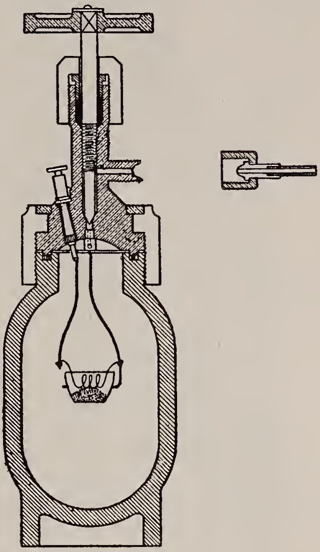

Fig. 99.—Mahler-Cooke Bomb.

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 one of the latest and best calorimeters for taking the calorific power of gases. A definite volume of gas is burnt, the amount consumed being measured by means of a meter, and a stream of water is kept flowing steadily through the apparatus. The volumes of gas and water and the rise of temperature of the latter supply the necessary data for calculating the calorific power.

"A flame, 28 (Fig. 100), 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.Th.U.), this is for illuminating gas 4 to 8 cubic feet, or producer-gas 16 to 32 cubic feet.”

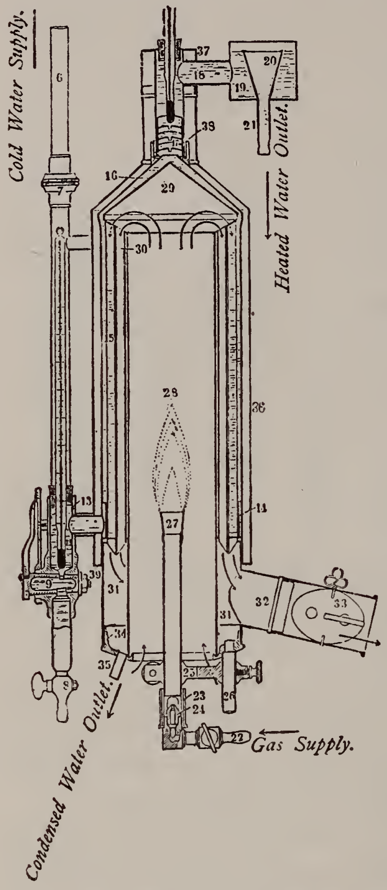

FIG. 100.—Junker's Gas Calorimeter.

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

To be strictly accurate, the water should be weighed, as 1 c.c. is not exactly equal to 1 gramme.

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,

$$H = \frac{2 \times 18}{\cdot 344} = 104{\cdot}65.$$

When it is desired to know the net calorific value 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 ·6, so that the latent heat of the condensed water would be

$$\frac{\cdot 6 \times 53}{2} = 15{\cdot}9,$$

which must be deducted from the value obtained above, leaving 88·75 calories as the calorific power.

Fig. 101 shows the new type of Junker's calorimeter.

Boys' Gas Calorimeter.—This is another very good type of gas calorimeter which gives results differing from those of the Junker's calorimeter by not more than a quarter of

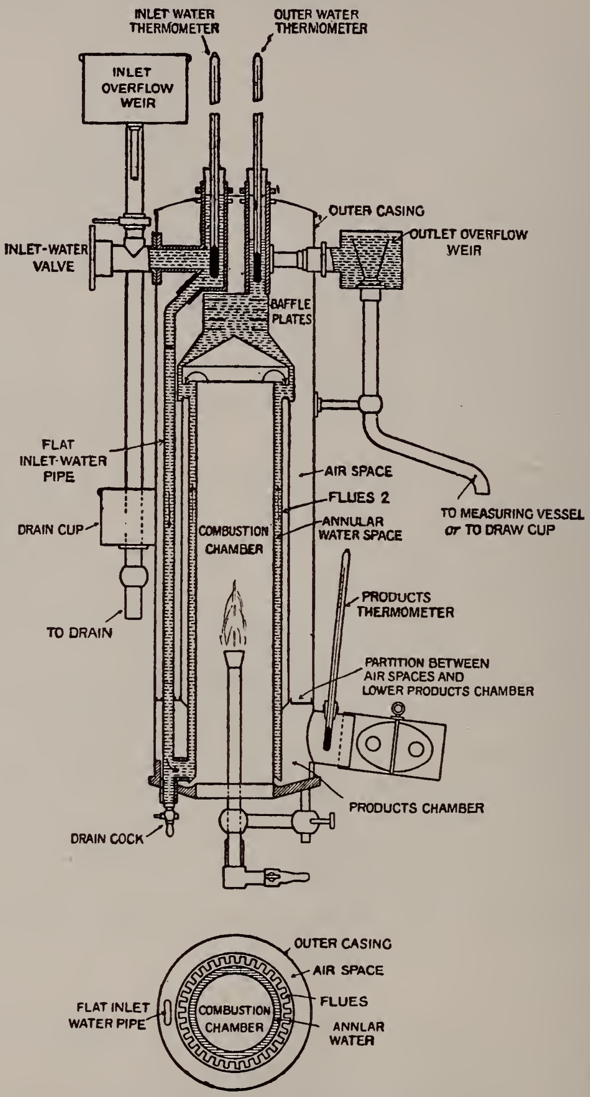

FIG. 101.—Junker's Gas Calorimeter (new type).

1 per cent. It is the instrument prescribed for gas-testing in

London by the Metropolitan Gas Referees, whose description is as follows:

"The gas calorimeter which has been designed by Mr. Boys is shown in vertical section in Fig. 102. It consists of three parts, which may be separated, or which, if in position,

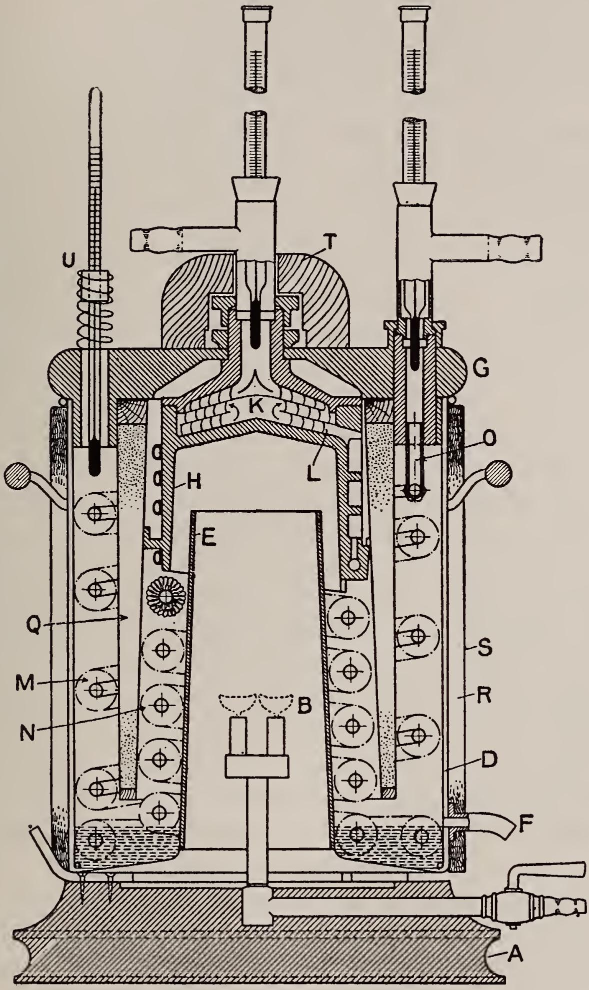

FIG. 102.—Boys' Gas Calorimeter.

may be turned relatively to one another about their common axis. The parts are (1) the base A, carrying a pair of burners B, and a regulating tap. The upper surface of the base is covered with a bright metal plate held in place by three centering and lifting blocks. The blocks are so placed as to carry (2) the vessel D, which must rest upon the horizontal portion of the blocks and not upon their upturned ends. The vessel is provided with a central copper chimney E and a condensed water outlet F. It is jacketed with felt R, protected by a sheet of metal S. The diameter of the chimney E at the base is 3½ inches and at the top 2½ inches and its thickness $\frac{1}{20}$ inch. The base of the outer vessel shown in the drawing as a separate piece is preferably spun in one piece with the chimney. In order to prevent obstruction of the flow of condensed water from the outlet F by the accidental contact of the thin brass protecting wall of the pipe system, a small dimple is punched in the outer casing on either side of the outlet F so as to project inwardly about $\frac{1}{16}$ inch. Resting upon the rim of the vessel D are (3) the water circulating system of the calorimeter attached to the lid G. Beginning at the centre where the outflow is situated there is a brass box which acts as a temperature equalizing chamber for the outlet water. Two dished plates of thin brass K K are held in place by three scrolls of thin brass L L L. These are simply strips bent round like unwound clock springs, so as to guide the water in a spiral direction inwards, then outwards, and then inwards again to the outlet. The lower or pendant portion of this box is kept cool by circulating water, the channel for which may be made in the solid metal, as shown on the right side, or by sweating on a tube, as shown on the left. Connected to the water channel at the lowest point by a union are five or six turns of copper pipe such as is used in a motor-car radiator of the kind known as Clarkson's. In this a helix of copper wire threaded with copper wire is wound round the tube, and the whole is sweated together by immersion in a bath of melted solder. A second coil of pipe, of similar construction, surrounding the first is fastened to it at the lower end by a union. This terminates at the upper end in a block, to which the inlet water box and thermometer holder are secured by a union as shown at O. An outlet water box D and thermometer holder are similarly secured above the equalizing chamber H. The lowest turns of the two coils M N are immersed in the water which in the first instance is put into the vessel D.

"Between the outer and inner coils M N is placed a brattice Q made of thin sheet brass, containing cork dust to act as a heat insulator. The upper annular space in the brattice is closed by a wooden ring, and that end is immersed in melted rosin and beeswax cement to protect it from any moisture which might condense upon it. The brattice is carried by an internal flange which rests upon the lower edge of the casting H. A cylindrical wall of thin sheet brass, a very little smaller than the vessel D, is secured to the lid, so that when the instrument is lifted out of the vessel and placed on the table, the coils are protected from injury. The narrow air space between this and the vessel D also serves to prevent interchange of heat between the calorimeter and the air of the room.

"The two thermometers for reading the water temperatures and a third (U) for reading the temperature of the effluent gases are all near together, and at the same level. The thermometer U, divided on the Fahrenheit scale, is supported as shown in Fig. 102 by means of a cork and an open spiral of wire, so that the bulb is a short way above the circulating coil, and with its stem passing through one of the five holes provided for the effluent gases. The lid may be turned round into any position relatively to the gas inlet and condensed water drip that may be convenient for observation, and the inlet and outlet water boxes may themselves be turned so that their branch tubes point in any direction. A wood shield T, made in two halves, serves to protect the outlet water box from loss of heat.

"A regular supply of water is maintained by connecting one of the two outer pipes of the overflow funnel to a small tap over the sink. The overflow funnel is fastened to the wall about 1 metre above the sink and the other outer pipe is connected to a tube in which there is a diaphragm with a hole about 2·3 mm. in diameter. This tube is connected to the inlet pipe of the calorimeter. A piece of stiff rubber pipe, long enough to cover the outflow water clear of the calorimeter, is slipped on to the outflow branch and the water is turned on, so that a little escapes by the middle pipe of the overflow funnel and is led by a third piece of tube into the sink. The amount of water that passes through the calorimeter in four minutes should be sufficient to fill the graduated vessel shown in Fig. 103 to some point above the lowest division, but insufficient in five minutes to come above the highest division. If this is not found to be the case, a moderate lowering of the overflow funnel or reaming out of the hole in the diaphragm will make it so. The overflow funnel should be provided with a lid to keep out dust. The graduated vessel (Fig. 103) shall have been previously examined and certified by the Gas Referees. An impression of the stamp on the base of the vessel shall be accepted as proof that the vessel has been thus certified.

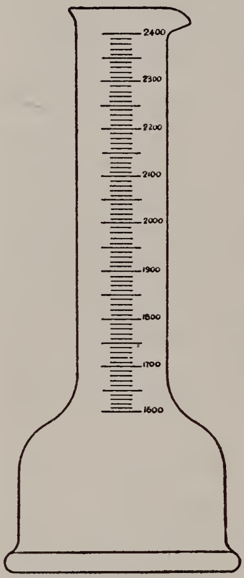

Fig. 103.—Graduated Vessel.

“ The thermometers for reading the temperatures of the inlet and outlet water should be divided on the Centigrade scale into tenths of a degree, and they should be provided with reading lenses and pointers that will slide upon them. The thermometers are held in place by corks (not india-rubber) making an air-tight fit within the inlet and outlet water boxes. Care must be taken that the bulbs are fully immersed.”

There are several forms of recording gas calorimeters on the market. Some of these are not at all reliable. Others are very expensive and short-lived. The Gas Regulation Act, 1920, makes their use almost imperative.

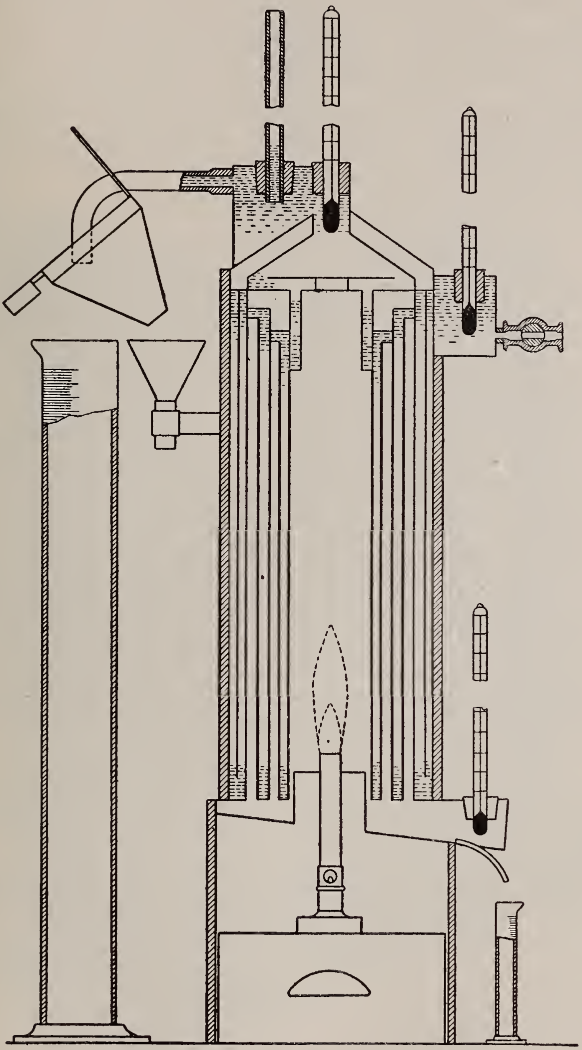

FIG. 104.—Simmance-Abady Gas Calorimeter.

Fig. 104 shows the construction of the ordinary Simmance-Abady gas calorimeter, and Fig. 105 (plate) the same apparatus adapted for recording the gross calorific value.

Calorimeters for very Volatile Liquids.—For very volatile liquid fuels, such as petrol, the ordinary forms of calorimeter are, if not inapplicable, at least unsatisfactory. In such purposes a modified form of gas calorimeter is best suited, the fuel being burnt in a lamp.

The "Darling" calorimeter is shown in Fig. 106. The fuel is burnt in the lamp A, which has a capacity of 3 or 4 c.c., fitted with an asbestos wick. The lamp is burnt in the bell-jar B, and is ignited electrically. The oxygen required is introduced by the tube I, and enters through the copper tube O, impinging on the top of the lamp. The products of combustion pass away by the tube T and bubble up through the water through holes in the perforated base plate H. For very volatile liquids, such as petrol, the lamp is surrounded by cold water during combustion.

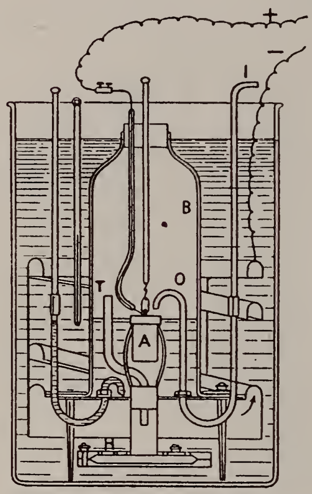

Fig. 106.—"Darling" Calorimeter.

This form of apparatus, or an adaptation of the ordinary gas calorimeter, gives satisfactory results.

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. They are based on the assumption that the elements evolve the same amount of heat when burnt in the condition of combination in which they exist in the fuel that they would do if burnt in the free condition, which is obviously not correct. If the bodies in which they exist were formed with the evolution of heat the

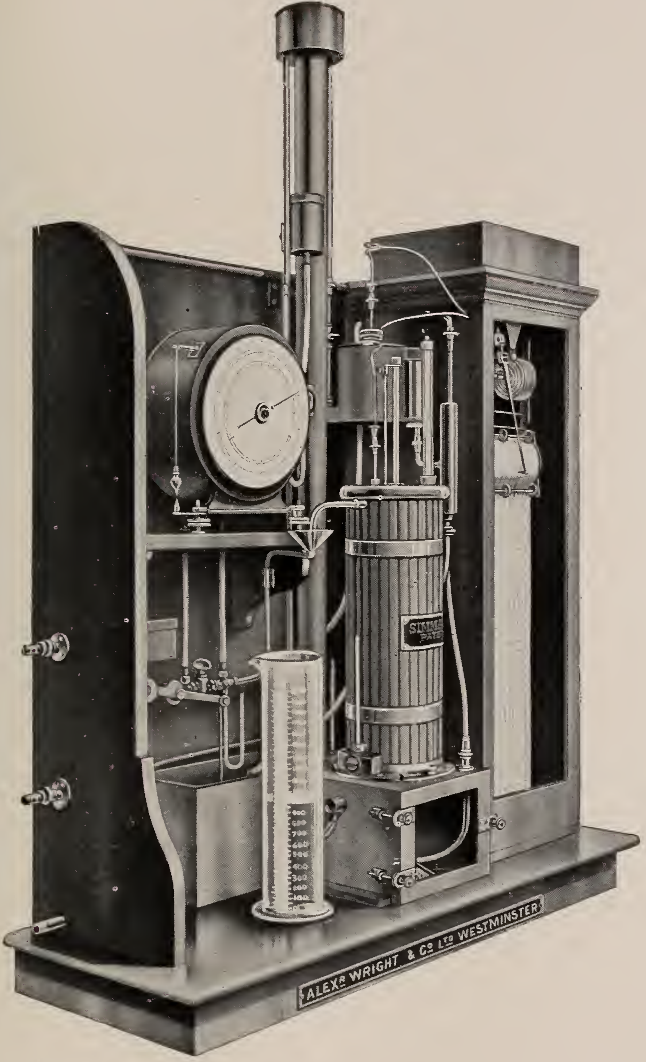

Fig. 108.—Simmance-Abady Gas Calorimeter adapted for recording the gross calorific value

results calculated from ultimate analysis will be too high, if with absorption of heat the calculated results will be too low. In the case of solid fuels the form of combination in which the elements are present is quite unknown, but probably they are mostly comparatively unstable, and so are formed with but little heat change. The same is true in the case of liquid fuels, but in the case of a gaseous fuel the proximate composition of which is known the calculated figures should be more accurate. A determination of the heating power by means of a calorimeter is always preferable to a calculation.

Of the various types of calorimeter in use for solid and liquid fuels the Bomb is decidedly the most accurate, and is generally used where accuracy is required. It is, however, rather expensive and perhaps too complicated for ordinary technical use. Next to it stand the oxygen calorimeters, which, when carefully used, give good results, whilst the most generally used instrument, the Thompson calorimeter, with a fusion mixture, is not to be depended on except for rough approximations.

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 778 foot-pounds, so that the energy given out by one pound of water cooling through 1° F. would raise 778 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 778 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 amount of energy it will give. Thus carbon, with its C.P. of 14,600, would give for each pound consumed 11,360,000 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 5·7 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

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[1] Anderson, *Conversion of Heat into Work.*

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 entirely prevented.

3. There is always loss by ashes falling hot from the fire-bars, ashes containing carbon, etc.

4. Evaporation of water in the fuel entails a loss in the heating power which 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 temperature of the fuel bed, and hence also the radiation, should be as high as possible.

The examples of tests of boilers on p. 318 will show the measurements that are necessary, and the results which were obtained in 1895.[1] These results can at the present day be greatly improved upon. In boiler tests it is not uncommon to get 75 per cent thermal efficiency from a Lancashire and 80 per cent from a water tube boiler with accessories.

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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, lb. .	35·75	62·1	54
Temp. of feed-water, average.	135·2° F.	48·9° F.	126° F.
Feed-water per hour, lb. .	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	53·75
,, ,, ultimate, C . .	65·05	60·22	65·00
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, lb. . .	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.Th.U.	Per Cent.	B.Th.U.	Per Cent.	B.Th.U.	Per Cent.
Utilized in heating water . .	5448	46·17	7823	70·79	5873	50·03
Loss by gases	5326	44·36	1901	17·19	3358	28·61
Loss by imperfect combustion .	..	..	..	..	..	..
Loss by moisture in fuel . .	94	·80	135	1·22	144	1·23
Loss unaccounted for . . .	1024	8·67	1145	10·36	2363	20·13
Calorific power, B.Th.U. . .	11892	100·00	11004	100·00	11738	100·00
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	

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 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 10 lb. per H.P. hour, in the best triple-expansion or large turbine condensing engines, to 60 lb. 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 75 per cent, and taking the efficiency of the best engine as 20 per cent the combined efficiency obtained from the fuel will be only ·75 × 20 = 15 per cent.

Amount of Fuel used per H.P.—One pound of coal, as has been shown, may have a calorific power of say 12000 B.Th.U., which is equivalent to 9,336,000 foot-pounds, which is equivalent to about 4·5 H.P. hours ; *i.e.* the combustion of 1 lb. 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 has actually been obtained :

	Steam per I.H.P. hour.	Coal per I.H.P. hour.
1. High-pressure non-condensing engine ; 100 lb. pressure ; 50 H.P. nominal	32	4·27
2. High-pressure non-condensing engine ; 120 lb. pressure ; 40 H.P. nominal	24	3·20
3. Triple-compound non-condensing engine ; 180 lb. pressure ; 30 H.P. nominal	20	2·66
4. Compound condensing engine ; 100 lb. pressure ; 30 H.P. nominal	18	2·46
5. Triple-expansion condensing engine ; 160 lb. pressure ; 20 H.P. nominal	14	1·86
6. 7 Indicated H.P.	..	8
7. 10 ,, ,,	..	5¼
8. 50 ,, ,,	..	2¾
9. 200 ,, ,,	..	2

With the advent in recent years of steam turbines of 10,000 H.P. and the most economical methods of steam

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[1] *P. S. Staff. Institute of Iron and Steel Works Managers*, 1894–1895, p. 41.

raising the best power installations can work on full load at a consumption of 1·4 lb. of coal per brake horse-power-hour.

This great improvement in the conservation of coal in the production of power is only possible by paying careful attention to the design and equipment of the whole installation. Not only must the most efficient engines be utilized—and for large powers of over 2000 brake horse-power turbines have the preference—but the steam must be condensed at the highest possible vacuum, and the condensed water returned to the boiler. Most important is the use of economizers. These are usually sets of vertical cast-iron pipes placed in the waste gas flues, through which the boiler feed-water is made to circulate. The water should thus attain a temperature of about 200° F. In some cases air economizers are used with success. The steam is superheated to eliminate losses through wet steam in the engine and to enable it to be carried without loss. Water-feed regulators constitute another economy ; these automatically maintain a constant level in the boilers. Water circulators are another adjunct which effect a slight economy.

It is highly important, finally, that combustion of the fuel should take place with the minimum excess of air, at any rate the percentage of carbon dioxide in the waste gases leaving the boiler furnace should not be less than 12 per cent. With good economizers it is then possible to reduce the temperature of the gases entering the stack to about 360° F. A boiler efficiency without the accessories may not exceed 65 per cent, but chiefly owing to the effect of the economizers this may be brought up to 80 or even slightly more.

Gas-engines.—The gas-engine is another means of converting the potential energy of fuel into actual energy. In 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 per cent to 50 per cent of the heat.

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

Any combustible gas may be used. Coal-gas is largely 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.

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. It is used with great economy and success in works which combine bye-product coke-ovens and blast-furnaces, the surplus coke-oven gas being in some cases mixed with the blast-furnace gas.

Oil-engines.—In the Priestman engine, which is one of 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.

In the best modern types of Diesel oil-engines almost any kind of oil, even thin coal-tar, can be used. The consumption of oil is sometimes as low as 0·35 lb. per brake horse-power.

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 rough estimate is obtained by powdering the coal as quickly as possible, weighing out about 5 grammes on a watch-glass, drying in an oven at 105° C. for an hour, cooling in a desiccator, and weighing with the watch-glass covered to prevent access of hygroscopic moisture.

A more accurate determination is made by taking the whole of a laboratory sample, say, 1000 grammes, and drying it down to about 1 to 2 per cent of moisture, then crushing the sample, quartering and grinding and finally weighing out about 2 grammes for drying in an oven at 105° C. for one hour. The percentage moisture in the small sample is added to that of the large.

Volatile Matter and Coke.—About 1 gramme of the powdered air-dried or partly dried coal of known moisture content is heated in a platinum crucible, with well-fitting lid, for seven minutes over a large Bunsen-burner flame. The burner flame should be about 8 inches high, and the crucible (about 30 c.c. capacity) should be $2\frac{1}{2}$ to $3\frac{1}{4}$ inches above the top of the burner. The crucible should be supported on a light triangle of platinum or silica. The loss of weight after deducting moisture represents what is known as volatile matter and the residue is the coke.

The use of a Méker burner, by reason of the higher temperature, gives higher values for volatile matter than those ordinarily obtained, but they are not subject to so much variation, as the expulsion of the volatile matter is nearly complete.

Ash.—Ten grammes of the powdered air-dried sample are placed in a shallow flat-bottomed silica dish, and heated, at first slowly, in a muffle-furnace until all combustible matter has been burnt. It is well to disturb the surface occasionally with a platinum or nickel wire or light silica rod.

Another method is to remove the lid of the crucible after determining the volatile matter, burn off the carbon from the same, place the crucible on its side, and heat strongly until there is nothing but ash left.

Sulphur.—This element, as already mentioned, exists in coal in at least three forms, as pyrites and as calcium sulphate, and as organic sulphur, the first being considered to be the most deleterious.

One gramme of the finely powdered coal is mixed intimately, in a 30 c.c. platinum crucible, with about 2 grammes of Eschka mixture (2 parts pure calcined magnesium oxide and 1 part anhydrous sodium carbonate, both proved free from sulphate), and is covered with about half a gramme additional of the mixture.

The crucible is placed in a slanting position over a Bunsen-burner, the mouth being shielded from the burner gases, which usually contain appreciable quantities of sulphur dioxide.

A gentle heat is applied for about half an hour, then more heat is applied until the crucible becomes red-hot. The contents are stirred occasionally with a nickel or light silica rod until all the black particles disappear. On cooling, the crucible is washed out into a beaker; a few c.c. of bromine water are added and the whole is boiled. After decantation, filtration, and washing, the clear liquid is acidified with hydrochloric acid and boiled to expel all the bromine. The sulphate contained therein is finally precipitated hot with barium chloride in the usual way.

By placing either distilled water or solution of pure sodium carbonate in the bomb, in the estimation of the calorific value, the sulphur, which is usually completely oxidized to sulphuric acid, is absorbed, and can thus be determined conveniently and quickly. The method is particularly suitable for oils.

Sulphur as Calcium Sulphate.—Weigh about 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 2 grammes of finely-powdered coal with about 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 × ·2474 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

$$S=\frac{W}{W-W'}\text{; } e.g.\ \frac{20}{20-4{\cdot}66}=\frac{20}{15{\cdot}34}=1{\cdot}31.$$

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 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 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.

Analysis of Coke.—The determinations required for the valuation of coke are almost identically the same as those required for coal. The determination of volatile matter, especially in the case of gas-coke, should not be omitted, as it is sometimes appreciable in quantity.

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 Flash-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, etc., 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]

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[1] Phillips, *Fuels*, 17.

Calorific Power.—This is most easily determined by means of the bomb 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.

The Kjeldahl method for the determination of nitrogen is not difficult to carry out. One gramme of the finely powdered coal is boiled with about 30 c.c. of sulphuric acid of highest concentration and half a gramme of mercury until the solution is nearly colourless. Oxidation is completed by adding a few crystals of potassium permanganate. The mercury is precipitated by adding potassium sulphide to the diluted solution, caustic soda is added in excess, and the ammonia is distilled over into a vessel containing 25 c.c. of normal sulphuric acid. The excess of acid is titrated with decinormal sodium carbonate solution, using methyl orange as indicator. The results are not very reliable, erring on the low side, and the more elaborate Dumas or modified Dumas combustion tube method is to be preferred for accurate work.

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.—There are numerous simplified gas analysis apparatus for the determination of carbon dioxide in furnace gases, which is a matter of great importance. There are also many successful mechanisms on the market for indicating and recording the percentage. These are of immense service in fuel-saving in all kinds of furnace work, but particularly in boiler installations, retort houses, etc.

One of the most successful modern instruments is known as the W.R.CO_2 indicator, the principle of which is shown by the diagram (Fig. 106A). The flue gas is aspirated through a filter, then through a chamber containing a porous cell in which is placed a cartridge of soda lime for absorbing the CO_2. The result is a partial vacuum within the cell. This is a measure of the amount of CO_2 present, and is indicated on a gauge which is graduated to read percentages.

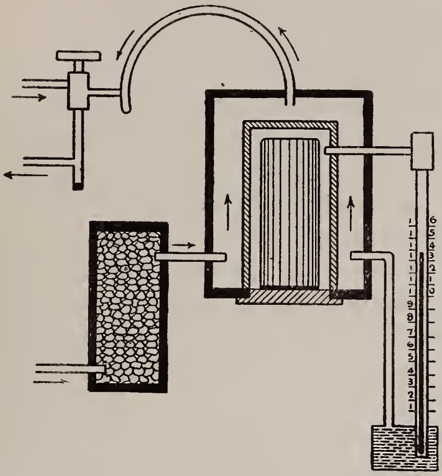

FIG. 106A.—W.R.CO_2 Indicator.

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 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, $Al_2Si_2O_7$, $2H_2O$, or Al_2O_3, $2SiO_2$, $2H_2O$.

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 $K_2OAl_2O_3$, $6SiO_2$. 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 is so, 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 talc-like 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 difficult to fuse, 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

The addition of silica to a fire-clay does not necessarily increase the refractoriness, in fact as a rule, depending on the nature of the silica, an increase causes a reduction in the refractoriness up to a certain point.

Examples of Fire-clays.—The following analyses will serve to illustrate the composition of fire-clays:

	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).

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 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

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[1] *J.I. and S.I.*, 1875, ii. p. 513.

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_2O_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, $FeS_2 + 5O = FeO + 2SO_2$, and 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, TiO_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.*

$$\frac{\text{O in Al}_2\text{O}_3}{\text{O in RO}} \div \frac{\text{O in SiO}_2}{\text{O in Al}_2\text{O}_3}.$$

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 per cent.

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
	101·43	101·40	100·05	100·00	99·91

1, Hard (Riley). 2, Soft (Riley). 3, Lowood (Snelus). 4, Scotch, Bonnymuir. 5, Lowood.

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[1] See Hofman and Demond, "Refractoriness of Fire-clays," *J.A.I.M.E.*, xxiv.

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, etc.	·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.

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, etc. 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, etc.

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 per cent of chromic oxide, and less than 6 per cent 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, Ca CO_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	
Oxide of iron . . .	1·22	. .	1·70		2·57
Carbon dioxide . . .	45·35	45·64	44·2		
Water	. .	. .		45·00	45·00

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 per cent 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 per cent 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). 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 Water	51	50·41	48·02

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—$x\text{Al}_2\text{O}_3$, $y\text{Fe}_2\text{O}_3$, $3\ \text{H}_2\text{O}$, 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 or 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—$2\ FeO, SiO_2$, approximately, 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_2O_3), magnetite (Fe_3O_4), burnt ore and Blue Billy (artificial Fe_2O_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

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[1] Percy, *Fuel*, p. 144.

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. Fire-clay bricks shrink very much on drying and firing. At St. Helens, "for a $9 \times 4\frac{1}{2} \times 2\frac{7}{8}$-inch brick the mould is $9\frac{5}{8} \times 4\frac{7}{8} \times 3\frac{1}{8}$ inches. For Glenboig clay a shrinkage of $\frac{1}{12}$ is allowed; that is, the mould for a 9-inch brick is made $9\frac{3}{4}$ 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

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[1] Snelus.

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 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. This kiln is worked

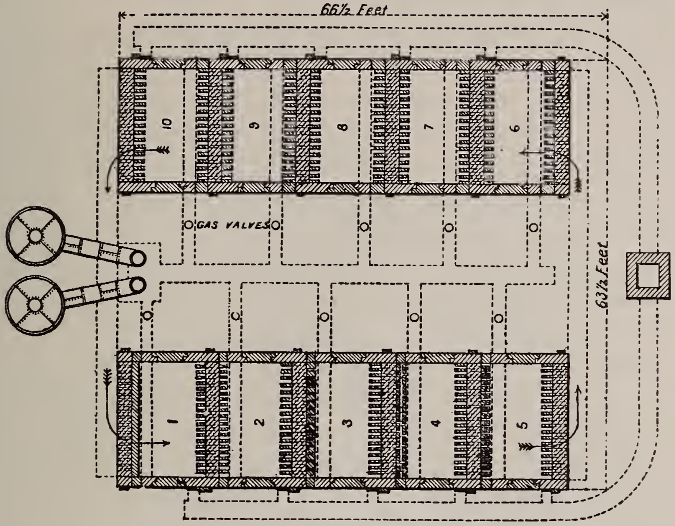

FIG. 107.—Dunnachie's Patent Regenerative Gas-kiln.

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

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[1] *Fuel*, p. 147.

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."

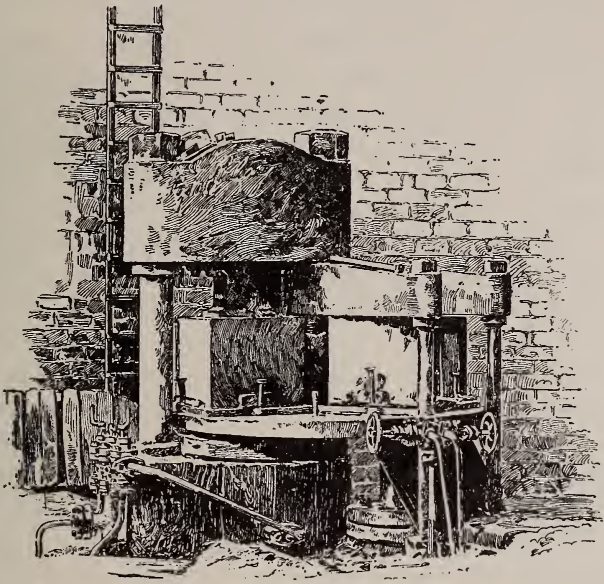

FIG. 108.—Basic Brick Press.

Silica bricks may be made by exactly similar methods from any siliceous material, ground flints, sand, and other similar materials being frequently used.

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.

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, etc.—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
	100·38	99·996	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]

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[1] Percy, *Fuel*, p. 151.

[2] *Fuel*, p. 152.

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.

"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

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[1] Percy, *Fuel*, p. 110.

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.

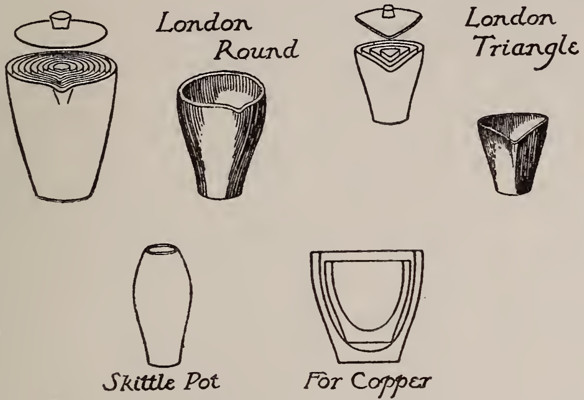

FIG. 109.—Forms of Crucibles.

Percy gives the following as an analysis of a good batch of these crucibles :

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.

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, etc.

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

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[1] *Fuel,* p. 116.

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 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. 110) 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.

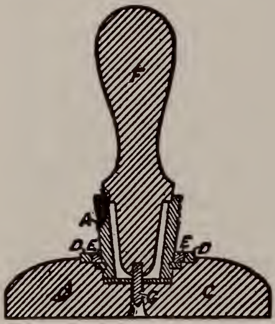

FIG. 110.
Laboratory Crucible-making Apparatus.

Every chemist is familiar with the high quality of Royal Berlin or Dresden porcelain, and its suitability for laboratory crucibles, basins, etc. It is manufactured from the best china clay, properly weathered, aged and worked up under scientifically supervised conditions. It is only thus that these articles can be guaranteed to withstand the highest temperatures and great fluctuations of temperature.

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. 111), 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.

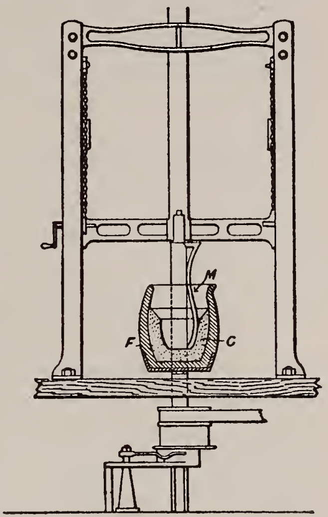

FIG. 111.
Apparatus for making Black-lead Crucibles.

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;

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[1] Abridged from account by Howe in *The Metallurgy of Steel*, p. 299.

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-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 saggers, 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 sagger 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 grey 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

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[1] Percy, *Fuel*, p. 141.

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 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 $\frac{7}{8}$ inch, $\frac{3}{4}$ inch, and $\frac{3}{4}$ inch, and the height $2\frac{3}{8}$ inches, and comparing their behaviour with Seger cones.

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. 352, first burning some of the clay to mix with the raw clay drying and firing them, and then subjecting 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.

The Refractory Materials Committee of the Institution of Gas Engineers has carried out a considerable amount of research during the last twelve years on the subject of firebricks and retort material and has issued standard specifications of great value both to manufacturers and users. The revised specifications are as follows :

I. Retort Material

1. The retorts, or retort-tiles, shall be made of a sufficiently seasoned raw clay and clean burnt-clay or " grog." No grog shall be used which will pass through a test sieve having 16 meshes to the linear inch.

2. A complete chemical analysis of the material is to be provided by the manufacturer when required by the purchaser for his personal information only.

3. A piece of the material shall show no sign of fusion when heated to a temperature not less than Seger cone 28 (about 1630° C.), the heat being increased at the rate of about 50° C. per minute in an oxidizing atmosphere.

4. All surfaces shall be reasonably true and free from flaws or winding ; and, after burning, no " washing " shall be done without the consent of the purchaser. The texture throughout shall be even and regular, containing no holes or flaws, and the " apparent porosity " shall not be less than 18 per cent nor more than 30 per cent.

5. The material shall be evenly burnt throughout and contain no black core. A test piece when heated to a temperature of Seger cone 14 (1410° C.) for two hours shall not show, when cold, more than $1\frac{1}{4}$ per cent contraction or expansion.

The size of a representative test piece shall be 4½ inches long by 4½ inches wide, the ends being ground flat and the contraction measured by means of Vernier callipers reading to 0·1 mm., a suitable mark being made in the test piece so that the callipers may be placed in the same position before and after firing :

II. FIRE-BRICKS, BLOCKS, TILES, ETC.

1. Two grades of material are covered by the specification :

    (1) Material which shows no sign of fusion when heated to a temperature of not less than Seger cone 30 (about 1670° C.).

    (2) Material which shows no sign of fusion when heated to a temperature of not less than Seger cone 26 (about 1580° C.).

2. Analysis as in I. 2.

3. Freedom from flaws as in I. 4.

4. A test piece when heated to a temperature of Seger cone 14 for two hours shall not show more than the following linear contraction or expansion :

No. 1 grade 1 per cent, No. 2 grade 1¼ per cent. The test piece shall be representative and measure 4½ inches long by 4½ inches wide.

5. In the case of ordinary bricks, 9 inches by 4½ inches by 3 inches or 2½ inches thick, there shall not be more than ± 1½ per cent variation in length, nor more than ± 2½ per cent variation in width or thickness ; and in all cases the bricks shall work out their own bond, with not more than ½-inch allowance for joint.

In the case of special bricks, blocks, or tiles there shall not be more than ± 2 per cent variation from any of the specified dimensions.

6. The material shall be capable of withstanding a crushing strain of not less than 1800 lbs. per square inch.

7. Cement clay shall be capable of withstanding the

same test for refractoriness. It may contain a suitable percentage of fine grog.

8. All bricks, blocks, or tiles shall be distinctly marked by means of a figure 1 or 2 to indicate the grade to which they belong.

III. Silica Bricks, Blocks, Tiles, Etc.

The material covered by this specification is divided into two classes:

(1) That containing 92 per cent and upwards of silica and called "silica" material.

(2) That containing 80 to 92 per cent of silica, and called "siliceous."

1. Test pieces of the material shall show no sign of fusion when heated to the following temperatures:

"Silica" material—not less than Seger cone 32 (about 1710° C.).

"Siliceous" material—not less than Seger cone 29 (about 1650° C.).

Conditions as in I. and II.

2. Analysis as in I.

3. Freedom from flaws as in I.

4. A test piece, at least $4\frac{1}{2}$ inches long by $4\frac{1}{2}$ inches wide, heated for two hours to a temperature of Seger cone 12 shall not show, on cooling, more than 0·75 per cent linear contraction or expansion.

5. Uniformity in measurement as in II. 5.

6. Cement clay as in II. 7.

The furnace recommended for testing purposes is one with Méker gas burners using compressed air at not less than 10 lb. pressure per square inch, or Hirsch's electric furnace working at about 90 volts and 90 amperes.

In testing for refractoriness it is advisable to make a preliminary test with a small conical piece of the material, using the small Seger cones 28, 30, and 32.

As fire-clay materials have no well-defined melting-points, the temperature at which they begin to melt is assumed to be that at which the edges of the materials lose their sharp angularity.

Best china clay fuses between cones 35 and 36, and this may be used to cement the test piece and Seger cones on to a refractory slab in the test furnace.

The "apparent porosity" is determined by means of the porosimeter made by Messrs. Gallenkamp & Co., London. The test piece should be about the size of half a brick. This is placed in a glass vessel fitted with a tap at the bottom and a close-fitting lid having a conical top. The tap is connected with a burette.

The porosity is determined by placing the dried piece of brick in the vessel, evacuating the air by pump, and measuring the total volume of the brick and that of the pores only by immersion in paraffin oil.

Refractoriness.—The practical man has long known that retorts and other fire-clay structures become deformed at temperatures very much lower than their melting-points as above defined. For example, it is dangerous to allow vertical retorts to attain, and maintain for any considerable length of time, a temperature of even 1300° C., although the material may be the best obtainable with melting or "squatting" point of 1700° or over. There may be little or no apparent fluxing, but serious damage may be done, especially to intermittent vertical retorts. Mellor and Moore published in vol. xv. (1915-16) of the *Transactions of the English Ceramic Society* very interesting experimental data on "The Effect of Loads on the Refractoriness of Fire-clays." The following are typical results:

No. of Trial.	Squatting Temperatures. No Load.		Load in lb. per sq. in.	Squatting Temperatures.		Load in lb. per sq. in.	Squatting Temperatures.	
	Cone.	° C.		Cone.	° C.		Cone.	° C.
1	29	1650	54	15	1435	72	13	1380
2	28	1630	54	14	1410	72	12	1350
3	31	1690	84	16	1460	112	13	1380
4	32	1710	84	18	1500	112	15	1435
5	30	1670	84	16	1460	112	13	1380

In all the tests made with different clays it was found that the greater the load the lower the squatting temperature.

It was also found by the same investigators that the decrease in the squatting temperature with unit increase of load is directly proportional to the squatting temperature.

The more siliceous the clay the less the difference between the squatting temperature with or without a load.

M. Gary had previously found that at temperatures near 1000° C. fire-bricks can withstand a greater compressive load than they can when cold. This accounts for the well-known fact that a red-hot crucible can withstand a blow which would shatter it if cold. It is evident that although, as the temperature rises, the crushing strength of fire-clays under load at first increases, it afterwards diminishes long before the melting-point is reached.

Some objections had been raised to the testing of fire-bricks and retort material in an oxidizing instead of a reducing atmosphere, as it is well known that ferrous iron has a far greater fluxing action than ferric iron. It is therefore to be anticipated that the contraction of a brick under reducing conditions will be greater than it is under oxidizing conditions. Recent researches (Mellor, *Transactions of Institution of Gas Engineers*, 1917) show that this is actually the case. Most silica bricks show an after-expansion when strongly heated; this is somewhat less in a reducing atmosphere than it is in an oxidizing one.

In another investigation Mellor determined the sizes of fire-bricks in the cold and hot state (about 1100° C.). Of 25 silica and fire-bricks tested the greatest expansion was 1·77 per cent and the least 0·26 per cent. Here the true thermal expansion, in some cases at any rate, may be obscured by effects due to the after-expansion or the after-contraction of the fire-brick taking place while the bricks are being measured. It is important to take into account the continued alteration in the character of bricks when heated repeatedly or for a long time.

The corrosive action of flue-dust on fire-bricks is a matter calling for the attention of all makers and users of fire-clay goods. The Refractory Materials Committee referred to have already published in the 1918 *Transactions of the Institution of Gas Engineers* the results of experiments carried out by Dr. Mellor.

The tests were carried out at 1400° C. with a variety of dusts which are well known to cause corrosion.

The general conclusions arrived at are as follows :

The penetration caused by the dust is greater in fire-clay bricks than in silica bricks. The bond is usually attacked first and the coarser grains last.

In silica bricks the depth of penetration by the dust is less where the grain is finer. In coarse-grained bricks it is only the bond that is attacked to any great extent.

Iron oxide does not exercise any appreciable corrosive effect on silica bricks in an oxidizing atmosphere. In a reducing atmosphere ferrous silicate is formed and acts as a corrosive flux. Fire-clay bricks are more severely attacked by iron oxides than silica bricks.

When the dust is such that it forms a surface glaze, the material is protected from further rapid attack. It is the practice of some retort makers, including the famous Stettin Company, to glaze the retorts in the interior. This is of distinct advantage for horizontal retorts which do not allow the glaze to flow to a lower level. Another benefit of the glazing is due to the fact that the retorts, otherwise very porous, are rendered impervious to the gas and thus effect a saving during the first few days of use.

In the case of coke-ovens and vertical retorts fluxing agents, such as sodium chloride (common salt), which are usually present to a greater or less extent (0·01 to 0·25 per cent) in the coals, exert a powerful influence in shortening the life of the fire-clay material. Some coke-oven builders limit their guarantees of durability of the ovens to the use of coals which yield wash water (from the water used in compressing the coke) containing less than one gramme of sodium chloride per litre.

The analyses of typical fire-clay and silica bricks are as follows :

	Fire-clay.	Silica.
Silica SiO_2	64·5	93·7
Titanic oxide TiO_2	1·3	0·3
Alumina Al_2O_3	29·5	2·0
Ferric oxide Fe_2O_3	3·0	0·8
Magnesia MgO	0·4	0·2
Lime CaO	0·3	2·0
Potash K_2O	0·6	0·6
Soda Na_2O	0·4	0·4
	100·0	100·0

NOTES AND TABLES

Heat Units

British Thermal Unit . .	1 pound of water	raised	1° F.
Centigrade Unit (often wrongly called a calorie) . .	1 ,,	,,	1° C.
Calorie	1 gramme	,,	1° C.
Large calorie . . .	1 kilogram	,,	1° C.

To convert Fahrenheit units into Centigrade units or to convert B.Th.U. per lb. into calories per kilogram:

$$\times \frac{9}{5} \text{ or } 1{\cdot}8.$$

To convert calories into B.Th.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 versa*:

$$F = \frac{9}{5} C + 32 \quad \text{or} \quad 1{\cdot}8\, C + 32,$$

$$C = \frac{5}{9} (F - 32) \quad \text{or} \quad {\cdot}5 \times (F - 32).$$

Mechanical Equivalent of Heat

1 B.Th.U . . . . = 778 foot-pounds.
1 Centigrade unit . . . = 1400 ,,
1 Large calorie . . . = 3087 ,,
1 Foot-pound . . . . = $1{\cdot}356 \times 10^7$ ergs.

1 Horse-power = 33000 foot-pounds per minute = $7{\cdot}46 \times 10^9$ ergs per second

English and Metric Weights and Measures

1 Metre = 39·371 inches.
„ = 3·2809 feet.
„ = 1·0936 yards.
„ = ·00006214 mile.
1 Litre = 61·027 cubic inches.
„ = ·035317 cubic foot.
1 Gramme = 15·432 grains.
„ = ·032151 Troy oz.
„ = ·0022046 Avoir. lb.

To convert	metres to inches	× 39·371
„	inches to metres	× ·02540
„	kilograms to lb.	× 2·2046
„	litres to gallons	× ·2200
„	gallons to litres	× 4·546
„	grammes to grains	× 15·432
„	grains to grammes	× ·06480
„	ounces to grammes	× 28·349

Specific Heat of Gaseous Substances at Ordinary Temperatures[1]

Air	·2375
Oxygen	·2175
Nitrogen	·2438
Hydrogen	3·4090
Carbon monoxide	·2450
Carbon dioxide	·2169
Methane	·5929
Ethylene	·4040
Steam	·4805
Sulphuretted hydrogen	·2432
Sulphur dioxide	·1540

Weight of Oxygen and Air required for Combustion

	Oxygen.	Air.
One part by weight of—		
Carbon	2·67	11·50
Hydrogen	8·0	34·5
Carbon monoxide	0·57	2·46
Methane	4·0	17·2
Ethylene	3·43	14·8
Acetylene	3·08	13·3

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[1] The specific heat of a gas is the number of heat units required to raise the temperature of unit weight of it one degree (water = 1).

Calorific Power of Various Combustibles

	B.Th.U.	C.U.
One pound weight of—		
Carbon to carbon dioxide	14600	8110
Carbon to carbon monoxide	4390	2440
Carbon monoxide to carbon dioxide	4370	2430
Hydrogen to water	61000	33900
Hydrogen to water vapour	51500	28600
Methane to carbon dioxide and water	23920	13290
Ethylene ,, ,, ,,	21310	11840
Acetylene ,, ,, ,,	20990	11660
Sulphur to sulphur dioxide	4000	2220
Gross Value—		
Wood	4500 to 7200	2500 4000
Coal	10000 to 15000	5560 8330
Anthracite	12500 to 15000	6940 8330
Coke	11000 to 14000	6110 7780
Natural oil	18000	10000
Coal-gas	13500	7500

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