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FUEL

SOLID LIQUID AND GASEOUS

BY

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PREFACE TO THE FIRST EDITION

In this volume the author has followed the general system which he has found successful in the courses of lectures on Fuel, delivered for some time past at the Sir John Cass Technical Institute, and the notes for these lectures have formed the basis of the work. The constant inquiries of engineers and technical men attending these lectures for a book on such lines leads the writer to hope it will prove of service in furnishing as complete an account of the subject as will meet the requirements of the large class to whom power production is of importance. The application of fuels to other purposes has not been overlooked, but primarily fuels are considered in their relation to power.

Every endeavour has been made to place before the technical man, who is not a fuel specialist, but who requires a good general knowledge of the subject, as full information on all fuels of importance as space permits ; at the same time the scientific principles underlying gas producer practice, combustion, etc., have not been neglected. As far as possible the diagrams have been chosen to illustrate principles and typical forms of plant and apparatus.

The material falls naturally under four headings : Solid Fuel, Liquid Fuel, Gaseous Fuel and the Analysis and Calorimetry of Fuels. In the last section are included also the question of purchase on a calorific basis and the scientific control of combustion.

Owing to its importance as practically the only native fuel available in this country, coal has received special attention, and every endeavour made to collect information on the composition of the coals of Great Britain and the Colonies, but in many cases but little is available. When it is realized that the annual output of coal in Great Britain is some 270 million tons, of which we consume about 180 million tons, it is surprising that no systematic study of our coals has been made, and the data, particularly in relation to Colonial coals, are surprisingly meagre.

That our coal supplies are not everlasting, and that every possible economy should be exercised in its use is admitted generally, but one of the first essentials in realizing this is better knowledge of our different coals and their special characteristics in relation to practice. The establishment of a Government Fuel Testing Laboratory, on the lines of the magnificent laboratories provided by the American Government, is greatly to be desired. In the United States Bureau of Mines Laboratories the analytical data and calorific value of many thousand samples of coal have been collected, hundreds of boiler tests with hand-firing and various mechanical stokers carried out, over 250 coals tested in gas-producer plants, besides briquetting, coking and washing tests, on a proper commercial scale. All the information is obtainable gratis, and must prove of immense service to producers, manufacturers of fuel plant and consumers.

If the value of such work is recognized in the States, which have large supplies of alternative fuel, surely the value of such a laboratory to a country dependent entirely throughout its industries on one fuel cannot be over-estimated.

In the section on Liquid Fuel, its use for steam-raising and heating purposes is considered, and later particular attention is given to fuels for use in internal combustion engines. The economic aspect of the use and supply of liquid fuels, especially those lighter spirits suited to petrol engines, has been dealt with at some length. The important position which alcohol as a fuel must assume sooner or later has led to its being considered more fully than its present importance might appear to justify, but its potentialities are such that the question of its production and supply demands careful consideration.

In dealing with Gaseous Fuel the principal object has been to enunciate the general principles and the great advantages arising from its employment. No attempt has been made to describe a large number of plants, but a selection has been chosen from good examples as illustrating current practice. A chapter is devoted to Fuel Consumption in power plants.

The material on Fuel Analysis and Calorimetry is necessarily curtailed, but the methods and apparatus are mostly those familiar to the writer, who has endeavoured to introduce the results of his own experience in this section.

The writer is indebted to many of the technical journals for information, and suitable references to the originals have been made in the text. Original memoirs occurring in Foreign Journals may be traced through the abstract referred to in one or other of these English publications.

The author desires to express his thanks to Engineer-Lieutenant G. Preece, R.N., and Mr. L. P. Scotcher, for valuable help in the preparation of the diagrams: to Mr. P. W. Robson, for permission to reproduce diagrams from his book on Power Gas Producers: and to Mr. G. Lorimer, for assistance in correcting the proof-sheets.

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Messrs. Baird & Tatlock, Ltd.: Calorimeters.

The Cambridge Scientific Instrument Co., Ltd.: Calorimeters and CO_2 Recorder.

The Leskole Co., Ltd. (Enfield): Recording Calorimeter.

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PREFACE TO THE SECOND EDITION

The First Edition being out of print, it became necessary either to prepare a completely revised Edition, or to reprint with a minimum of alteration. Owing to difficulties in the printing trade at the present time, the latter course was decided upon. It has, however, been possible to include some additional matter and to revise certain statistical matter.

The necessity for the conservation and better utilization of our fuel resources has been forced upon the nation, and reforms which might otherwise have been long delayed are being carried out. In no section is this more emphasized than in the recovery of by-products from coal distillation, where the demands of raw material for the production of explosives made the question imperative.

Following the work of a Fuel Economy Committee appointed by the British Association in 1916, it was announced early this year that a Board of Fuel Research, " to investigate the nature, preparation and utilization of fuel of all kinds," had been appointed, and the establishment of a Fuel Research Laboratory on the lines advocated in the Preface to the First Edition will shortly be realized.

J. S. S. B.

September, 1917.

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FUEL—SOLID, LIQUID AND GASEOUS

PART I

SOLID FUELS

Chapter I

INTRODUCTION

With the exception of natural oils, the origin of which still remains uncertain, all forms of fuel may be regarded as derived primarily from cellulose, often associated with materials of a gum or resin character. During the life of a plant the green colouring matter of the leaves has the power, under the influence of sunlight, of causing combination between the carbon dioxide of the air and the water in the plant to produce ultimately the cellulose, which is the main constituent of woody fibre, returning to the air the oxygen previously associated with the carbon dioxide. The wonderful mechanism by which these vital changes are brought about is quite unknown, but the final result is threefold—the amount of carbon dioxide is prevented from becoming excessive, which would be fatal to animal life, the renewal of the oxygen supplies is assured, and, what is of special importance since the change involves the absorption of radiant energy from the sun, available heat is stored up by the plant, which may be utilized afterwards by man for the thousand and one purposes for which he requires fuel.

Cellulose, in the form of wood; peat, where the cellulose has undergone some slight metamorphosis; lignite, brown coal, and finally, all the various kinds of coal, from highly bituminous to anthracite, certainly have derived their heat energy by this process, and whether we employ these cellulose derivatives in their natural form or convert them into forms more suitable than the original for special purposes, such as charcoal and coke, or employ them as liquids (tar) and gases, as is now such general practice, we are but recovering this energy stored up from the sun.

For a substance to be of value as a fuel it must fulfil the conditions of igniting with comparative ease, burning freely in some cases with a long flame, in others without flame, and possessing as high a calorific value as possible. From the economical point of view regular supplies must be available, and the cost sufficiently low.

Generally the proportion of hydrogen present is the determining factor in the ignition point of a fuel, this being well illustrated in the case of charcoal, which, if carbonized below a visible red heat (340° C.; 644° F.) ignites at 800° F., whilst if carbonized at a bright red heat (900° C.; 1634° F) it ignites at approximately 1000° F.

The ignition point of fuel oils has become a point of great importance in connection with the Diesel engine. Here again, for satisfactory working, hydrogen must not fall below a certain minimum.

The burning character will be dependent largely upon the draught conditions, *i.e.* the rapidity with which air is supplied to the fuel, and frequently for perfect combustion on the temperature of this air. For flame to be formed a solid fuel must give off a considerable quantity of hydrocarbon gases, in which case combustion is spread over a large area and high intensity is not attained. For this latter effect a solid fuel evolving little or no gas, but burning completely and rapidly on the fire bars or in direct contact with the material to be heated is requisite.

The calorific value is dependent upon the elements present in the fuel which are capable of undergoing oxidation with the production of heat, and for all practical purposes two elements only need be considered—carbon and hydrogen. If a fuel contains only these elements its calorific value will be the sum of their heat energies less any heat required to render them available for oxidation. In most fuels, however, a certain proportion of oxygen is already present, so that the hydrogen and possibly the carbon to some extent are already in combination with oxygen. The nature of this combination is not known, but it is customary to assume that the oxygen is associated wholly with the hydrogen, the balance being referred to as *available hydrogen*. In no substance used as a fuel is the amount of oxygen present more than sufficient to satisfy the hydrogen. It follows, therefore, that oxygen-containing fuels become proportionately poorer fuels as the percentage of oxygen present increases.

In considering the value of fuels from the economic point of view, to a large extent choice is limited by proximity of supplies of a certain type, since freight charges are diminished and interruption of supply is less likely to occur. At one time, for example, imported patent fuel (coal) from South Wales was the staple fuel on the Mexican railways, but with the discovery of oil-fields in Mexico it has naturally been superseded by oil fuel. Similarly, wood has been displaced by oil on many foreign railways. Given alternative supplies of fuel of a certain suitable kind the choice should be governed largely by the heat units available per unit of cost, or the purchase arranged on a basis of payment for actual heat units delivered, a matter that is slowly receiving the attention which its importance merits.

Before proceeding to a consideration of the various forms of fuel there are certain important matters relating to its combustion generally, which must be dealt with briefly.

Combustion.—As usually understood, combustion or burning of all commercial fuels is associated with chemical changes brought about by combination of the combustible constituents of the fuel with the oxygen of the air, the reaction developing heat and being easily manifest to the senses. Such a process is termed "rapid combustion," but similar changes may take place at a much slower velocity; the heat developed per unit weight of fuel is the same, but owing to the slowness of its production and its dissipation it is not always apparent. Such a process is termed "slow combustion."

For the desired chemical changes to be complete in order that the whole of the heat units in the fuel may be utilised, there must be no insufficiency of oxygen (or air), and from the composition of any fuel the theoretical amount of air requisite may be calculated, as is shown later. Incomplete combustion, resulting not only in losses of heat units through causes apparent to the eye, such as smoke, may also be present and escape observation, and can frequently be detected only by chemical analysis of the flue gases. A common case is the production of carbon monoxide by the incomplete combustion of the carbon of a fuel, which may occur under some conditions of boiler firing, or in the cylinders of internal combustion engines—notably when using petrol.

Incomplete combustion can be avoided only by proper attention to the supply of sufficient air; the intimate contact of the air with the fuel, either at its surface or by thorough admixture with the gases and vapours first evolved; lastly, by ensuring that there is no cooling of the system to a temperature below that necessary for the reactions to become complete. Smoke is the visible indication of incomplete combustion, and the above principles lie at the root of its prevention.

Production of Flame.—Flame is produced by the combustion of gases and vapours, in the case of solid fuels these being volatilized by heat from the fuel, or by the incomplete combustion of the carbon which gives rise to carbon monoxide, an inflammable gas. The temperature resulting from the combustion must be sufficiently high to maintain the reaction, otherwise the flame is extinguished. In the case of solid fuels, like coal, the amount of flame produced will be dependent largely on the ratio between the volatile combustible constituents and the carbon residue, which is non-volatile. It will be seen later that this ratio is highest with bituminous coals and falls to a minimum with anthracite.

When flame is produced, the heat units from the fuel are generated throughout probably several cubic feet of space. High local intensity with such fuels cannot be attained. When this is desired combustion must take place as far as possible on the grate, so that a fuel low in volatile constituents, such as anthracite, coke, or charcoal, must be employed.

In general, flame is inefficient for heating purposes where there is a great difference between its temperature and that of the surface being heated, as in a boiler. This is due to the checking of combustion by lowering of temperature, a thin layer of gases, which are poor conductors of heat, being formed along the surface of the plate. Much depends, however, on the luminosity of the flame. Owing to the presence of highly heated particles of solid carbon, to which most of the luminosity of all ordinary flames is due, the radiant effect from such flames is fairly high, whilst with a non-luminous flame radiation is almost negligible.

Ignition Point.—For active combustion to be initiated a definite temperature must be attained, and for its continuation this temperature at least must be maintained. The ignition point of all combustible substances is no doubt at a fixed temperature, but many conditions influence the ease with which combustion may be started, mass and fineness of division being the most important. Whilst a given coal in a finely divided condition will ignite at a low temperature, a lump of the same coal will require considerable heating up before it takes fire, due to the smaller surface exposed to the air in proportion to mass, which carries away the heat.

The ignition point of solid and liquid fuels is very difficult to determine, because so much depends upon the conditions of the experiment. Coal, for example, quickly yields smoke, vapours and gases, and with slow heating up the ignition point found is really that of the semi-coked residue. No pretension will therefore be made to give exact figures for the ignition points of various coals; at present they are too unreliable to be more than an approximation. It may be stated, however, in general terms that the ignition point falls more or less progressively as the coal passes from anthracite to the highly bituminous coals.

The following ignition points are approximately accurate for various coals :—

	°C.	°F.
Highly bituminous gas coal	370	700
Ordinary bituminous coal .	400–425	750–800
Welsh steam coal . . .	470	875
Anthracite	500	925

In the case of highly volatile spirits and of gases the ignition point of the mixture with air, as employed in internal combustion engines, is, however, of great importance, since on this the question of the pre-ignition of the charge on compression is chiefly dependent, and the degree to which compression of the charge may be safely carried.

The ignition temperature of a gaseous mixture is not constant, although according to Dixon the proportion of gases may vary within wide limits without effect. The most reliable determinations at present available are those of Dixon and Coward (*Trans. Chem. Soc.* 1909, 514), whose values are given in Table I.

TABLE I.

Ignition Temperatures of Gaseous Mixtures in °C. at Ordinary Pressures.

Gas.	In oxygen.	In air.
Hydrogen	580–590°	580–590°
Carbon monoxide	637–658	644–658
Methane	556–700	650–750
Ethane	520–630	520–630
Ethylene	500–519	542–547
Acetylene	400–440	406–440

It will be noted that, whilst in the case of simple gases like hydrogen and carbon monoxide, the ignition temperature variation is small, in the case of hydrocarbon gases the temperature is uncertain to over 100° C. Further, whilst there is close agreement between the values in oxygen and air, in other cases there is a marked discrepancy.

K. G. Falk (*J. Amer. Chem. Soc.* 1907, 29, 1536) determined ignition temperatures by instantaneous compression, which, if carried out with sufficient rapidity, is claimed to be adiabatic. Dixon has shown that the method is liable to error, but the results are sufficiently valuable to merit consideration. They are shown in Table II., together with Dixon's amended figures (in brackets) where possible.

TABLE II.

IGNITION POINT OF GASEOUS MIXTURES (Falk).

Hydrogen, Oxygen, and Nitrogen Mixtures.

Volumes.			Ignition temperature.
H_2	O_2	N_2	°C.
4	1	0	605
2	1	0	540 (536)
2	1	1	573
2	1	4	650
1	1	0	514 (530)
1	1	1	547
1	1	2	578
1	1	4	637
1	2	0	530 (520)
1	2	1	564
1	2	4	640
1	4	0	571 (507)

Carbon Monoxide, Oxygen, Nitrogen Mixtures.

CO	O_2	N_2	
4	1	0	630
4	1	1	652
4	1	2	667
2	1	0	600
2	1	1	645
2	1	2	685
1	1	0	630
1	1	1	706
1	1	2	812

Hydrogen, Carbon Monoxide, Oxygen Mixtures.

H_2	CO	O_2	
1	1	2	586
1	4	2	615
2	2	3	552

Theoretical Air for Combustion.—This is a most important consideration, governing to a large extent the arrangements for the supply of air, especially in internal combustion engines, and, further, enabling the theoretical composition of the flue or exhaust gases to be determined, which, as will be dealt with fully later, has an important bearing on fuel economy.

Custom has established somewhat firmly the calculation of the air required in pounds, and weight units do not involve corrections for temperature, but since gases are measured in cubic feet and thought of in terms of volumes and not weight, it seems more reasonable to consider their consumption in such units. In either case the calculation is simple, being based on the known combining values of oxygen with the individual combustible constituents, using their ordinary expression in the form of chemical equations for convenience.

The following data are of great service in such calculations, since they apply to all cases of chemical combination where gases are involved.

	At 0° C. and 760 mm. pressure.	At 60° F. and 30 inches pressure.
The molecular weight in grams always . =	22·32 litres	23·52 litres
The molecular weight in pounds always . =	357·5 cubic ft.	377 cubic ft.

Conversely, the weight of 1 cubic foot in pounds will equal $\frac{\text{molecular weight}}{357{\cdot}5}$ at 0° C. and 760 mm., and $\frac{\text{molecular weight}}{377}$ at 60° F. and 30 inches.

Further, the composition of air is—

	By weight.			By volume.		
	Per cent.	Ratio N/O	Ratio air/O	Per cent.	Ratio N/O	Ratio air/O
Nitrogen . . .	77	3·35	4·35	79	3·76	4·76
Oxygen . . .	23	1	1	21	1	1

Full information as to the weight and volume of both oxygen and air for combustion, the products of combustion, etc., for elementary fuel constituents, and the principal constituent gases of ordinary gaseous fuels, will be found in Table I., Appendix. An example of the method of calculation of these values is given below, the instance chosen being the combustion of carbon to carbon dioxide.

$$\begin{array}{lcl}
 & \text{Carbon.} & \overbrace{\qquad\qquad\qquad\qquad}^{\text{Air.}} \qquad \overbrace{\qquad\qquad\qquad\qquad}^{\text{Flue gases.}} \\
 & C & + \; O_2 \; + \; (\text{nitrogen}) \; = \; CO_2 \; + \; (\text{nitrogen}) \\
\text{Weight in} \left.\right\} & 12 & + \; 32 \; + \; (107) \; = \; 44 \; + \; (107) \\
\text{grams or lbs.} \left.\right\} & 1 & + \; \underbrace{2{\cdot}66 + (8{\cdot}93)}_{11{\cdot}6} \; = \; \underbrace{3{\cdot}66 + (8{\cdot}93)}_{12{\cdot}6}
\end{array}$$

Volume in litres.

$$\begin{array}{ll}
\text{At 0° C.} \left.\right\} & 12 \text{ grams} + 22{\cdot}32 + (84{\cdot}0) = 22{\cdot}32 + (84{\cdot}0) \\
\text{and 760 mm.} \left.\right\} & 1 \quad ,, \quad + \underbrace{1{\cdot}86 + (\ 7{\cdot}0)}_{8{\cdot}86 \text{ litres}} = \underbrace{1{\cdot}86 + (\ 7{\cdot}0)}_{8{\cdot}86 \text{ litres}}
\end{array}$$

$$\begin{array}{ll}
\text{At 60° F.} \left.\right\} & 12 \text{ grams} + 23{\cdot}52 + (88{\cdot}4) = 23{\cdot}52 + (88{\cdot}4) \\
\text{and 30 in.} \left.\right\} & 1 \quad ,, \quad + \underbrace{1{\cdot}96 + \ (7{\cdot}36)}_{9{\cdot}32 \text{ litres}} = \underbrace{1{\cdot}96 + \ (7{\cdot}36)}_{9{\cdot}32 \text{ litres}}
\end{array}$$

Volume in cubic feet.

$$\left.\begin{array}{r}\text{At } 0^\circ\text{ C.}\\ \text{and 760 mm.}\end{array}\right\}\begin{array}{llcl} 12\text{ lbs.} & + 357{\cdot}5 + (1345) & = & 357{\cdot}5 + (1345)\\ 1\ \ ,, & + \underbrace{29{\cdot}8 + (112)}_{141{\cdot}8\text{ cu. ft.}} & = & \underbrace{29{\cdot}8 + (112)}_{141{\cdot}8\text{ cu. ft.}}\end{array}$$

$$\left.\begin{array}{r}\text{At } 60^\circ\text{ F.}\\ \text{and 30 in.}\end{array}\right\}\begin{array}{llcl} 12\text{ lbs.} & + 377{\cdot}0 + (1418) & = & 377{\cdot}0 + (1418)\\ 1\ \ ,, & + \underbrace{31{\cdot}4 + (118)}_{149{\cdot}4\text{ cu. ft.}} & = & \underbrace{31{\cdot}4 + (118)}_{149{\cdot}4\text{ cu. ft.}}\end{array}$$

Composition of flue gases (by volume).

$$CO_2\,\% = \frac{29{\cdot}8 \times 100}{141{\cdot}8} = 21{\cdot}0 \qquad N_2\,\% = \frac{112 \times 100}{141{\cdot}8} = 79{\cdot}0.$$

The volume (or weight) of oxygen or air for any fuel will be arrived at by the sum of the volumes (or weights) required by the ultimate elementary constituents per lb. in the case of solid or liquid fuels, and in the case of gaseous fuels from the like quantities required for the separate combustible gaseous constituents per cubic foot of the whole gas.

Calorific Value.—The calorific value is expressed in terms of various units of heat. For scientific purposes in this country the centigrade system forms the basis, but most practical men prefer the system based on the Fahrenheit thermometer scale, the results being expressed as British Thermal Units (B.Th.U.)

The *calorie* represents the quantity of heat necessary to raise 1 gram of water through 1° C. A slight variation is found in the actual amount required for this over different temperature ranges, but no standard has yet been adopted, and the difference is generally neglected.

The *Calorie* (large calorie) of 1000 times greater than the above, representing the heat required to raise 1000 grams of water through 1° C.

The *British Thermal Unit* is defined as the amount of heat required to raise 1 lb. of water 1° F. (from 60° to 61° F.).

Suppose then a given unit of heat raises 1000 grams of water 1° C.; since 1000 grams = 2·2 lbs., and 1° C. = 1·8° F., this same unit of heat would raise 1 lb. of water 2·2 × 1·8 = 3·96° F., or, stated otherwise, 1 Calorie (kilogram degree centigrade unit) = 3·96 B.Th.U.; conversely, 1 B.Th.U. = 0·252 kilogram degree centigrade unit.

A fourth unit of heat—the *pound degree centigrade unit*, being the amount of heat required to raise 1 lb. of water 1° C., is generally employed in stating the calorific value of solid and liquid fuels, and is what is generally understood by "Calorie" in this country. It is related obviously to the B.Th.U. as are the centigrade and Fahrenheit thermometer degrees, namely

$$\frac{\text{Fahrenheit degree}}{\text{Centigrade degree}} = \frac{180}{100} = 1{\cdot}8$$

A concrete practical example will make this evident: 1 gram of coal burnt in a calorimeter raised the temperature of 3000 grams of water 2·5° C. Its calorific value = 3000 × 2·5 = 7500 calories. 1 lb. of coal would have obviously raised 3000 lbs. of water 2·5 × 1·8 = 4·5° F., or its calorific value = 3000 × 4·5 = 13,500 B.Th.U. The calorific values of all solid and liquid fuels referred to subsequently have this ratio between B.Th.U. and calories.

It is frequently convenient to express these values in foot-pounds

1 kilogram degree centigrade	= 3087	foot-pounds
1 pound degree centigrade	= 1400	,,
1 British Thermal Unit	= 778	,,

Gross and Net Calorific Values.—When a fuel containing hydrogen is burnt water is produced invariably, and if this water is condensed it gives up its latent heat as steam together with the heat liberated on cooling from its condensation point to the temperature of the calorimeter. The total calorific value, *gross*, or higher heating value of a fuel is the total theoretically available heating value of the fuel, and includes the heat mentioned above.

In many cases, however, this heat carried by the water produced from hydrogen during combustion, or stored in water evaporated from the fuel, is not available for conversion into work. Thus, it plays no part in raising the flame temperature of burning gases, or in developing energy in a gas engine. For all such computations it must be eliminated, and the value after this deduction is termed the *net* calorific value.

No definite agreement is to be found in the literature on fuel as to whether the net value shall be deduced simply from the latent heat of steam, or whether by deduction from the gross of both the latent heat and sensible heat in cooling from 100° C. (212° F.); in the latter case it would be necessary to fix the temperature to which the products are finally reduced. In English practice it is usual to take the second course and estimate the products as cooled to 60° F. In France the latent heat is alone deducted.

The latent heat of steam being 536·5 Calories or 966 B.Th.U., the total deduction at 15·5° C. (60° F.) would be 536·5 + (100 − 15·5) = 621 Cals.; or 966 + (212 − 60) = 1118 B.Th.U. In general it is sufficiently accurate if the deduction is taken at the round figures of 600 Cals. or 1080 B.Th.U.

For thermo-dynamic calculations the net value is of great service, but its real value must not be misconstrued. The error has arisen that the net value is the true measure of the practical heating value of the fuel. Flue gases and exhaust gases are seldom cooled to anything approaching 100° C. (212° F.), and must carry away not only the latent heat units in the uncondensed steam, but all the additional sensible heat units in the flue gas, which will depend primarily on their temperature. To quote Prof. C. V. Boys, under practical conditions "every user of gas should be equally entitled to a special net value to meet his requirements." The net value is a useful convention but is in reality an artificial figure.

Although the net calorific value has received official recognition as a standard in the case of coal gas, it is agreed generally that the gross value is the proper one to take. The inability of most of our appliances to convert all the heat units into other forms of energy is no logical basis for rating fuels on a value which is not their true one, indeed in some cases it is practicable to utilise at least a considerable proportion of the latent heat units. In the United States, where the calorific value of gas is considered rightly as of the highest importance, opinion is almost unanimous in favour of the gross value as the standard. In 1906, the Association of German and Austrian Engineers agreed that calorific values should be calculated on the assumption that the whole of the products are cooled to 100° C., with the water remaining as steam.

When it becomes a question of comparison between different samples of coal or of oil, the net value offers so little advantage over the gross as to be negligible, because with coals of the same class, or oils of the same character, the hydrogen content is so similar in different samples, that the difference between the gross and net values is nearly constant. The extra labour involved in determining the hydrogen by the combustion process—which is the only method available giving the requisite accuracy—is not commensurate with the gain.

Calculation of Calorific Value.—In general, actual determinations in some form of calorimeter are preferable to calculated values; comparison between the methods is dealt with under Calorimetry (p. 315), but the general method of calculating the values is referred to here in order that other points may be elucidated.

It is assumed in practically all such calculations that the heating value of the constituent elements of the fuel is the same as the value for these same elements in the free condition, and that no heat is generated beyond this, or no heat utilised in setting free the constituent elements in a condition for their combustion by oxygen, assumptions which certainly cannot be substantiated.

When carbon is burnt in oxygen with the formation of carbon dioxide, the weights of material involved and the heat evolved may be expressed by a *thermo-chemical equation*, thus—

$$\begin{array}{ccccccc} C & + & O_2 & = & CO_2 & + & 97{,}644 \\ \text{12 grams} & & \text{32 grams} & & \text{44 grams} & & \text{calories} \\ \text{Carbon} & & \text{Oxygen} & & \text{Carbon dioxide} & & \end{array}$$

and when hydrogen burns with the formation of water at constant pressure as—

$$\begin{array}{ccccccc} H_2 & + & O & = & H_2O & + & 69{,}000 \\ \text{2 grams} & & \text{16 grams} & & \text{18 grams} & & \text{calories} \\ \text{Hydrogen} & & \text{Oxygen} & & \text{Water (condensed)} & & \\ & & & & \text{Water as (steam)} & + & 58{,}100 \end{array}$$

It follows that 1 gram of carbon gives 8,137 cals. (14,646 B.Th.U.), and 1 gram of hydrogen 34,500 cals. (62,100 B.Th.U.), if the steam produced is condensed to water at 0° C.; if the steam remains as such at 100° C., 29,050 cals. (52,290 B.Th.U.).

The calculated calorific value (gross) of any fuel containing only these two elements will be found from the equation—

$$\frac{(\text{Carbon } \% \times 8137) + (\text{Hydrogen } \% \times 34{,}500)}{100} = \text{calories (gross)}$$

A large number of fuels already contain oxygen, and therefore a smaller quantity of this gas will be required for their consumption, and the heat produced will be proportionately less. The assumption is made that any oxygen present is already wholly in combination with hydrogen; again, this is certainly not the case, but since nothing is definitely known as to the actual distribution of oxygen between the hydrogen and other elements present, it affords the only possible working hypothesis. Since it is known that in water 8 parts by weight of oxygen are combined with 1 part of hydrogen, it is customary to deduct from the total hydrogen an amount equal to one-eighth of the oxygen present, calling the remainder the *available hydrogen.* The formula thus becomes—

$$\text{Calories (gross) per gram} = \frac{(C\% \times 8137) + \left\{\left(H - \frac{O}{8}\right) \times 34{,}500\right\}}{100}$$

In the most complete form, such as may be applied to coals, the following extended formula is employed:—

$$\text{Calories} = \frac{(C \times 8137) + \left\{H - \frac{(O+N-1)}{8} \times 34{,}500\right\} + (S \times 2220) - (H_2O \times 600)}{100}$$

Here a fixed deduction of 1 per cent. is made for the nitrogen present in the fuel, this being regarded as a fair average, although somewhat low for English coals; sulphur, in the form of pyrites, is regarded as furnishing heat, and an approximate deduction is made for the evaporation of the moisture present in the fuel.

In the case of gaseous fuels the calorific value must not be calculated from the elementary constituents, but from the sum of the calorific values of the constituent gases themselves, the values for which are well established, and are given in Table I., Appendix.

With gaseous fuels the results calculated from the values for the constituent gases at constant volume are found to be in good agreement with determinations made in calorimeters of the usual pattern—Junkers, Boys, etc.

In the case of gaseous fuels it is important to note that the calorific value is higher when burnt at constant pressure than it is at constant volume, for example, in cases where the final products occupy a less volume than the original, *e.g.* with hydrogen, where the steam occupies two-thirds of the former volume, and may ultimately condense to a negligible volume. In the case of actual determinations of calorific values of solid and liquid fuels in a bomb calorimeter, the difference is negligible.

Calorific Intensity.—Whilst any given fuel is capable of developing on combustion a given number of heat units, the actual temperature attained by the combustion will depend not only on the calorific value but on a number of other conditions—the weight of the products of combustion and of any excess air, their specific heat and the heat losses which take place. Assuming that the whole of the heat is utilized without loss in raising the temperature of the products, then it is possible to calculate the maximum theoretical temperature attainable. Such a figure is probably some distance from the truth, for accurate knowledge of the actual variation in specific heat of gases with rise of temperature is wanting. Again, the temperature can never be attained in practice, for it is seldom possible to burn a fuel without excess air, and it is certainly impossible to avoid big heat losses.

Certain practical considerations however arise. Imagine a fuel is burning under a boiler, and a steady temperature has been attained, that is, the heat production and losses have reached a certain equilibrium. Increase of the rate of combustion by increasing the draught will not raise the amount of heat given out per pound of fuel, but the production of heat increases proportionately much faster than the loss of heat, consequently a higher calorific intensity is attained. Again, the use of excessive air for combustion will greatly lower the temperature. The effect of inert gases, or large excess of air, may be well illustrated with approximate figures for the combustion of hydrogen. With the theoretical volume of pure oxygen the theoretical attainable temperature is over 6000° C. (say 11,000° F.); with the theoretical volume of air 2300° C.; with twice the theoretical air 1400° C.

In the case of regenerative furnaces, where the waste heat from the gaseous products is utilized for heating up the air required for combustion (with the poorer gaseous fuels the fuel is heated also) it will be seen how greatly this must add to the calorific intensity of the reaction; indeed, the success of such low calorific value fuels as "producer gases" is dependent entirely on this possibility of increasing the intensity by regeneration. For example, the theoretical temperature for the combustion of carbon monoxide with twice its volume of air, both gases supplied at ordinary temperatures, is less than 1600° C., but if by regeneration the initial temperature of the combustible gas and the air is 500° C., then a temperature of a little over 2000° C. is theoretically attainable.

Exothermic and Endothermic Compounds.—If the simplest of the formulæ on p. 11, that for a fuel containing carbon and hydrogen alone, be applied to the two gases, methane or marsh gas (CH_4) and acetylene (C_2H_2), it is found that in the case of methane the calculated value is much higher than that found by a calorimeter, whilst in the latter case it is considerably lower. Some of the heat is expended in breaking down the methane before combustion; in the case of acetylene, surplus heat is actually noted.

The explanation is to be found in the conditions attending the formation of the two gases. When methane is formed from its elements, carbon and hydrogen, heat is evolved, and to separate these elements again and enable them to enter into fresh combination with oxygen during the combustion, as much heat must be expended as was given out originally. Compounds which evolve heat on formation are termed *exothermic*. Acetylene, conversely, absorbs heat on formation; this heat is evolved on decomposition, and adds to the heat generated by the combustion of its constitutent elements. Compounds whose formation demands heat are termed *endothermic*.

It follows that all formulæ for calculating calorific values must fail unless the heat of formation of the fuel is either only slightly positive or negative. Such formulæ apply fairly well to most coals, simply because coal is very slightly endothermic, its endothermic character increasing with the amount of oxygen present. In the case of gaseous fuels, where the heat of formation of the constituent gases may be either markedly positive or negative, calculation from elementary composition will obviously give misleading results.

Evaporative Values.—It is common practice to state the thermal value of a fuel in terms of its power of evaporating water from a temperature of 100° C. (212° F.) into steam at the same temperature.

The evaporative value will therefore equal $\frac{\text{Calories (or B.Th.U.)}}{\text{Latent heat of steam}}$. In calories per gram the denominator will be 536·5; in B.Th.U. per lb. 966.

The latent heat of steam (or latent heat of vaporization) falls with increase of temperature (*i.e.* higher boiler pressures). According to Regnault, up to 230° C. (404 lbs. absolute pressure), it equals $606{\cdot}5 - 0{\cdot}695t$, where t equals the boiling temperature. The important point, however, in practice is the total amount of heat in steam at a given temperature. This obviously will be the sum of the latent heat of vaporization and heat required to raise the water from feed temperature to its boiling-point. According to Regnault, the feed being 0° C. (32° F.), the value for the total heat up to 230° C. is equal to $606{\cdot}5 + 0{\cdot}305t$ calories. From this value the temperature of the feed water must be deducted. The value in B.Th.U. will be 1·8 times as great.

As an example, a boiler is worked at 115 lbs. absolute pressure; the feed water is at 15·5° C. (60° F.). At this pressure the water boils at 170° C. (338° F.). The total heat equals $606{\cdot}5 + (0{\cdot}305 \times 170) = 658$ cals. or 1184 B.Th.U. The heat required to convert 1 kilogram of water to steam under these conditions will be $658 - 15{\cdot}5 = 632{\cdot}5$ cals., or 1 lb. of water 1138 B.Th.U. If the coal has a calorific value of 7500 calories (13,500 B.Th.U.), the theoretical evaporative power will be $\frac{7500}{632{\cdot}5}$ or $\frac{13{,}500}{1138} = 11{\cdot}8$ lbs.

Limits of Combustion.—Mixtures of combustible gases or vapours with air are capable of burning only within fairly well-defined limits. Quoting from an admirable paper by Burgess and Wheeler (*Trans. Chem. Soc.* 1911, 2013)—"To ensure propagation of flame, it is necessary (1) that the initial source of heat should be of a volume, intensity and duration sufficient to raise the layer of gases in its immediate vicinity to a temperature higher than, or as high as, the ignition temperature of the mixture; and (2) that the heat contained in the products of combustion of this first layer should be sufficient to raise the adjacent layer to its ignition temperature."

"THE SMALLEST QUANTITY OF ANY COMBUSTIBLE GAS WHICH, WHEN MIXED WITH A GIVEN QUANTITY OF AIR OR OXYGEN, WILL ENABLE THIS SELF PROPAGATION OF FLAME TO TAKE PLACE, IS TERMED THE LOWER LIMIT OF INFLAMMATION OF THE GAS."

A "lower limit mixture" is one such that a given volume must, under the conditions of its combustion, evolve just sufficient heat to raise an equal volume to its ignition temperature. There are three factors which determine this—(1) the calorific power of the gas, (2) the relative volume and specific heat of the diluent gases, (3) the ignition temperature of the mixture.

The results obtained by H. Bunte (1901) for the explosive mixtures of the commoner gaseous fuel constituents and for vapours are given in Table III. The limits vary somewhat with the shape and size of the vessel, being extended in wider vessels, and with the method of ignition. Further, more dilute mixtures can be exploded under pressure. Bunte's experiments were carried out in a tube 19 mm. ($\frac{3}{4}$ inch) diameter over water, the mixture being fired by a spark.

TABLE III.

Explosive Limits for Mixtures of Combustible Gases and Vapours with Air at Ordinary Pressures (H. Bunte).

	Hydrogen (H_2)	Carbon monoxide (CO)	Methane (CH_4)	Ethylene (C_2H_4)	Acetylene (C_2H_2)	Pentane (C_5H_{12})	Benzene (C_6H_6)	Ether ($C_4H_{10}O$)	Alcohol (C_2H_6O)	Water gas.	Coal gas.
Upper limit	66·4	74·95	12·8	14·6	52·3	4·9	6·5	7·7	13·65	66·75	19 %
Lower limit	9·45	16·50	6·1	4·1	3·35	2·4	2·65	2·75	3·95	12·4	7-9%

More recent determinations of the lower limit for saturated hydrocarbons are those of Wheeler and Burgess (*loc. cit.*), which are as follows :—

Lower Limits determined.

Methane	5·5 – 5·7	per cent.
Ethane	3·0 – 3·2	,,
Propane	2·15 – 2·30	,,
*n*Butane	1·60 – 1·70	,,
*n*Pentane	1·35 – 1·40	,,
*iso*Pentane	1·30 – 1·35	,,

According to Dr. Eitner, the lower limit for acetylene is 2·5 per cent.

Velocity of Flame Propagation in an Explosive Mixture.—This is an important factor in relation to the possible maximum speed of an internal combustion engine, and in determining whether combustion is completed during the outward stroke of the piston. Laboratory experiments carried out at ordinary pressure by the usual method of passing the explosive mixture through a tube at such a velocity that the flame just fails to strike back are of little value in this connection.

Unfortunately, few data by other methods are to be found, and hardly any experiments with commercial gases and vapours at ordinary pressures are recorded. Hopkinson, with air-coal gas mixtures of 12/1 and 9/1 in a closed vessel at ordinary pressures, came to the conclusion that even in the weakest mixtures combustion once started is almost instantaneously complete. Results at higher pressures for commercial gases, etc., are greatly wanted.

Mallard and Le Chatelier, by the open tube, obtained the following velocities for hydrogen and air:—

Per cent. hydrogen . .	20	25	30	35	40	50	67
Volume of air to 1 volume of hydrogen	4	3	2·33	1·86	1·5	1	0·5
Velocity, feet per second	6·56	9·2	11·1	12·4	14·3	12·3	7·55

The theoretical mixture for perfect combustion would contain 29·6 per cent. of hydrogen. The maximum rate, however, occurs at about 40 per cent.

Michelson determined the following rates for mixtures of carbon monoxide and oxygen:—

Per cent. carbon monoxide . .	25	30	35	40	45	50	60	70	80
Velocity, ft. per second	0·98	1·31	1·61	1·90	2·16	2·40	2·72	2·98	2·79

Chapter II

WOOD, PEAT, AND MINOR SOLID FUELS

Classification of Fuels.—Fuels are employed in the solid, liquid and gaseous condition. The solid fuels are essentially naturally occurring materials, principally wood, peat, and coal, although for special purposes they are carbonized for the production of charcoal and coke. Liquid fuels are mostly direct natural products, such as the petroleum oils, but considerable quantities are obtained as the result of destructive distillation of solid fuels (tars, etc.); whilst gaseous fuels occur naturally only to a very limited extent (natural gas), but are mainly the result of destructive distillation of solid fuels (coal gas, coke oven gas) or liquid fuels (oil gas), or the result of the incomplete combustion of solid fuels in gas producers either by an air blast (producer gas), steam (water gas), or a combination of air and steam (Dowson or semi-water gas).

Solid Fuels.—The chief solid fuels are as follows:—

$$\begin{array}{ll} \text{Wood . . . } = & \text{Wood charcoal} \\ \text{Peat . . . . } = & \begin{cases} \text{Peat charcoal} \\ \text{Briquettes} \end{cases} \\ \text{Lignites and coal} = & \begin{cases} \text{Coke} \\ \text{Briquetted fuels.} \end{cases} \end{array}$$

In addition to the above important solid fuels, large amounts of various waste materials are frequently available in certain industries—spent tan, bagasse (the residue of canes after sugar extraction), Nile sud, cokernut and other nut shells, etc.

Wood

Composition and Thermal Value of Wood.—The abundance of wood throughout man's existence, its comparatively rapid growth and reproduction, and the ease of obtaining supplies, naturally made it one of the earliest and most generally used of all fuels. At the present it is only of importance as a fuel in countries where large forests abound.

The combustible portion of all wood consists mainly of a form of cellulose (lignin), which has the empirical composition $n(C_6H_{10}O_5)$, containing—

Carbon	44·44 per cent.
Hydrogen	6·17 ,, ,,
Oxygen	49·39 ,, ,,

In many woods, more particularly the coniferous, considerable quantities of resinous substances of much higher calorific value than lignin are found. It will be noted that in cellulose the hydrogen and oxygen are present in the proportions existing in water—in other words, as far as calorific effect is concerned the hydrogen is negligible, and the heating value is dependent on the carbon and any resinous constituents present. The average calorific value of cellulose is 4150 calories (7500 B.Th.U.).

The average composition and thermal value of dry wood is given in Table IV.

TABLE IV.

COMPOSITION AND CALORIFIC VALUE OF DRY WOOD (Gottlieb).

	Carbon.	Hydrogen.	Oxygen.	Ash.	Calories per kilo.	B.Th.U. per lb.
Ash	49·18	6·27	43·91	0·57	4710	8480
Beech	49·06	6·11	44·17	0·57	4774	8591
Elm	48·89	6·20	44·25	0·50	4728	8510
Oak	50·16	6·02	43·36	0·37	4620	8316
Fir	50·36	5·92	43·39	0·28	5035	9063
Pine	50·31	6·20	43·08	0·37	5085	9153

In general, woods containing much resinous matter, as with fir, pine, etc., exhibit a higher calorific value, a pine knot examined by Slossen giving about 6005 calories (10,860 B.Th.U.).

Perfectly *dry* wood, therefore, is but a poor fuel from the point of view of thermal value, but in practice the best attainable condition is that resulting from prolonged air-drying. When freshly cut the moisture in different woods varies throughout a wide range, from 26 per cent. in willow to over 50 per cent. in poplar. Great variation is also found in the same wood at different seasons and in different parts of the plant. By proper air-drying the range of moisture content is reduced, so that it lies usually between 15 and 20 per cent. Low as is the calorific value of perfectly dry wood, it is apparent that the value is still further reduced by the presence of this residual moisture.

Under the most favourable conditions wood will be of low value as a fuel, for (1) only some 80 per cent. is actual combustible; (2) the calorific value of this combustible is low; (3) the large amount of moisture present demands much of the available heat for its vaporization. On the other hand, wood is easy to ignite, and is for that reason employed largely to kindle less easily ignited fuels; it can be burned completly without difficulty, and contains but little ash, seldom exceeding 1 per cent. on the air-dried material. The composition of the ash is very variable, but since the amount is so small it is a factor of such minor importance from the fuel point of view that its further consideration is unnecessary.

Wood Charcoal.—Wood charcoal is obtained by the destructive distillation of wood which, if carried to completion, leaves a residue retaining the original shape and structure of the wood, and which consists almost entirely of carbon. With lower temperatures the distillation is less complete, and combined hydrogen and oxygen are left to a greater or less extent in the mass.

By carbonization there is necessarily a large loss of heat units in the liquid and gaseous products, and the yield of solid fuel is very low. Although wood contains from 49 to 50 per cent. of carbon, under the most economical conditions of carbonizing in retorts 27 per cent. is the highest attainable yield. Wasteful as the process usually is, unless careful attention is paid to utilization of the liquid tars, etc., certain great advantages result. Since the useless constituents of the wood, the combined hydrogen and oxygen, are mostly removed, the charcoal has a high calorific value, 11,000 to 13,500 B.Th.U., and owing to its porosity and combustion without flame it has high calorific intensity. Since concentration results the ash will be considerably higher than in the original wood.

Charcoal was formerly a metallurgical fuel of great importance, and the production at one time was so large as to cause complete denudation of forests, so that restrictive legislation on the output was imposed.

The introduction of coke and raw coal for iron smelting has displaced charcoal entirely from its position of importance, and now its use is confined almost wholly to certain metallurgical operations where great purity of fuel is desired, for owing to the low mineral content and freedom from sulphur, phosphorus, etc., charcoal has great advantages.

Production of Charcoal.—This was at one time carried out entirely by restricted combustion in heaps, a portion of the wood furnishing the necessary heat for the carbonization of the remainder. This process is necessarily wasteful, the yield seldom exceeding 15 per cent., and at present it is confined to countries where waste is not considered or where deforestation is a desired object If the wood had a calorific value (dry) of 8500 B.Th.U., the yield of charcoal was 20 per cent., and of the highest calorific value, 13,000 B.Th.U., the actual percentage of heat units in the product would be about 30.

The production of charcoal by dry distillation of wood in closed retorts externally heated enables valuable by-products to be recovered. Where charcoal reproduction is the primary object the distillation is carried out at a high temperature, and the liquid distillate is wood creosote, which, owing to its great preservative value, is employed largely for creosoting timber.

Distillation of wood, however, is now largely practised, more particularly for the valuable liquid products, and charcoal is the by-product. In order not to impair the value of these products the temperature employed is lower than for complete carbonization. In recent practice oil-heated retorts are used with an initial temperature of 200° C. (392° F.) and finishing temperature 330–340° C. (625° F.). The yield of the various products per cord of wood (4000 lbs.) is—

Best turpentine	40 gallons
Light oils	16 ,,
Heavy oils	128 ,,
Charcoal	950 lbs.

(T. W. Pritchard, *J. S. C. I.* 1912, 418).

In addition to the liquid products of distillation large volumes of gases are also evolved during the process. Lawrence (*J. S. C. I.* 1911, 728) gives the following analysis of such gases :—

Heavy hydrocarbons	8·16 per cent.
Methane	12·32 ,,
Carbon dioxide	31·45 ,,
Carbon monoxide	35·08 ,,
Hydrogen	10·94 ,,
Nitrogen	2·05 ,,

Charcoal obtained as a by-product is not of high quality; the wood is selected as far as possible to give the most valuable distillates and not for the production of charcoal primarily, and further the low temperatures employed do not permit of complete carbonization.

It is of interest to note that the destructive distillation of wood involves a strong exothermic reaction which, according to Fawsitt and Klason, sets in at 275° C. Hornsey estimates that 12 per cent. of the heat of combustion of the wood thus becomes available for the distillation process.

In many wood-producing countries very large quantities of otherwise waste wood are available for treatment for by-products and charcoal, and the large extent of this industry in the United States is shown by Table V.

TABLE V.

Products from Wood Distillation (from United States Returns, 1909).

	Hard woods (beech, birch, maple).	Soft woods (chiefly long-leafed pine).
Cords, carbonized	1,149,847	115,310
Charcoal—bushels	53,075,102	2,403,401
Crude alcohol, gallons	8,468,083	682,702 turpentine
Gray acetate, lbs.	148,769,479	4,850 gallons pyroligneous acid
Brown acetate, lbs.	2,156,907	
Iron acetate, lbs.	302,624	
Oils, gallons	37,995	323,226
		1,364,984 gallons tar

(For Utilization of Waste Wood, Geo. Walker, *J. S. C. I.* 1911, 934, and Products from Hard Woods, Hawley and Palmer, 1912, 865).

Composition and Properties of Charcoal.—If distillation is carried out to the highest extent the products should be simply carbon and ash. Charcoal, however, has enormous absorptive powers for gas and is fairly hygroscopic. After exposure to air, even when fully carbonized, it contains much occluded gas and moisture, up to 8 or 9 per cent. If incompletely carbonized, it retains in combination hydrogen (2 to 3 per cent.) and oxygen (12 to 14 per cent.).

If charred at quite low temperatures red charcoal (rothköle, charbon roux) is obtained, and this contains actually a higher percentage of combustible than the high temperature product.

PEAT

Importance of Peat.—Enormous quantities of peat are available for fuel purposes, but owing to the situation of the bogs in sparsely populated districts, difficulties in removal of the excessive water, to its low density and low calorific value, its utilization has been only on a small scale. Modern methods of treatment are, however, being successfully exploited, and give every promise of producing a useful fuel, cheap power gas, and valuable by-products. By the utilization of the gas in gas-engines, and the distribution of the electric energy so generated, these outlying peat-producing districts are likely to play an important part in our fuel economy. Even without the stimulus of decreasing supplies of other fuels at present, the problem of using these vast fuel resources is being attacked by many skilled scientists, and their work has already passed the experimental and realised the commercial stage.

In Europe the peat area is estimated at 140 million acres, whilst in Great Britain and Ireland there are approximately 2 million acres; in Ireland alone Frank estimates the available peat as equal to 2500 million tons of coal. Of the Colonies, Canada is possessed of some 30 million acres. Now that the difficulty of the economic application of these huge fuel resources appears to have been successfully solved, it is out of the question that they should remain unproductive any longer, and active steps are being taken for their utilization. Peat, then, from its practically negligible position as a fuel in the past, must now be regarded as the most likely of all fuels to assume an importance second only to coal, certainly in countries not fortunate in having coal or oil supplies.

Formation of Peat.—Peat consists of partially decomposed vegetable matter, the result of luxuriant growth of lower forms of plant life, mostly mosses, under such favourable conditions as moisture and temperate climate. While the lower part of the stem dies off the upper part continues its growth, so that in the course of time a thick deposit results; as the under portions become buried deeper and deeper in the swamp decomposition through bacterial and other agencies progresses. The result is that whilst the upper parts of the bed are a matted, water-saturated sponge, the lower portions have largely lost their vegetable characteristics, and have become a semi-solid brown to black mass, in which greatly disintegrated vegetable structure is visible under the microscope.

When sufficiently felted together the upper parts are cut into blocks, air-dried and used for fuel. At greater depths the material is removed by suitable mechanical means, elevators, grabs, etc., then usually pressed and cut into suitable blocks. The lower slimy portions may be pumped from the bog, spread on the land to dry, to be afterwards treated in gas-producers or carbonized by such a process as the Ekenberg.

Moisture in Peat.—A well-drained bog may yield peat still containing from 84 to 90 per cent. of water, with an average of 87·5 (Ekenberg); in other words, for every ton of peat substance 7 tons of water are present. The amount largely depends upon the depth at which the sample is taken; from an English bog the author obtained 75 per cent. from the upper layers, and 90 per cent. from the bottom.

When air-dried the amount of water remaining will depend largely on climatic conditions and season. The drier air of Germany will obviously permit of better drying than the warm moist climate of Ireland. According to Sankey, with six weeks' air-drying on peat originally containing 90 per cent. of moisture, the moisture in summer averages 24 per cent., in spring or autumn 46 per cent., and in winter 80 per cent. Attempts to further dry by heat prove unsuccessful, as the expenditure of fuel required more than counterbalances the enhanced value of the dried product. Further, it is impossible to press out from bog peat any appreciable quantity of water, because, as Ekenberg has shown, there is present a hydrocellulose which, although small in amount, is of such a jelly-like slimy character that it almost immediately blocks the pores of any filtering material employed. In the more felted portions the water is held much as in a sponge, and may be removed largely by pressing.

Composition of Dry Peat.—The composition of the pure peat substance, *i.e.* with water and ash eliminated, varies over only a moderate range. The following data are mainly from analyses by Bunte on Bohemian peats, and for British by the author. There is quite close agreement between the results in each case—

	Limit.	Average.
Carbon	56 – 63	57·5
Hydrogen	5·7 – 6·3	6·1
Sulphur	0·6 – 1·0	—
Nitrogen	1·3 – 2·7	—
Oxygen	31 – 38	34·9

The ash in peat is a very variable quantity. It is exceptional to find less than 3 per cent., but not uncommon for over 10 per cent. to be present. The lower layers will contain usually high ash as compared with the felted peat.

In view of the production of ammonium sulphate in the gasification of peat, nitrogen is of greater importance than the other elements. The distribution of nitrogen in the bog seems variable. Whilst in a few cases the upper portions contain the highest percentage, in general it seems to occur in greater amount in the soft bottom portions.

Calorific Value of Peat.—On the air-dried peat this will be naturally a very variable factor for the same peat, owing to moisture variation under different conditions. For air-dried peat, 25 per cent. of moisture, Ekenberg takes an average of 3450 calories (6230 B.Th.U.).

Andersson and Dillner (*J. S. C. I.* 1902, 459) give the following for dry peats:—

Average from bog	4490 cals. (8100 B.Th.U.) to 6140 cals. (11,000[1] B.Th.U.)
Reed grass peat	4140 cals. (7450 B.Th.U.) to 5460 cals. (9820 B.Th.U.)
Mud peat	4360 cals. (7825 B.Th.U.) to 4560 cals. (8200 B.Th.U.)

The average of three samples from the Bog of Allen (Gray) gave 4790 cals. (8620 B.Th.U.).

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[1] Is certainly exceptionally high.

The calorific value of the pure peat substance by various observers who use some form of bomb calorimeter, ranges between 5280 cals. (9500 B.Th.U.) and 5900 cals. (10,600 B.Th.U.). With British peats the writer has never found one exceeding 5525 cals. (9950 B.Th.U).

Use of Peat as a Fuel.—The methods may be classified as—

1. Direct burning of air-dried peat or dried peat powder.
2. Conversion into peat charcoal.
3. Briquetting after semi-carbonization (Ekenberg process).
4. Gasifying, with ammonia recovery.

Owing to the low density of air-dried peat (which of course varies very greatly between the turf-like type and soft bog peat) and its low calorific value, untreated peat has never been, and is never likely to prove, a commercial fuel. Successful results have been obtained in the use of dry peat powder for steam raising in Sweden, injection by air heated to 200° F. being employed. From 1·2 to 1·4 lbs. of dry peat were equivalent to 1 lb. of coal, the relative cost per ton being stated as 16/6 and 9/4, but some coal is required when starting up. This method seems unlikely to find wide application.

Peat Charcoal.—Owing to the nature of the original peat, charcoal obtained from it by ordinary processes has little coherence and is very bulky. As so much peat contains a high percentage of ash, which, moreover, is frequently very fusible, such raw material is inadmissible for carbonization. Good peat charcoal, however, has a high calorific value, and that made by the Ziegler method is hard and dense.

Block peat has been carbonised in many districts in heaps, much as with charcoal burning, and also by retort processes with utilization of the waste gases for heating. The most recent plant on this system is the Ziegler ((1) O. K. Zwingenberger, *Eng. and Min. Journ.* 1907, 83, 143; (2) Sankey, *Brit. Assoc.* Sept., 1908) which is being worked on a large scale in Germany and Russia. Air-dried peat is further dried down to 25 per cent. moisture by heat from waste gases, and then completely or half-coked in specially constructed retorts (*Engineering*, November 15, 1907). The following are the yields and composition given by the process:—

	Peat coke, 33 %. Tar, 4–5 %.	Semi-coke, 45–50 %. Tar, 2 %.
Carbon	86–88 %	74 %
Hydrogen	2·0	3·6
Oxygen	5·2–5·5	14·5
Sulphur	0·3	0·2
Calorific value . . .	14,500 B.Th.U.	12,400 B.Th.U.

The by-products are of considerable importance, and the yields for a plant working 35,000 tons of air-dried peat per annum are given from two sources: (1) Zwingenberger, *Eng. and Min. Journ.* 1907, 83, 143; and (2) Captain Sankey, *Brit. Assoc.* September, 1908, from actual results at Beuerberg, Munich.

35,000 tons air-dried peat give—

	(1)	(2)
Peat coke	11,655 tons	13,800 tons
Ammonium sulphate	140 ,,	184 ,,
Calcium acetate	210 ,,	270 ,,
Methyl alcohol	70 ,,	92 ,,
Oils, heavy and light	1240 ,,	1380[1] ,,
Paraffin, solid	117 ,,	230 ,,

[1] Assuming average gravity of 0·85.

The charcoal has proved of value for carburizing armour plate, and the semi-coked peat has been tried as fuel in the German Navy; but although no data can be quoted as to its density, such fuel is unlikely, however carbonized, to prove sufficiently dense to be a useful bunker fuel.

Ekenberg System of Wet Carbonizing.—This process undoubtedly gives by far the best results for the utilization of peat in a solid form, and in combination with a system of gasification gives every promise of rendering available for fuel and power purposes the very large deposits of peat in this and other countries. A large plant on these lines is already in operation near Dumfries.

The great advantages of the process are that the water can be removed by a far smaller expenditure of fuel than by other processes, that briquette blocks of a density but slightly lower than that of coal are obtained, and that the fuel is of good calorific value. The writer found that when blocks averaging $4\frac{7}{8} \times 2\frac{1}{2} \times \frac{3}{4}$ inches were closely packed the weight per cubic foot was 77 lbs., equal to 30 cubic feet per ton, whilst the storage value of coal will approximate to 45 cubic feet per ton. Taking the average calorific value of the dry peat blocks as 11,000 B.Th.U., and of dry coal as 12,500 B.Th.U., the ratio of calorific value per cubic foot of stowage is as 1·3 to 1.

Ekenberg claimed that the pressed material contained only from 8 to 14 per cent. of the original water; but this appears to be a low estimate and certainly unlikely to be attained in practice, the pressed peat on the large scale seldom containing less than 60 per cent. of moisture. The estimated fuel expenditure, measured in terms of calorific value, for the carbonizing process was equal to 15 per cent. of the dry peat substance, whilst an additional 15 per cent. was requisite for the artificial drying of the pressed material, which, together with the briquetting power, made a total demand equal to

37 per cent. of the heat units calculated on the original dry peat. By utilization of sensible heat from the outflowing hot peat for warming the ingoing peat sludge a saving is possible ; and further, where worked in conjunction with gas producers, there will always be a considerable amount of otherwise waste heat, which may be profitably employed for artificial drying; but, as Ekenberg himself realized, the fuel consumption involved will be too high for successful commercial results without some system of by-product recovery, that is, by utilization of his process in conjunction with gasification of a portion of the output, 45 per cent. of the total output being requisite with ammonia recovery to furnish the power necessary for operating the plant, heating the pulp in the carbonizer, etc.

The Ekenberg Process.—The wet peat is passed through a disintegrating machine, and the pulp forced by a sludge pump through the carbonizer at a pressure of from 200 to 300 lbs. per square inch, in some cases even more water being added. The tubes are double, the pulp passing first through the outer space and back in the reverse direction through the inner tube, which is geared for mechanically rotating. About one-half of the whole length of the tube is heated by gas firing, so that the in-going raw peat is warmed up by the outflowing carbonized peat, the raw peat being thus considerably heated before actually passing into the portion of the tubes situated in the heater proper. Undoubtedly the strong exothermic reaction already mentioned when discussing the production of wood charcoal (p. 20) plays an important part in the economy of the process. In the early battery 52 tubes were employed, capable of dealing with 180 tons raw peat in 24 hours.

The carbonized sludge is now filter-pressed, and the cakes may be employed directly in gas producers. If briquettes are to be made, the cubes are further disintegrated, partially dried by waste heat, and finally on bands through a suitable drier from which the material, now containing about 5 per cent. of water, passes to an ordinary briquetting press, such as is largely employed on the Continent for making lignite briquettes. Paraffin-like bodies are developed during the process, which serve as an efficient binding material in the press, no other binding agent being required.

Gasification of Peat.—The working conditions for wet peat containing as much as 60 per cent. of water are now as well known as those for coal, and many makers of producer gas plant are prepared to supply suitable generators of either pressure or suction type. Small plants are in operation in many districts, and one of 4000 H.P. is working at Dammer Moor, Hanover. Large schemes for the generation of power have already been put forward, and extensive development is probable in many peat districts where industries have hitherto been crippled by want of fuel. An important national question may be solved through this means. Sir William Ramsay has pointed out our dependence on foreign supplies of nitrates for the production of military explosives, and the necessity there is for us to produce at least a proportion in this country. As is well known, large quantities of nitrates are now made from the atmosphere by high-tension electric discharges, and for this cheap generation of the electric energy is essential. The Irish peat bogs will probably furnish this energy, and even if not competing in price with foreign supplies of nitrates, will enable them to be produced at a rate sufficiently low to justify the fostering of their home production.

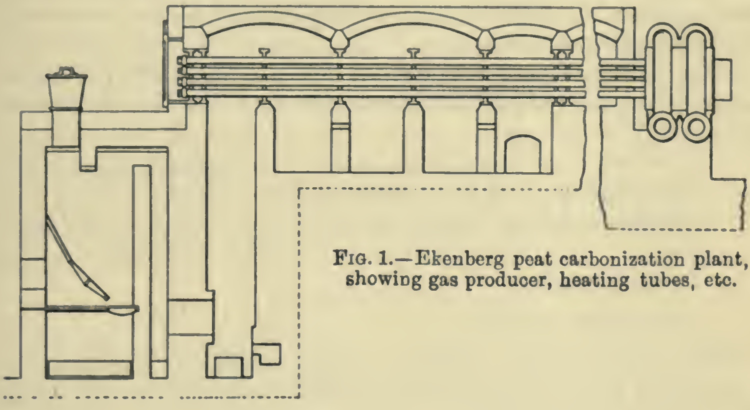

FIG. 1.—Ekenberg peat carbonization plant, showing gas producer, heating tubes, etc.

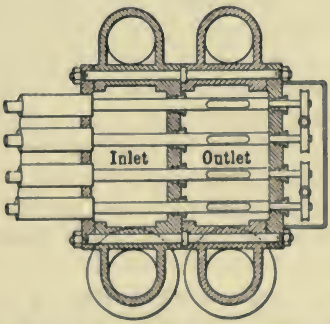

FIG. 2.—Supply and discharge chambers with gearing for rotating tubes.

The gasification of peat is dealt with under the section of Producer Gas (p. 276). Here consideration need be given only to the results already obtained and the economic side of the question. The whole financial success depends in the first place upon obtaining peat economically in a suitably dry condition for the producers, and in the process being practically independent of varying climatic conditions. At present the Ekenberg system is the only one which meets these requirements.

Secondly, the recovery of by-products of highly remunerative character must be carefully provided for, notably sulphate of ammonia and calcium acetate, the profit from these being more than sufficient to cover working costs, leaving the large volume of gas suitable for power purposes as a balance.

The following figures are given on the authority of Mr. Rigby, and are amply supported by other tests made by the Power Gas Corporation and others :—

	Per metric ton (dry peat substance).
Cubic feet of gas at 0° C. and 760 mm.	99,000
Calorific value per cubic foot	157 B.Th.U.
Tar	110 lbs.
Calcium acetate	9 ,,
Ammonium sulphate	165 ,,

From the available results it may be confidently expected that 1 ton of dry peat substance will yield 90,000 cubic feet or over of gas of a calorific value of 140 B.Th.U. per cubic foot.

Taking these figures as a basis, and assuming that a good gas engine will, under varying working loads and everyday running, give an efficiency of 25 per cent., thus requiring 10,180 B.Th.U. per H.P. hour, one ton of theoretically dry peat will be equal to an output of 1240 H.P. hours, or 1·8 lbs. per H.P. hour. High-class modern gas engines, working at or near full load, will require only 8500 B.Th.U. per H.P. hour, and on this basis one ton of dry peat may be expected to give 1480 H.P. hours, equal to 1·51 lbs. per H.P. hour. Converted into electric energy the consumption of dry peat per kilowatt would be therefore about 2 lbs.

The nitrogen in bog peat is very variable, an average figure of 1·6 being usual, although many deposits contain over 3 per cent. The theoretical yield of sulphate from nitrogen is given by—

$$\frac{\text{Molecular wt. of ammonium sulphate (132)}}{\text{Molecular wt. of nitrogen (28)}} \times \text{percentage of nitrogen}$$

The actual yield of course depends largely on working conditions, and over 80 per cent. of the theoretical has been obtained. Working with a peat containing 2·2 per cent. nitrogen, Messrs. Crossley Bros. obtained in their earlier trials 140 lbs. sulphate per ton (= 63 per cent. yield), and later 177 lbs. (= 80 per cent. yield).

The selling price of sulphate of ammonia has ranged between

£12 and £14, and there is no reason to believe that the output will, for many years at least, so increase in relation to the demand as to lower the price appreciably. Taking £12 a ton as the selling price, the average nitrogen present as 1·6 per cent., and the yield as low as 65 per cent., the production of sulphate per ton of dry peat will be 110 lbs., and its value 11*s.* 9*d.* The actual cost of manufacturing sulphate is so well known from gas works and producer gas plants that it may be stated confidently to be under £4 per ton. To this must be added the cost of getting the peat from the bog to the producers, which will be a very variable factor, and about which very little data are available; but it will be clear that under any possible conditions there will be a handsome margin on the working costs derived from the sulphate sales alone, whilst the calcium acetate produced is another asset. Of course it must be remembered that with 90 per cent. of water in the peat some ten tons actually must be excavated and prepared in order to yield the ton of theoretically dry peat on which these figures are necessarily based.

MINOR SOLID FUELS

As these are closely allied to either wood or peat, consisting chiefly of cellulose, they may be considered here conveniently.

Bagasse (*Engineering*, 1910, 89, 197) is a fuel of considerable importance in cane sugar producing countries, and consists of the residual crushed cane after the extraction of the juices. It is usually burnt under boilers, the best results being obtained when over 100 lbs. per hour are burnt per square foot of grate area.

Bagasse contains—

Fibrous material (cellulose) . .	33–50	per cent.
Sugar	7–10	„
Water	32–56	„

Naturally the amount of fibrous material available for fuel is dependent largely on the degree to which the juices are pressed out.

The calorific value of dry bagasse ranges from 4600 cals (8280 B.Th.U.) to 4800 cals. (8650 B.Th.U.), with an ash content of 1·6 to 2·25. The value of the pure combustible approximates very closely to 4750 cals. (8560 B.Th.U.).

Spent Tan.—This will have much the same composition as wood. According to D. M. Myers (*School of Mines Quarterly*, 1910, 31, 116), hemlock tan has the following ultimate composition :—

Carbon	51·8	per cent.
Hydrogen	6·04	„
Oxygen	40·74	„
Ash	1·42	„

The calorific value of air-dried bark is 3150 cals. (5675 B.Th.U.), and of the wet tan 1480 cals. (2665 B.Th.U.), the average moisture being 65 per cent. (Myers).

Spent tan has been successfully employed in suction gas plants.

Nile Sud.—Considerable attention has been given to the utilization of the enormous quantities of grass clumps which at certain seasons are carried down the Nile, it being realized that in a country dependent almost entirely on imported fuel, the application of this sud for fuel purposes is an important economic factor. The material is collected, sun-dried, disintegrated, and finally briquetted. It is claimed that, produced on the banks of the Nile, the fuel is 50 per cent. cheaper than imported fuel.

Town Refuse.—The disposal of the waste material from dust-bins, etc., is an important sanitary problem, and its destruction by burning in suitable "destructors" is not only a satisfactory method from a sanitary point of view, but can generally become remunerative when the heat is utilized for steam raising. As an adjunct to the ordinary boiler plant in electricity generating stations "destructors" have considerably reduced fuel consumption, and with a good type of destructor little nuisance from dust, etc., should be experienced.

Refuse varies considerably in character according to the towns, and with the season; the average amount of combustible matter for London is stated to be about 38 per cent. From numerous evaporation results with "destructors" refuse has a calorific value of about 1200 Calories per kilo (2160 B.Th.U. per lb.), actual evaporations from 1·25 to 3·5 lbs. of water per lb. of refuse having been obtained.

Chapter III

COAL AND ITS CONSTITUENTS

Coal.—There is ample evidence of the vegetable origin of coal, although Donath has put forward the view that, whilst lignites are derived from woody fibre (lignin), bituminous coal is derived from proteids of animal origin, and Bertram and Renault have claimed that Boghead cannel is formed from colonies of gelatinous algæ; but Jeffreys, in a recent paper before the American Academy of Arts and Sciences, conclusively shows it to be built up of the spores of vascular cryptogams (which are of a resinous character). Any mineralized vegetable remains which are capable of combustion may be regarded as coal, but care must be taken to exclude natural bitumens, whatever may be their origin, which are distinguished from coal by the almost complete solubility of their organic constituents in carbon disulphide and similar solvents. Space permits only of the consideration of the probable chemical changes resulting in the production of the principal descriptions of coal.[1]

Composition of Coal.—Coal, when freshly mined, consists of the pure coal substance (the combustible), frequently holding occluded in its pores considerable quantities of inflammable and other gases; mineral matter (or ash), which may in part be derived from the original plant and partly from material deposited amongst the growing or decaying vegetation; and moisture.

For a proper comparison of different classes of coal or coal from different sources, it is necessary to eliminate the accidental and greatly varying constituents, the moisture and ash, so that only the true coal substance is taken into account, although from a commercial point of view the moisture and ash are of great importance.

The elements present in the *combustible* are principally carbon, hydrogen, oxygen and nitrogen, together with small quantities of sulphur and phosphorus. An analysis showing the proportion in which the elements occur is termed an *ultimate analysis*. Just as the

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[1] For a complete consideration of the processes involved in the formation of the coal deposits, the reader is referred to Gibson's excellent treatise on *The Geology of Coal and Coal Mining* (London: Edward Arnold).

ultimate analysis of an organic compound fails to throw light on the actual characters of that compound—indeed, as is well known, compounds of exactly the same ultimate composition often have entirely different properties and therefore constitution—so with coal it does not follow that those having approximately the same *ultimate* composition are conglomerates of the same compounds or have the same properties. In general, however, there is a close connection between ultimate composition and properties.

When coal is subjected to the action of heat in a vessel under such conditions that, whilst any volatile matter resulting from its decomposition may escape, access of air is prevented, gases and liquid products distil off, and a residue of coke, which includes the ash, remains. The results obtained therefore yield the amount of volatile matter, the coke, and, if the latter is finally heated with access of air, the ash alone remains, so that the loss during this latter operation is due to carbon (usually together with a little hydrogen) which remained in the coke and is termed *fixed* carbon. Such an analysis is termed the *proximate analysis*, and although again it gives no information as to the real compounds existing in the coal, it is invaluable from the information it affords as to the character of the coal and its suitability for practical purposes, besides affording the simplest and probably the best method of classifying the various coals.

A general relationship is found between the results of the proximate examination and the ultimate composition, the volatile consttuents being highest when the total carbon is low and the oxygen content high, as occurs with lignites and bituminous coals; whilst with anthracitic coals, where the total carbon is high and the oxygen low, the volatile matter is lower than with any other class of coal.

The general relationship in ultimate and proximate composition of the pure coal substance for typical coals is shown in Table VI.

TABLE VI.

ULTIMATE COMPOSITION OF COAL.

	Carbon.	Hydrogen.	Oxygen and nitrogen.	Fixed carbon.	Volatile matter.
Lignites and brown coals . .	69·5	5·5	25·0	52·0	48·0
Splint coal (Fife)	82·0	5·0	12·8	61·0	39·0
Gas coal (Durham)	85·0	5·5	8·2	66·0	34·0
Coking coal	87·3	5·05	6·9	73·5	26·5
Smokeless steam (Welsh) . .	91·3	4·05	3·9	85·5	14·5
Anthracite (Scotch)	91·1	3·5	4·65	88·5	11·5
Anthracite (Welsh)	91·0	3·9	4·28	93·0	7·0

Broadly speaking, the amount of volatile matter in coal is dependent, then, on the presence of certain bodies rich in oxygen. It does not follow that in two coals of the same ultimate composition the oxygen-containing substances are identical, indeed, as will be shown later, they may probably be of a totally different type, so that it is not surprising that coals identical in ultimate composition behave quite differently under the action of heat, both in the actual yield of volatile constituents and in the character of the coke which results.

Composition of the Coal Substance.—Coal must be regarded as a complex mineral in which the constituent bodies vary not only in composition, but also in the proportions in which they occur. Our knowledge of these bodies is, however, very limited, and much valuable research work remains to be done in elucidating the problem.

Cellulose, $n(C_6H_{10}O_5)$, is the main constituent of plant fibre, and must certainly have been one of the principal parent substances of coal, and the study of the course of its decomposition should throw light upon the possible sequence of changes which have resulted in the production of coal.

In peat bogs bacterial and other agencies are at work bringing about the decomposition of cellulose in a manner probably closely allied to that by which the initial decomposition of this compound was brought about during the earlier stages in the formation of coal, *i.e.* whilst the decaying vegetable matter was at or near the surface. Again, in many lignites the original vegetable structure is so well preserved that they might be expected to throw light on the course of decomposition as far as its earlier stages are concerned. The composition of decaying peat and of lignites has been determined by several observers, and some results are given in Table VII., where in order that the changes may be emphasized, the oxygen and hydrogen are calculated as for 100 parts of carbon.

TABLE VII.

ULTIMATE COMPOSITION OF PEAT AND LIGNITE.

	Carbon.	Hydrogen.	Oxygen and Nitrogen.	Observer.
Cellulose	100	13·9	111·0	
Peat	100	7·85	58·5	Mulder, Einof, Proust, and others
Peat	100	7·50	53·7	
Lignite	100	7·96	46·8	Herz
Lignite	100	7·65	52·7	
Lignite (Khirgis Steppes) . .	100	7·8	54·0	Bramo

These bodies have been termed humic or carbo-humic acids and ulmic and carbo-ulmic acids, but it must not be inferred that they are definite chemical compounds.

That similar changes can be produced in wood has been shown by Stein, who heated it together with water in sealed vessels to various temperatures. Stein's results for 5 hour treatment were as follows:—

Temperature °C.	Carbon.	Hydrogen.	Oxygen.
265	100	6·5	30·9
275	100	6·1	29·0
280	100	5·3	23·6
290	100	4·7	18·3

The decomposition clearly results in the elimination of oxygen and hydrogen, and from the gases evolved during the decomposition and those found occluded in the freshly mined coal, these two elements escaped in association with much of the original carbon as carbon dioxide and hydrocarbons (methane, etc.), and, together, as water.

F. Bergius (*J. S. C. I.* 1913, 463) found on subjecting pure cellulose to a temperature of 340° C. under pressure, a black substance having the composition: C = 84 per cent., H = 5 per cent., O = 11 per cent., was obtained. Peat under these conditions for twenty-four hours yielded a very similar product.

To illustrate the general course of such changes, Percy constructed his well-known table, which, with certain additions, is given below (Table VIII.), in which all figures refer to carbon taken as 100 parts.

TABLE VIII.

Carbon = 100.

	Hydrogen.	Oxygen.	Available hydrogen. $\left(\text{Hydrogen} - \frac{\text{Oxygen}}{8}\right)$
Cellulose, pure	13·9	111·0	0·0
Wood, average	12·0	88·0	1·0
Peat	10·0	57·0	3·0
Lignite (Khirgis Steppes)	7·8	54·0	1·1
Brown coal (Europe)	7·9	36·0	3·4
Lignite (Europe)	6·9	30·0	3·5
Bituminous coal (Staffs.)	6·0	21·0	3·4
Steam coal (Welsh)	5·0	5·5	4·3
Anthracite (Welsh)	4·75	5·2	4·1
Anthracite (Penns.)	2·8	1·8	2·6
Graphite	0·0	0·0	0·0

Whilst such a comparison is useful it really throws little light on the enormous differences in ultimate composition of the great number of coals where metamorphosis has proceeded so far as to have frequently eliminated all traces of vegetable structure. A very large number of factors have undoubtedly contributed to the production of the various coals, among which may be mentioned—

1. Difference in character of the original vegetable matter.
2. Variations in the course of decomposition at or near the surface.
3. Variations in the decomposition after covering under varying geological conditions, such as differences in temperature, time and pressure.

From microscopic examination of thin sections of certain coals and from botanical considerations, it is certain that the bulk of the plants from which the coals were formed were propagated by means of spores, which were of a highly resinous character, and possibly resinous bodies existed in the plant cells themselves. These resinous bodies are far more resistant to decay than the cellulose of the plant, indeed, masses of resin are sometimes found in peat bogs and lignite beds. At moderate temperatures they would undergo destructive distillation, as in the manufacture of turpentine, with the production, first, of complex liquid hydrocarbons, and finally, at higher temperatures, of gaseous hydrocarbons and solid or semi-solid complex products, which would permeate the material resulting from the decomposition of the woody parts of the plant.

Our knowledge of the actual constituent bodies of coal is very slight. With coal of a particular character these are probably both numerous and complex, and when the large number of coals of widely varying properties is considered, it will be seen that this variation of character may arise through the presence of different primary constituents, and through the proportion in which constituents common to the different coals may exist. Microscopic examination in a few cases shows variation in structure to exist, but the application of this method is impossible in the large number of coals, since the thinnest possible sections are opaque. The analytical method appears to be the only one likely to lead to advances, and here the processes seem to be confined to distillation under reduced pressure (although this may not entirely avoid decompositions), and the differential action of solvents on the finely powdered coal.

The most valuable work in this latter direction appears to be that of Smythe, made to the Commissioners of the 1851 Exhibition, whose work is referred to in Bedson's paper on "The Proximate Constituents of Coal" (*J. S. C. I.* 1908, 149). From this paper the condensation of Smythe's results given in Table IX. has been made.

TABLE IX.

SUMMARY OF SMYTHE'S RESULTS.

	Benzene extract (3 % extracted). Re-precipitated by petroleum ether. Treated with ethyl ether.			Chloroform extract (1·8 % extracted). Re-precipitated by petroleum ether.
	Soluble.	Insoluble.		
		Total.	Soluble in acetone.	
Melting-point	135–140° C.	80–83° C.	78–80° C.	94° C.
Carbon	77·2	77·75	79·23	76·45
Hydrogen	8·26	11·77	12·83	9·91
Oxygen	14·54	10·48	7·94	13·64
Approximate constitution	$C_{14}H_{18}O_2$	$C_{10}H_{18}O$	$C_{13}H_{26}O$	$C_{15}H_{24}O_2$

Ether, petroleum ether and acetone yield only very small amounts of extractives.

Smythe also found that by distillation at 8 mm. pressure of the portion of the benzene extract which was insoluble in ethyl ether, and recrystallizing the waxy solid distillate from benzene, and benzene with petroleum ether, a body identical with that from the acetone extract of the same original substance was obtained.

It is important to note that the composition of all Smythe's products practically falls within the limits of that of the various resins examined from peats and lignites, as the following analyses of the latter by several observers show :—

	Maximum.	Minimum	Average.
Carbon	81·47	75·12	78·65
Hydrogen	15·37	8·71	11·36
Oxygen	14·67	6·36	9·88

Pictet and Ramseyer (*Chem. Zeit.*, 1911, 35, 865, 907) with benzene as solvent (or by distillation at 10 mm. pressure) have isolated recently a definite hydrocarbon, hexahydrofluorene, from coal. Other hydro-aromatic substances could not be identified.

Of the many solvents which have been employed those of a basic character, aniline and pyridine, are found to give by far the highest amount of extractive. Resins are composed mainly of acid bodies, and therefore the solvent must combine with these, and, if the product is soluble in excess of the solvent, it will pass into solution, which is proved to be the case by the total nitrogen in the residue and extract considerably exceeding that in the original coal. Pyridine again is not without action on some of the constituents other than resins. The action of pyridine has been investigated by Bedson (*Trans. N. E. Min. Engs.* 1899, 82; *J. S. C. I.* 1902, 233, and 1908, 147), Baker (*Trans. N. E. Min. Engs.*, 1901, 23), Anderson and Henderson (*J. S. C. I.* 1902, 233), A. Wahl (*Compt. Rend.* 1912, 154, 1094). In no case has it been found that the ultimate composition of the extracted bituminous matter approaches that of Smythe's extractives, *i.e.* it does not agree with that of resins.

In this connection it must not be overlooked that the coals examined may have differed materially from those of Smythe. It is highly improbable that with the several coals examined all were free from resins, and therefore in all probability their presence is entirely hidden through the complex nature of the pyridine extract. Further, possible changes in the resinous bodies may have occurred to a greater or less degree.

Whilst by the action of pyridine no definite constituents of coal have been isolated, certain interesting points are established. The extract may amount to over one-third of the total weight of the coal; in certain cases the extract is as high as the volatile matter in the coal, but unfortunately in such cases the volatile matter (if any) in the residue has never been estimated. In a large number of cases the volatile matter in the residue considerably exceeds that in the original coal, which is entirely contrary to what would be expected, and can be ascribed only to pyridine entering into combination with the formation of insoluble compounds.

Of considerable interest and importance is the loss of coking power which feebly-coking coals suffer on pyridine extraction, and the reduction in this property with strongly-coking coals. Closely associated with this is the similar loss of coking properties when many coals are exposed to the action of the air, that is, when certain constituents have been oxidized.

Burgess and Wheeler (*Chem. Soc. Trans.* 1911, 99, 649) have examined the gases evolved from a coal after pyridine extraction and from the extract itself. Whilst the former yielded principally hydrogen, carbon monoxide and carbon dioxide at a temperature of 900° C., the extract gave chiefly paraffin hydrocarbons and hydrogen, the hydrogen increasing as the temperature of distillation was raised. It is tentatively suggested that coal contains two constituents, one easily decomposable and yielding mainly paraffins, extracted by pyridine and derived from resinous bodies, the other more stable, which is derived from the celluloses present in the parent plant.

That coal contains unsaturated compounds is shown by its property of absorbing oxygen, and by its absorption of bromine and iodine in a manner similar to the absorption taking place with oxidizable natural oils.

W. Carrick Anderson (*Proc. Glas. Phil. Soc.* 29, 72) and Anderson and J. Roberts (*J. S. C. I.* 1898, 1013) examined exhaustively the coals from the Clyde basin, more especially with a view to determining the cause of coking. They found that by extraction with 5 per cent. potash solution the long flame splint and gas coals lost their normal feeble coherence on heating, in each case the potash being more or less coloured brown, whilst it had little effect on the coking power of good coking coals, and was only faintly coloured.

On heating to about 300° C. in an atmosphere of carbon dioxide, in order to prevent oxidation, coals yielding slightly coherent cokes lose their coking power, whilst with strongly-coking coals this power is somewhat reduced. On treating the powdered coals with dilute nitric acid (1·2), evaporating to dryness, dissolving the residue in ammonia and re-precipitating by hydrochloric acid, they obtained substances of fairly uniform composition from a number of coals, which substances invariably contained nearly three times the nitrogen present in the parent coal. Taking now a coal giving coke of feeble coherence, this was heated to 300° C. in carbon dioxide, when the residue lost its cohering property, and on nitric acid treatment yielded "coal acid," identical in composition with that from the raw coal.

The inference drawn by Anderson from his results is that there is present in feebly-coking coals a resinoid body to which they owe their properties, this body being soluble in potash and volatile at 300° C., whilst in good coking coals there is a nitrogenous oxidizable substance to which coking is primarily due. No consideration is given to the possibility of the latter being nitro-derivatives of some of the aromatic bodies undoubtedly present in all coals, and not being a nitrogen compound existing in the raw coal itself.

Boudouard (*Compt. Rend.* 1908, **147**, 986) has examined the extracts obtained from coals by treatment with 5 per cent. and 25 per cent. potash, using raw coal, coal extracted with alcohol, and after nitric acid oxidation. The results of analyses showed the following range:—

Carbon	52–67 per cent.
Hydrogen	3–5 „
Oxygen	30–44 „

A comparison of these figures with those for resins (p. 30) will show that they are of an entirely different character, and more of a "humic" or "ulmic" character, *i.e.* degradation products of cellulose, etc.

Later (*Compt. Rend.* 1909, **148**, 348), Boudouard describes the action of several reagents, and draws the conclusion that the coking power is due to complex condensation products of celluloses, and that the humic acid found in non-coking coals is the result of their further oxidation. Where oxidation has proceeded to completion, as in anthracite, humic acid is no longer present.

It will be seen that the results are very inconclusive as regards the probable constitution of the complex body, coal, and that the subject offers a valuable field for research. It is hoped that the above condensation of the principal work of those who have experimented in this direction may stimulate others and serve as some guide. At present we may conclude that the various classes of coal owe their distinctive properties to variation in the proportion, in some cases to the entire absence, of constituents of the following classes:—

1. Carbonaceous residues incapable of any considerable further change (probably form the bulk of anthracites).
2. Degradation products of celluloses, including "humic acid," or capable of oxidation to "humic acid."
3. Unaltered or slightly altered resinous bodies, easily decomposed or volatilized at moderate temperatures.
4. Oxidation products of resins.
5. Destructive distillation products of resins, principally solid hydrocarbons and possibly free carbon residues.

Moisture in Coal.—The moisture in coal may be divided into accidental moisture, and the moisture due to the hygroscopic properties of the coal itself. Thus an oven-dried coal will again absorb moisture up to a certain limit, or a wet ground coal exposed to the air will lose water down to a certain limit. Lignites and brown coals frequently contain from 30 to 45 per cent. of moisture as mined, and, even in summer, on exposure to air retain frequently 20 per cent., in this respect resembling wood. Ordinary coals may contain from 1 to 4 per cent. after air-drying.

High moisture is of course prejudicial to the buyer: it is paid for and transported at fuel prices, it adversely affects the coal in the furnace by chilling the fire, so giving greater chances for smoke to form, and it demands heat for its vaporization. This latter loss seldom needs to be taken into account, for as is shown later (p. 347), even under poor conditions of flue gas temperature it approximately amounts to 0·1 per cent. of the total calorific value for each per cent. of moisture.

Ash in Coal.—The mineral matter is derived in part from that present in the original vegetable substance, in part from material carried by flood water, etc., amongst the decaying vegetable matter, and may also be due partly to shale, etc., derived from the strata adjacent to the coal seam, which it has been impracticable to remove by picking or washing, even where this has been attempted

Ash is inert material in the coal; it is valueless mineral matter paid for at coal prices, and in addition may detract seriously from the value of the coal by choking the air passage through the grate, thus lowering the rate of combustion and the output of the boiler; frequent cleaning of the fires is necessary with the accompanying losses through open fire doors; the loss of carbon carried through into the ash pit may be considerable; it causes deposits in tubes and flues, and in addition, if of a fusible character, is especially troublesome through the formation of clinker. In producer gas practice this is a serious question, and coals otherwise suitable may be unworkable except with such excessive steam supply that the efficiency is adversely affected.

The ash of coal is seldom below 1 per cent.; up to 5 per cent. quite usual, and not infrequently it amounts to 10 or 12 per cent. With coal from a given seam it is usually considerably higher in the small sizes, due to the easy separation of pure lump coal with the corresponding concentration of mineral matter into the smaller stuff. The following results with an American anthracite [1] strikingly illustrate this point.

Description.	Screening.		Ash on dry coal.
	Passed through.	Passed over.	
	in.	in.	
Egg	2·5	1·75	5·82
Stove	1·75	1·25	10·30
Chestnut	1·25	0·75	13·00
Pea	0·75	0·50	15·05
Buckwheat	0·50	0·25	17·10

With infusible ash, the value of two coals of similar character will be fairly proportional to their relative ash content, but it is quite otherwise if one gives a fusible and the other an infusible ash. A low ash content of a fusible character may be far more detrimental than a high ash of infusible character.

Essentially the ash consists of silicate of alumina together with the basic oxides lime (CaO), magnesia (MgO), and iron (Fe_2O_3), together with traces of sulphates, carbonates and phosphates. Wood ashes are characterized by the presence of high proportions of alkalies, potash (K_2O), and soda (Na_2O), in combination with carbonic acid, with little or no alumina. Peat ash contains a high percentage of lime and a little alumina. Coal ash is characterized largely, then, by the high percentage of alumina which is present. It may be noted that alumina as a constituent occurs in any quantity only in those

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[1] *Trans. Amer. Inst. Min. Engs.* **24**, 720.

plants existing to-day which are allied to those of the coal formations. Silicate of alumina (clay), however, would be the principal substance carried amongst the decaying vegetable matter when in a partially submerged state, judging by the usual shale beds accompanying the coal seams.

Although the composition of wood and peat ash varies over wide limits, the examples given in Table X. will serve for a comparison with the coke ashes.

TABLE X.

Principal Constituents of the Ashes of Pine, Peat, and Coke.

	Pinus sylvestris (Bottinger)	Peat (Ronalds).	Coke (Warwick).		
			Non-clinkering.	Fair.	Clinkering.
Silica, SiO_2	3·04	16·25	54·67	46·23	46·40
Alumina, Al_2O_3	—	2·80	41·95	31·93	16·45
Ferric oxide, Fe_2O_3	1·67	6·34	trace	14·54	18·15
Lime, CaO	31·36	34·79	1·82	5·04	11·80
Magnesia, MgO	19·76	3·60	1·46	2·26	4·63
Potash, K_2O	2·79	3·56	—	—	—
Soda, Na_2O	15·99	0·37	—	—	—

Whilst it is impossible to correlate composition of the ash with clinkering property, it is certain that the nearer the composition approaches that of aluminium silicate ($Al_2O_3.2SiO_2$; $Al_2O_3 = 45·8$ per cent., $SiO_2 = 54·2$ per cent.), the more infusible it will be; that on replacement of part of the alumina by other bases, such as lime and magnesia, and more particularly iron oxide, the more easily fusible will it become, due to the formation of double silicates, which are far more fusible than the simple ones.

A red ash, arising from the presence of iron oxide, is justly regarded as a bad indication from the point of view of fusibility. A red ash is indicative also of a fair percentage of iron pyrites (FeS_2), which on heating in contact with air loses sulphur as the dioxide and is converted into ferric oxide. High sulphur may, however, be present without the ash being red if the sulphur is in organic combination.

Combined Oxygen in Coal.—In a United States Geological Survey Bulletin, 1909, White deals with the effect of oxygen in coal, and shows that it has nearly as bad an anti-calorific effect as ash, that is, dry coals of the same total carbon, but with high oxygen and low ash will have nearly the same calorific value as coal where these constituents are in the reverse proportion, high ash and low oxygen.

The efficiency of coals will, therefore, agree approximately to the order of the ratio of the carbon to the oxygen plus ash, the average variation being about 1 per cent.

Nitrogen in Coal.—It is unusual to find less than 1 per cent. of nitrogen in the coals of this country or more than 2·5 per cent.; indeed, it is exceptional to find a coal giving such a high figure, and the average will lie between 1·3 and 1·5 for the bituminous coals. The nitrogen content of anthracite and semi-anthracite coals is of small importance, consequently very few data are available, the nitrogen and oxygen being grouped together in most analyses. It is stated to be lower than with bituminous coals.

Although the amount of nitrogen is small its economic importance cannot be over-estimated. It is from this source that practically all the ammonia salts of commerce are derived, and the formation of ammonium sulphate in gas-producer plants is an important factor in their economical operation. By the ordinary distillation of coal in retorts or coke ovens about 15 per cent. of the nitrogen is evolved as ammonia, accompanied by small quantities of cyanogen and other compounds; a small quantity appears in the tar, mainly as bases such as pyridine, but usually 50 per cent. remains in the coke. The recovery of most of this residual nitrogen is a problem which may be solved by gasification of the coke, otherwise it is wasted, which is the usual but unsatisfactory course. It is evident that certain of the nitrogen compounds are very stable, since they do not break down at the high temperatures of the gas retort.

Sulphur in Coal.—This element is found to about the same extent as nitrogen, viz. 0·5 to 2·5 per cent. It occurs in three forms: in pyrites in combination with iron as FeS_2, which on heating under oxidizing conditions becomes iron oxide (Fe_2O_3) with liberation of sulphur dioxide; as organic sulphur compounds, from which the sulphur compounds in tar and gas are mainly derived; as sulphates, principally calcium sulphate ($CaSO_4$), forming a constituent of the ash. In some cases it is desirable to distinguish between the fixed sulphur (occurring in the coke) and volatile sulphur.

Sulphur is of great importance in fuels, especially those used for metallurgical purposes, since it may pass into the metal under treatment. Pyrites loses part of its sulphur by distillation on strongly heating, hence, when raw coal containing pyrites is burnt part of the sulphur set free may be absorbed by the grate bars, and since the sulphide of iron formed is comparatively fusible, may give rise to serious trouble, whilst, if the sulphur be burnt to sulphur dioxide, serious corrosion of copper tubes, etc., with which the gases come in contact may occur.

When coal containing sulphur is distilled in retorts or coke ovens the sulphur found in the coke is always somewhat less than in the coal, the actual loss probably being dependent mainly on the organic sulphur compounds present. Pyrites also may lose some of its sulphur, becoming the iron mono-sulphide (FeS), and calcium sulphate may be reduced by contact with the hot carbon to the sulphide. In the majority of cases the coke will still contain over 80 per cent. of the original sulphur of the coal, and this residual sulphur may not be as objectionable in its altered condition of combination. It is quite conceivable that pyrites gives off elementary sulphur vapour which is readily absorbed by iron or other metal, but that iron sulphide loses sulphur only as the dioxide which may have little effect on the metal.

Numerous processes have been proposed for the further reduction of the sulphur left in the coke, but the most satisfactory method is that of washing the crushed coal, when a fair proportion of the pyrites may be mechanically separated (see p. 70).

Iron pyrites has been credited with the main responsibility for the spontaneous ignition of coal, but little importance is now attached to this theory. The question is fully discussed later.

Some discussion has arisen as to whether sulphur present in pyrites should be regarded as a heat-giving constituent in fuels, an important consideration when the calorific value is calculated from the elementary composition. Whilst calcium sulphate cannot undergo combustion, sulphur in organic combination and as pyrites may do so and add to the calorific value. Lord (*Trans. Amer. Inst. Min. Eng.* 1897, 27, p. 960) investigated the question, and concluded that practically the iron and sulphur give nearly the same heat as when burned in the free condition, and therefore the calorific effect of sulphur should find a place in formulæ used in such calculations.

Phosphorus and Arsenic.—These two elements occur in coal and coke in small quantities. They are of no importance where the fuel is used for power purposes, but both are highly objectionable if present in anything more than traces in metallurgical fuels—phosphorus more particularly in the metallurgy of iron, and both in the case of copper. Arsenic, again, in fuels used for malting has been proved to contaminate the malt, on which it is deposited by volatilization; especially is this the case where gas coke has been employed.

Wood, Smith, and Jenks (*J. S. C. I.* 1901, 437) give the following proportions of fixed and volatile arsenic:—

	Grains per lb. of fuel.	
	Volatile Arsenic.	Fixed Arsenic.
Anthracite	1/250	1/35
Coke breeze	1/90	1/2
Gas coke	1/45	1/2

Chapman (*Analyst*, 1901, 26, 253) gives the following for the arsenic in six coals and in the coke prepared from them :—

Grains per lb.		Grains per lb.	
In coal.	In coke.	In coal.	In coke.
1·4	1·7	0·7	0·6
0·5	0·7	0·9	1·1
0·7	1·0	0·8	0·6

Gases in Coal.—In addition to the solid constituents coal contains occluded gases, principally nitrogen, oxygen, carbon dioxide, and saturated hydrocarbons, of which methane forms by far the largest proportion. Carbon monoxide also is sometimes present in small quantities.

The quantity and composition of these gases have been investigated by a large number of observers, notably E. V. Meyer, Thomas (*Journ. Chem. Soc.* 1875, 28, 793; 1876, 29, 144), Bedson and McConnel (*Trans. Fed. Inst. Min. Eng.* 1892, 307), Trobridge (*J. S. C. I.* 1906, 25, 1129), and Porter and Ovitz (*U.S. Bureau of Mines, Technical Paper*, 2, 1911).

Obviously these gases are of great importance, the evolution of such a highly inflammable gas as methane rendering seams in which it occurs "fiery" and extremely dangerous; but although the coal from such seams yields a large quantity of methane, the outbursts of this gas which cause such unfortunate disasters are due more particularly to gas confined in hollows and other spaces under pressure rather than to that which diffuses only slowly from its occluded state, or is generated by decomposition in the coal substance. With bunker explosions, however, the occluded or generated gas must be the cause of the trouble, since any large pockets of gas are out of the question. Porter and Ovitz (*loc. cit.*) found that with coals of a bituminous and semi-bituminous character obtained from dangerous mines the methane escaped rapidly at first, that its escape ceased in from 3 to 18 months, that during crushing of the sample the methane escaping equalled 25 per cent. of the volume of the coal, and that from 50 to 150 per cent. escaped on continued exposure. The maximum evolution was found where 27 lbs. of coal gave 0·6 cubic feet of methane in 1 year 5 months.

This evolution of methane from broken coal over a period of months is clearly against the gas being retained in pores under pressure, and is not wholly in agreement with the occlusion theory. It seems obvious that methane must be generated by decompositions still proceeding in the coal; that the compounds giving rise to these decompositions are limited in amount and soon become exhausted; that the amount of such compounds present will vary with different coals, and, consequently, their liability to generate dangerous gases.

Occluded gas from decompositions prior to mining and methane generated after are together responsible in varying degree for the hydrocarbon gases evolved.

That great variation in the quantity of gas and its composition should be found in the results by different observers would be expected. The course of decomposition leading to the coal formation is unlikely to have always been the same, the porosity of the coals varies widely, and also the conditions under which the sample was crushed and exposed to the air. Freshly cut coal rapidly absorbs oxygen and nitrogen from the air, the former the more rapidly, and, if the temperature does not rise much above 100° C., with formation of little carbon dioxide. The examination of the gases from coal necessitates crushing, hence absorption of oxygen and nitrogen, and the quantity of these gases obtained afterwards by exhaustion is probably due almost entirely to this absorption, the carbon dioxide and methane being the principal natural gases occluded.

Table XI. gives two results obtained by Trobridge; three separate analyses are given, (*a*) of the last portions of air during exhaustion of the apparatus, (*b*) the gases evolved at ordinary temperatures, (*c*) the gases obtained on heating the coal at 100° C.

TABLE XI.

GASES IN COAL (Trobridge).

Coal.		Vol. of gas in c.c. per 100 gr. coal.	Oxygen.	Nitrogen.	Carbon dioxide.	Carbon monoxide.	Paraffin hydrocarbons.
Busty seam (Durham)	(*a*)	—	22·5	58·4	3·0	—	16·1
	(*b*)	21·6	3·2	35·7	7·0	0·7	53·4
	(*c*)	139·0	0·3	1·0	4·0	0·8	93·9
Fernio coal (British Columbia) . . .	(*a*)	—	10·6	73·3	7·5	0·0	8·6
	(*b*)	22·2	7·2	57·1	10·5	0·9	24·3
	(*c*)	23·1	1·0	2·6	35·4	7·9	52·7

Classification of Coal.—The satisfactory classification of coal offers numerous difficulties, and no really good system has so far been elaborated. Until something more definite is known of the constituent bodies, resins, humus, etc., it is unlikely that any great advance will be made. It is well known that pure chemical compounds exhibit isomerism, *i.e.* whilst having the same percentage composition exhibit entirely different properties. Although coal is not a definite compound, the same condition is found. Anderson has pointed out that the splint coals from the Clyde basin are frequently almost identical in composition with the softer coals of the same district, and instances might be multiplied; variations not only in the external physical characters but in the other properties, notably that of caking, are found with coals of practically the same ultimate composition. There is further the gradual change of character from coal of one class to that of another; the agreement in one constituent and disagreement in others, so that hard and fast boundaries are impossible—if they are proposed they are purely arbitrary.

Classification based on commercial application is far too general, with bituminous coals it is not uncommon to find one equally useful, and described as "steam, gas or manufacturing."

For any system of classification it is essential that the combustible substance alone is considered—the great variables, ash and moisture, must be eliminated. From the proximate analysis there is no difficulty in differentiating between anthracites and semi-anthracites, semi-bituminous coals and the large class of bituminous coals, but it is just with this last and most general class that the proximate analysis fails. Further, the ultimate composition for the former classes can be correlated roughly with the proximate analysis, since the volatile matter appears to be dependent mainly on oxygen-containing compounds; but again this is impossible with the more bituminous coals.

Every possible ratio of the principal elementary constituents, carbon, hydrogen and oxygen, has been suggested. The United States Geological Survey (1902) adopted the simple carbon-hydrogen ratio after considering all other systems. No attempt at nomenclature was made, but the combustible carbonaceous bodies from wood to graphite were divided into twelve groups, the limit for several of them being only tentatively suggested. On attempting to apply this system to the large number of English coals in Table XVII. the results were not satisfactory.

Seyler has elaborated what is certainly the most scientific system at present on certain defined limits to the carbon and hydrogen. Below 84 per cent. (lignitious coals) the genus is sub-divided entirely on the carbon, whilst above this figure five genera are distinguished by the hydrogen content, as shown in Table XII.

TABLE XII.

CLASSIFICATION OF COALS (Seyler).

Genus.	Hydrogen.	Approximate volatile matter.	Typical coals.
Anthracite	Below 4%	Below 10%	Anthracite.
Carbonaceous	4·0–4·5	10–16	Smokeless steam.
Semi-bituminous . . .	4·5–5·0	16–24	Navigation (bunker).
Bituminous	5·0–5·8	Over 24	Gas, steam, etc.
Per-bituminous . . .	Over 5·8	—	Long flame steam, etc.

Seyler further sub-divides the genera into species, bituminous into semi-bituminous, sub-meta-bituminous, sub-ortho-bituminous, and sub-para-bituminous, these species being dependent on the amount of carbon, the hydrogen being the same for the whole genus.

It is seldom necessary in practice to make the ultimate analysis of a coal, so that any satisfactory system based on the proximate analysis offers obvious advantages. The ratio of the fixed carbon to the volatile combustible matter, termed the "fuel ratio," has been used somewhat widely, but except for highly carbonaceous coals is of little value.

Whilst the ultimate composition and proximate composition cannot be strictly correlated, there is a general agreement such that it is possible to assign a fairly definite range for each with coals of certain common characteristics, though hard and fast lines cannot be drawn. Grüner appears to have been the first to attempt a classification on these lines for bituminous and semi-bituminous coals, and with some modifications his table is most generally used.

From a study of the classical researches of Scheurer-Kestner and Meunier-Dolfus (1868) on the composition and heating power of European coals, Grüner concluded that the real value of a coal was indicated by the proximate better than by the ultimate analysis; but this, convenient as it would be, is not the case. Further, he believed that the heating power was proportional to the fixed carbon, but this latter contention cannot now be maintained. Grüner divided the bituminous and semi-bituminous coals into five classes, the character and composition of the coals and of the cokes obtained from them being given in Table XIII.

TABLE XIII.

GRÜNER'S CLASSIFICATION OF BITUMINOUS COALS.

No. of class.	Character of coal.	Carbon.	Hydrogen.	Oxygen.	Ratio $\frac{O}{H}$	Volatile matter.	Nature of coke.
I.	Dry, long flame, non-caking	75–80	4·5–5·5	15–19·5	4–3	40–50	Powdery or slightly coherent.
II.	Fat, long flame	80–85	5·0–5·8	10–14·2	3–2	32–40	Caked, but friable.
III.	Fat, properly so called	84–89	5·0–5·5	5·5–11·0	2–1	26–32	Caked, moderately compact.
IV.	Fat, short flame	88–91	4·5–5·5	4·5–6·5	1	18–26	Caked, very compact, lustrous.
V.	Lean coals—anthracite	90–93	4·0–4·5	3–5·5	1	10–18	Powdery or slightly coherent.

It is at once apparent that Grüner's classes must be extended to include on the one hand the anthracite, and on the other hand such coals as those of a character between the true lignites and bituminous coals. Again, the range of composition for a class is not wholly consistent with that of this class as found in Great Britain, neither is the terminology best suited for a general classification. For these reasons the author has extended and modified Grüner's Table (XIV.).

TABLE XIV.

Grüner Classification modified for Coals of Great Britain.

No. of class.		Name of class.	Carbon.	Hydrogen.	Oxygen.	Volatile matter.
I.		Lignitious	75–80	4·8–5·5	12–20	35–47
II.		Ligno-bituminous	78–84	4·5–6	8–13·5	35–45
III.	Bituminous.	Long flame, non-caking (steam, etc.)	82–86	5–6	6–12	30–40
IV.		Long flame, partly caking (gas)	82–86	4·5–5·5	5–9	30–40
V.		Short flame (coking)	85–89	4·5–5·5	4–7·5	20–30
VI.		Semi-bituminous	89–92	4–5	2–4·5	13–20
VII.		Semi-anthracite	91–93	3–4·5	3–5	8–13
VIII.		Anthracite	over 92·5	below 4	below 3	below 8

It must again be emphasized that no such system can be rigid; for example, a gas coal towards the lower limit of volatile matter may be satisfactorily worked for coke in a suitable oven, and a semi-bituminous caking coal may be equally good for coking whilst not so well suited for burning owing to its caking properties.

CHAPTER IV

COMMERCIAL VARIETIES OF COAL

LIGNITE

Nature and Occurrence of Lignite.—Reference has been made already to the intermediate position which lignites occupy naturally between peat and coal. Lignites vary very widely in character and composition according to the metamorphosis which the lignin of the plant has undergone, from bituminous wood to material so closely resembling "dry" bituminous coal that it is difficult, if not impossible, to distinguish between them. They are characteristic of strata more recent than that of the true coal formations, but frequently have become so altered by local conditions as to merge into bituminous coals or even semi-coked material resembling anthracite.

Lignites are of no importance in the British Isles, but are important fuels in parts of India, the colonies, and most European countries. In Victoria, Australia, a lignite bed 100 feet thick is found; in Canada it is the most important fuel deposit, Manitoba alone having deposits estimated to cover 60,000 square miles; in New Zealand again, lignites form the principal fuel deposits.

Lignites are classified by their physical characters: those retaining their woody structure and usually dark brown in colour, as "fibrous"; powdery, soft lignite, "earthy"; hard compact masses, "brown coal," the latter passing imperceptibly into blacker varieties closely akin to bituminous coals, and frequently having a conchoidal fracture, from which they receive the name of "pitch coal." Jet is a form of lignite.

As mined, lignite usually contains a very high percentage of moisture, much of which is retained on air-drying; Bischoff records an average of 44 per cent. on German lignite; Schrötter 57 per cent. on Austrian samples. The ash varies over a wide range, depending chiefly on foreign material washed among the decaying vegetable matter, and the amount is frequently so great as to preclude the use of the material except in gas producers or by distillation for tar oils, etc.

Composition of Lignite.—So many carbonaceous fuels of distinctly vegetable characters are classed as lignites, frequently on their geological occurrence, that it is extremely difficult to state an approximate composition. In one table of the composition of lignites the two following analyses are included (corrected to the pure combustible):—

Carbon.	Hydrogen.	Oxygen.	Volatile hydrocarbons.
55·9	6·48	37·62	46·3
89·5	3·87	6·63	12·65

With bodies so utterly divergent in composition the only satisfactory way of ascertaining the probable range for true lignites is that of analysis of a large number of results, and in Table XV. a classification is made from 62 analyses of European samples.

TABLE XV.

Composition of Lignites (European). (Calculated on the pure combustible.)

Range of Carbon.	No. of samples.	Carbon per cent.		Hydrogen per cent.		Oxygen per cent.	
Below 60 per cent. . . .	5	57·1	59·2 55·1	5·79	6·07 5·07	37·11	38·93 34·78
60–65 per cent.	8	63·3	64·8 62·0	5·61	6·58 4·71	31·09	32·52 29·20
65–70 ,, ...	25	67·1	70·0 65·2	5·52	6·66 4·85	27·38	29·66 24·96
70–75 ,, ...	19	72·6	75·0 70·6	5·83	7·42 4·64	21·57	24·00 18·16
75–80 ,, ...	2	76·3	76·6 76·0	7·29	8·27 6·32	16·41	17·68 15·15
Above 80 ,, ...	3	84·4	86·6 82·2	5·40	6·64 3·95	10·20	13·16 8·96

Note.—In all tables where the composition of fuels is given as above, the mean figures are shown in larger type, and the maximum and minimum figures in small type.

It will be seen that over 90 per cent. of the samples in Table XV. contain under 75 per cent. of carbon and over 20 per cent. of oxygen. The last three have a composition in good agreement with a large number of English coals (for which the term "lignitious" or "lignobituminous" has been suggested). Since classification based on geological evidence is evidently capable of including totally dissimilar fuels, it is suggested that the alternative, classification on composition, would be more satisfactory, lignites proper containing under 75 per cent. of carbon and over 20 per cent. of oxygen. The small class containing carbon between 75–80 per cent. differ from the suggested "lignitious coals" of Table XV. only in containing over 6 per cent. of hydrogen, and, to harmonize with the general scheme, this small class of infrequent occurrence might well be termed "semi-lignites." The classification would then become :—

		Carbon.	Hydrogen.	Oxygen.
Lignites	Lignites	under 75%		over 20%
	Semi-lignites	75–80	over 6	12–20
Coals	Lignitious coals	75–80	4·8–5·5	12–20
	Ligno-bituminous	78–84	4·5–6·0	8–13·5

The volatile hydrocarbons of lignites falling within the above range are seldom less than 48 per cent.; they usually exceed 50 per cent., but in a large number of cases the ratio of volatile hydrocarbons to fixed carbon is approximately 1 to 1.

Chemical tests have been suggested for differentiating between lignites and coals. Lignite is said to impart a brown colour on boiling with a solution of potassium hydroxide (caustic potash), whilst coal gives no colour. Muck has pointed out that all lignites do not colour the solution, and reference has already been made to the work of Anderson and Roberts, who showed that all the coals examined by them with this reagent coloured it brown, so this test is obviously worthless. Donath and Ditz (abs. *J. S. C. I.* 1903, 921) suggest boiling with nitric acid (sp. gr. 1·055) when lignite is strongly attacked but not coal. They claim that in mixtures containing 10 per cent. of bituminous coal or 5 per cent. of lignite, distinction can be made.

Calorific Value of Lignite.—This will be dependent to a very large extent upon the closeness or remoteness of its composition in relation to wood on the one hand and lignitious coals on the other, and to the amount of moisture and ash present. In practice this excessive moisture entails great loss of heat units by its vaporization.

The calorific value of the combustible may range from 5000 to 7600 calories (9000 B.Th.U. to 13,880 B.Th.U.).

Lignite as Fuel.—The amount of moisture and ash generally present makes lignite an inferior fuel, and many brown coals are simply submitted to distillation for the tar products. Where the percentage of combustible matter is high, lignite may be efficiently used for steam-raising, some Continental electric light stations being run on it, and it is also used on the Italian railways.

Lignite (brown coal) is converted into briquettes on the Continent; in 1909 there were 900 plants for this purpose in Europe. According to C. L. Wright (*U.S. Bureau of Mines, Bull.* 14, 1911) the amount of matter soluble in carbon disulphide is a good guide to the briquetting properties. Under 1·4 per cent. the material would not bind; between 1·4 and 1·5 per cent. it was difficult, and the results in practice doubtful; with over 1·5 per cent. the material gave good 1 lb. blocks at a pressure of 20,000 lbs. per square inch.

Lignite has been employed very successfully in gas producers for metallurgical purposes, and rapid developments have been made in recent years in its application to power. The amount of nitrogen present is about the same as in coal, so that with ammonia recovery very economic use will doubtless be made of the large deposits found in the British Dominions. Tests made in the United States (*U.S. Geol. Survey*, *Bull.* 416, 1910) gave the following average over 18 tests, the results being calculated to the dry material:—

B.Th.U. per lb.	Lbs. per sq. ft. of fuel bed.	Lbs. per B.H.P.	Cubic ft. of gas per lb.	B.Th.U. per cub. ft.
11,290	9·13	1·63	45·7	158·4

Taken on the average moisture (26·6 per cent.), 2 lbs. of lignite as delivered were required per B.H.P.

CANNEL COAL

This variety of coal differs in character from the lignites and true bituminous coals, and the organic matter from which it was derived differed no doubt from that from which the other varieties were produced. According to Bertrand and Renault, boghead cannels are composed mainly of gelatinous algæ; but Jeffrey disputes this, and contends that they are composed mainly of the spores of vascular cryptogams. Fish and other animal remains are found frequently with cannel coals, which, together with the usual form of deposition in beds thinning right out at the edges, indicates that they were deposited from fairly stagnant water.

Cannel coal has been of great importance in the manufacture of gas, since on distillation it gives a good gas yield of exceptionally high candle power; hence, when illuminating value was of far more importance than it is now, owing to the introduction of the incandescent mantle, cannel was commonly used with ordinary gas coal to give the necessary illuminating power, but naturally this application has greatly declined. It derives its name from the candle-like flames emitted on burning; some varieties split with a crackling noise on heating, and are termed "parrot" coals; others, from the odour emitted on burning, as "horn" coal. A variety of coal-like material known as boghead cannel or Torbane mineral is generally regarded in this country as a species of cannel, but on the Continent it is not admitted to be a coal. It is characterized by a high percentage of hydrogen, a very high yield of volatile hydrocarbons, and exceptionally high ash. Excepting even these boghead coals the proximate and ultimate constituents vary within such wide limits that it is impossible to correlate properties and composition, but clearly there are certain bodies present in cannels which on destructive distillation yield a much higher proportion of relatively stable gaseous hydrocarbons than is the case with ordinary bituminous coals. The following Table XVI. shows the ultimate and proximate composition of the combustible constituents of typical boghead and cannel coals :—

TABLE XVI.

COMPOSITION OF BOGHEAD AND CANNEL COALS.

	Total carbon.	Hydrogen.	Oxygen.	Fixed carbon.	Volatile hydrocarbons.	Ash on dry coal.
Boghead cannel (Torbane Hill)	78·1	10·43	11·47	12·2	87·8	33·0
St. Helens	79·0	6·05	14·97	47·25	52·75	3·05
Wigan	82·4	5·70	11·90	—	—	2·70

The proportion of volatile hydrocarbons to the "fixed carbon" usually is high (50–50), but there are many exceptions in which this ratio is no higher than in an ordinary bituminous coal (33–66). Lesmahagow cannel is frequently taken as a standard of comparison for gas-making purposes, and from various authorities the ratio of the above proximate constituents on the pure combustible is—

Volatile hydrocarbons	54–56 per cent.
Fixed carbon	44–46 „

BITUMINOUS COALS

It has been shown that the amount of volatile hydrocarbons present in the coal substance is the principal determining factor on the properties of the coal, and affords the most useful basis of classification. The volatile hydrocarbons consequently govern largely the character of the combustion, determine its suitability for special purposes, and the design of grates and furnaces for the most efficient combustion of the different classes of coal.

Flame is produced entirely by the combustion of these distillation products, which form a mixture of hydrocarbon gases and vapours, complex tarry vapours, etc. Smoke results entirely from their incomplete combustion. It follows that the proportion of the total heating units of a coal derived from combustion on the grate and in the combustion spaces respectively vary with the amount of volatile matter. Dr. Schniewind estimates that in a coking coal 72 per cent. of the heat units are available in the coke, 23 per cent. in the gases, and 5 per cent. in the tar. For bituminous coals it may be taken approximately that one-third of the heat units are present in the volatile hydrocarbons. Owing, however, to variation in composition of the volatile matter, its heating value is not always proportional to the amount in different coals.

Where intense local heating is required, it follows that a fuel with little volatile matter must be employed, such as anthracite; whereas, on the other hand, where long flame is essential, as in a reverberatory furnace, the proportion of volatile matter, which provides the necessary combustible gases, must be high; that is, the greatest number of heat units possible must be obtained away from the grate. For steam-raising these considerations obviously will govern the relationship between grate area and combustion space, the admission of air above and below the grate, for the best results to be obtained for coal of a given type.

For steam-raising then, although high calorific value is essential, other considerations are equally important, and these depend largely on the amount of volatile constituents. The effect of ash and moisture has already been dealt with. The ignition point of coals low in volatile matter is high (p. 5), and generally the rate of combustion is low, so that strong draught is necessary; bituminous non-coking coal ignites easily, and burns readily with moderate draught.

Constam and Schläpfer have investigated the influence of volatile constituents on combustion (see *Eng.* 1909, xc. 93), and found that coals containing about 20 per cent. (calculated on the combustible) yield the highest temperature and thermal efficiency. With too high volatile matter gases escape unburnt, and excessive air must be admitted above the grate; and, on the other hand, with low volatile matter an excessive air supply is requisite for the fuel on the grate. Further, whilst the carbon from any coal yields the same number of heat units, equal weights of the volatile constituents develop comparatively less heat as the volatile matter increases. The highest economic efficiency will be attained, therefore, with coals of medium volatile content, say, from 16 to 23 per cent.

The steaming capacity, or output of the boiler, will be dependent on the furnace temperature, which again is dependent on calorific value, but more especially on the rate at which the coal can be consumed, anything tending to lower this being prejudicial. The influence of ash has been considered; very small coal, by interfering with the free passage of air, will greatly affect this, so also will tendency to cake, which, if the draught is moderate, may seriously lower the rate. It follows, therefore, that the ratio of grate area to heating surface and the draught conditions for a given coal may yield far from the best result with another coal, and therefore that the selection of a coal for given conditions is dependent on many considerations outside of calorific value. Although fine coal interferes with combustion, small coal frequently is an excellent fuel if free from dust; uniformity of size is desirable in general.

By far the largest proportion of coal in common use for steam-raising contains very much higher volatile matter than that found most economical by Constam and Schläpfer. Complete combustion without objectionable smoke is difficult to ensure, even with considerable excess of air, unless some suitable form of mechanical stoker is employed. Good efficiency can be obtained, but this necessitates careful and scientific control of the combustion by attention to the composition of the flue gas; without such attention the losses generally are enormous.

In producer-gas practice the volatile constituents of the fuel govern entirely its suitability for different types of producers, or, conversely, the design of the plant for the most economical fuel available. Again, the presence or absence of volatile constituents will determine largely the character of the gas; where present the latter will obviously consist of a mixture of the products of destructive distillation (coal gas) with producer gas proper, and since the former has the higher calorific value, the mixture should be richer than that obtained from a fuel yielding practically only producer gas, such as from anthracite. Part of the products of destructive distillation of a bituminous fuel must be tar, and it is the difficulty of removing this in most suction plants that limits the choice of fuel to anthracite or coke. The question of tar may not be altogether one of quantity; it may be that the character of the tar from certain forms of coal is very different from that of others, and can be dealt with more easily, but this requires extended investigation.

Caking coal is inadmissible in producer practice; it would need constant poking to work it, and large channels would form, through which the blast would pass and fail to yield good combustible gas. Uniformity of size is another important factor. The influence of the fusibility of the ash has been dealt with already (p. 40), but it should be mentioned that a coal with a very low and infusible ash sometimes does not give nearly such satisfactory results as a coal of fairly high ash.

Coking coal is distinguished from other bituminous coals by its property of undergoing a partial fusion when subjected to heat, and, decomposition ensuing at the same time, the gases evolved give a cellular structure to the coke. The coal loses its original form and structure entirely, thus distinguishing it from coals which do not possess this property of fusion, the cokes from the latter inheriting more or less the original shape of the lump and frequently retaining their individuality. Necessarily there are intermediate grades between these extremes, and a coal may possess the fusion property only in a moderate degree, so that selection of a suitable form of oven and carbonizing conditions is essential to the production of serviceable coke from it.

Reference has been made already to the impossibility of correlating this fusing property with the ultimate composition of the coal. Results from a particular coal field are sometimes fairly concordant, and this has given rise to the fixing of dogmatic limits of composition within which coking properties are found, but these same limits are frequently quite inapplicable to another coal field. It is certain, however, that as the coals approach the lignites on the one hand, and anthracites on the other, no tendency to coke is observed. Lewes has discussed the question of the probable constituents of coal before the Royal Society of Arts (Cantor Lectures on *The Carbonization of Coal*, 1912), and comes to the following conclusions, assuming, as all present evidence justifies, that the various coals owe their characteristic properties to varying total amounts and individual ratios of humic bodies, resinous products and hydrocarbons, coking is dependent on a high ratio of the latter two to the humic derivatives of cellulose; in non-coking highly bituminous coals (lignitious and ligno-bituminous) the humic bodies predominate, whilst, as anthracite coals are reached, the humic bodies are removed almost completely, but the resinous products and hydrocarbons are present in such small amount as to be incapable of exercising their binding effect on decomposition.

Whilst the nature of these so-called "resinous bodies and hydrocarbons" is quite undetermined at present, there can be no doubt but that they break up first into gases, vapours, and pitch, which latter deposits amongst the coal substance already more or less itself decomposed, and as the temperature rises this pasty pitch undergoes further decomposition, leaving a cellular residue of carbon luting together firmly the carbon residue from the other coal constituents, a view which receives considerable support from the fact that quite firm coke may be made by incorporating coal-tar pitch with anthracite or semi-anthracite coals.

Authorities are agreed that the only sure guide to determine whether a coal is suitable for coking is a practical test. Valuable information often is to be gained from the nature of the coke obtained during proximate analysis in a platinum crucible, but the rate of heating in some cases may modify considerably the result. Rapid heating will, with some coals, drive off all the volatile hydrocarbons so quickly that the cementing action of the pitch has little chance, whereas slow heating may yield a fair coke. The Campredon coking test is designed to give a "coking index" for various coals; it represents the amount of fine white sand which 1 gram of the coal is capable of just binding into a coherent mass. A good coking coal will cohere with 9 to 15 grams of sand. Lessing (*J. S. C. I.* 1912, 671), has proposed a new method of ascertaining the character of the coke. The method is referred to in detail on p. 301. Porter and Durley recommend a test on 50 lbs. of the coal, brought into the condition in which it would be in practice, packed into a rectangular box with perforations and lined with paper to prevent small coal falling out. This is placed in a coke oven with the ordinary charge, drawn at the same time as the charge, lightly quenched and weighed.

NAVIGATION, BUNKER, AND SMOKELESS STEAM COALS

No term descriptive of coal is employed so widely as that of "steam coal," which appears to include all coals except the strongly caking and anthracites. The above coals are used principally for navigation purposes, and are of a less bituminous character than the steam coals in general use for manufacturing purposes. Scotch Navigation coals are frequently almost identical in composition with some of the best coking coals, but of course must have little tendency to cake. The volatile matter is moderately high, so that smoke is inevitable under marine boilers. The following is an average composition taken from five coals:—

Total carbon.	Hydrogen.	Sulphur.	Nitrogen.	Oxygen.	Fixed carbon.	Volatile hydrocarbons.
87·6	4·9	0·7	1·5	5·3	76·5	23·5

Bunker coals and smokeless steam coal are the well-known valuable Welsh coals. Similar coals to the former have been shown by borings to exist in the Kent coal fields. Both these coals are so low in volatile matter that there is no difficulty in burning with little or no smoke, and the difference between them broadly is that, owing to somewhat higher volatile matter, the bunker coals are not entirely smokeless; they are second-grade smokeless coal. Obviously no hard line can be drawn between the two. Such coals burn freely with a fair draught, and show no tendency to cake. From average analyses of both classes their relationship is given below:—

	Total carbon.	Hydrogen.	Sulphur.	Nitrogen.	Oxygen.	Fixed carbon.	Volatile hydrocarbons.
Bunker coal . .	90·0	4·6	0·9	1·1	4·0	81·5	18·5
Smokeless steam	91·0	4·4	1·0	1·1	2·5	87·0	13·0

ANTHRACITE

Anthracite is the least widely distributed of the coals and one of the most valuable. A great increase in the demand has arisen since the introduction of suction gas plants. The most notable deposits are those of South Wales and Pennsylvania, in both of which anthracite of very high quality is obtained. Anthracite is hard and lustrous, and does not soil the fingers. The ash is lower than in bituminous coals. In many parts coals of the composition of the best anthracites are found, which have resulted from the intrusion of igneous rocks into bituminous coal measures. Here the ash is higher than in the unaltered coal, and such anthracitic coal may be regarded really as a semi-coke. True anthracite appears to derive its special characteristics from the nature of the original deposited carbonaceous matter, or from changes brought about in it very shortly after deposition, and existed as anthracite before denudation or serious disturbance of the strata took place. Where great subsequent disturbance of the strata has taken place, the anthracite still has the same characters and composition, but has become broken down into a coarse powder called "culm."

Two grades are commercially recognized in South Wales, anthracite proper, which contains less than 8 per cent. of volatile hydrocarbons with 93 per cent. or over of carbon, and a lower grade, with a higher percentage of volatile matter. Still more nearly approaching the Welsh smokeless steam coals are the Scotch anthracites, in which the volatile hydrocarbons approximate to about 12 per cent. The following compositions may be taken as typical:—

	Total carbon.	Hydrogen.	Sulphur.	Nitrogen and oxygen.	Fixed carbon.	Volatile hydrocarbons.
Scotch	90·9	4·2	0·9	4·0	87·0	13·0
Welsh (2nd grade)	91·5	4·2	1·3	3·0	90·5	9·5
Welsh (best) . .	93·5	3·2	0·8	2·5	94·5	5·5

COMPOSITION OF COALS OF THE BRITISH EMPIRE

Great Britain.—In Table XVII. (p. 60) the author has summarized the information on the composition of over 270 samples of coals of Great Britain. The data for many important fields are very incomplete, and serve to emphasize the necessity for a thorough systematic study of the composition of our coals. In commercial practice it is seldom necessary to make a complete analysis, and the ultimate composition, so essential for comparison, very rarely need be ascertained, which accounts for the difficulty of obtaining data in most instances. A very valuable collection of analyses, mainly of commercial form, has been published by the *Colliery Guardian* for some hundreds of British coals. For a proper knowledge of the composition of our coals it is essential to have both proximate and ultimate analyses and reliable data as to calorific value. In general, when the calorific value has been given for a coal the type of calorimeter employed is seldom mentioned; where mentioned, it is rarely of an accurate type; in many instances the result has been obtained by calculation. So much uncertainty exists on this point that calorific values have been omitted from the Table.

The data in connection with Indian and Colonial coals are very incomplete, being confined almost entirely to proximate analyses. Dunstan has published a paper on "The Coal Resources of India" (*Journ. Roy. Soc. Arts*, 1902, 50, 371), in which the proximate composition of a large number of coals is given, and a few ultimate analyses. The results have been summarized in Table XVIII. (p. 62), and will serve to indicate the general character of these coals. It will be seen that the majority are either lignites or lie between the true bituminous coals and the lignites, forming classes similar to the lignitious and ligno-bituminous coals (p. 50). In addition, however, coals are found in Bengal and Central India agreeing well in composition with some of the best English coking coals, and many Indian coals yield excellent coke. Practically all Indian coals contain exceptionally high ash and are generally very soft and friable. Immense deposits occur, and some of the seams are of remarkable thickness, one bed in Assam being 100 feet thick, and the greater part excellent coal. It will be seen that this Assam coal averages much lower ash than Indian coals generally.

Australia.—Large deposits of coal are found in Queensland and New South Wales, the latter deriving its name from the occurrence. The output is greater than for any other colony, amounting to from 7·5 to 8 million tons. There is little information available, however, as to composition, but lignites and highly bituminous coals occur in

TABLE XVII.

Coals of England, Scotland and Wales.

Average composition and extreme limits of constituents of the pure coal substance (*i.e.* moisture and ash free). The results are arranged in order of the ratio of (carbon + hydrogen) to (oxygen + nitrogen).

District.	No. of samples.	Carbon.		Hydrogen.		Sulphur.		Nitrogen.		Oxygen.		Fixed carbon.		Volatile matter.		Ratio $\frac{C+H}{O+N}$
Leicester	5	75·5	77·3 72·6	5·23	5·40 5·05	1·21	1·95 0·78	1·38	1·61 1·23	16·7	20·17 14·40	58·2	64·3 53·2	41·8	46·8 35·7	4·5
Stafford (A)	2	75·6	75·9 75·3	5·17	5·20 5·15	2·50	2·83 2·17	1·35	1·43 1·28	15·4	15·44 15·33	58·4	59·2 57·5	41·6	42·5 40·8	5·0
Derby	5	78·0	80·5 77·3	5·10	5·27 4·83	1·50	2·10 0·73	1·30	1·68 1·07	14·0	14·4 12·9	59·0	65·5 54·0	41·0	46·0 34·5	5·4
Nottingham (A)	9	78·3	81·7 77·0	5·00	5·33 4·80	1·20	2·03 0·74	1·10	1·49 0·53	13·8	16·0 12·0	56·0	—	44·0	—	5·6
Warwick	2	80·5	81·7 79·4	5·00	5·46 4·52	0·73	0·76 0·71	1·34	1·36 1·32	12·4	14·0 10·8	64·2	67·2 61·2	35·8	38·8 32·8	6·24
Northumberland (A)	3	80·9	81·9 79·0	5·00	5·20 4·70	0·86	0·95 0·77	1·30	1·87 1·05	12·0	13·5 11·0	64·0	—	36·0	—	6·45
Durham (A)	2	81·7	82·6 80·9	4·43	4·63 4·24	1·48	1·62 1·34	1·10	1·08 1·10	11·2	12·4 10·1	66·0	—	34·0	—	7·0
Lanark Argyll } splint	5	81·7	83·4 78·6	5·11	5·32 4·86	0·53	0·61 0·45	—	—	10·6	13·0 8·7	61·0	63·0 60·0	39·0	40·0 37·0	7·1
Ayr Haddington } soft	16	82·2	83·9 80·0	5·46	6·16 5·00	0·82	1·56 0·47	1·64	2·02 0·85	10·0	12·7 7·4	63·5	64·0 56·4	36·5	43·6 36·0	7·5
Lancashire	28	81·9	85·6 77·5	5·60	6·38 4·00	1·50	3·26 0·54	1·40	2·64 0·52	9·7	19·5 5·5	60·0	69·0 53·0	40·0	47·0 31·0	7·9
Denbigh	2	83·3	84·5 82·2	5·34	5·46 5·22	1·20	1·42 0·90	1·60	1·64 1·51	8·5	9·3 7·9	58·0	58·0 58·0	42·0	42·0 42·0	8·7

Nottingham (B)	5	83·3	85·0 81·9	5·60	5·95 5·17	1·10	1·66 0·73	1·64	1·93 1·39	8·5	9·3 6·5	62·5	—	37·5	—	8·8
Northumberland (B)	15	83·6	86·6 81·6	5·30	5·92 4·90	0·85	1·90 0·60	1·55	2·33 0·73	8·4	9·9 7·0	64·5	72·0 59·5	35·5	40·5 28·0	8·9
Yorkshire	15	82·9	85·6 80·9	5·35	5·62 4·94	1·95	5·41 0·60	1·55	2·15 0·80	8·3	10·3 6·2	64·0	70·0 62·0	36·0	38·0 30·0	9·0
Forest of Dean	8	83·3	85·5 82·5	5·30	5·55 5·00	1·70	2·43 0·92	1·85	2·32 1·28	7·9	8·9 5·1	—	—	—	—	9·1
Stafford (B)	1	83·9	—	5·75	—	0·74	—	1·27	—	8·3	—	64·3	—	35·7	—	9·3
Lanark, Dumbarton Fife, Edinburgh (A)	6	84·3	85·2 83·3	5·60	6·10 5·32	0·80	1·25 0·26	1·62	1·93 1·54	7·6	8·7 7·0	66·5	70·5 60·5	33·5	39·5 29·5	9·7
,, ,, (B)	8	86·6	88·6 81·7	5·20	5·40 5·00	0·77	0·86 0·68	1·70	2·11 1·30	6·0	7·3 4·2	73·0	78·5 70·2	27·0	29·8 21·5	11·9
Durham (B)	20	85·0	88·6 84·2	5·30	5·50 5·00	1·25	2·17 0·76	1·45	1·82 0·95	6·0	7·5 4·1	69·0	76·0 66·0	31·0	34·0 24·0	12·1
Kent (A)	10	86·5	88·2 85·0	5·10	5·6 4·5	1·21	1·39 0·86	1·04	1·29 0·72	6·1	7·9 4·4	71·5	73·5 69·5	28·5	30·5 26·5	12·8
Somerset	2	86·7	86·8 86·7	5·26	5·62 4·90	0·83	0·71 0·96	1·50	1·47 1·55	5·5	5·9 5·4	64·7	69·4 60·0	35·3	40·0 30·6	13·2
Glamorgan (A)	5	87·0	87·9 85·8	5·40	5·51 5·29	0·90	1·21 0·70	1·20	1·25 1·12	5·5	6·9 4·4	71·0	74·5 69·3	29·0	30·7 25·5	13·3
Kent (B)	14	87·8	89·8 86·0	4·76	5·05 4·45	1·18	2·4 0·7	1·06	1·24 0·86	5·1	6·5 3·3	78·0	80·0 74·5	22·0	25·5 20·0	15·0
Monmouth	7	88·3	90·0 86·2	5·05	5·57 4·31	1·10	1·90 0·60	1·05	1·70 0·63	4·5	7·2 3·3	—	—	—	—	20·3
Kent (C)	25	90·0	91·7 87·7	4·44	4·91 3·52	0·92	1·92 0·54	1·02	1·36 0·72	3·4	4·90 1·7(?)	84·4	88·8 81·3	15·6	18·7 11·2	21·0
Scotland (anthracite)	3	91·8	92·6 90·8	3·70	4·21 3·20	0·55	0·87 0·10		3·96	4·84 2·80		89·0	90·4 87·0	11·0	13·0 9·6	24·0
Glamorgan (B)	10	90·6	91·5 89·7	4·65	5·00 4·23	0·90	1·63 0·70	1·15	1·49 0·92	2·65	3·81 1·93	85·5	90·5 80·0	14·5	20·0 9·5	25·0
Wales (anthracite)	16	93·2	93·8 92·5	3·50	4·00 3·22	0·85	1·23 0·44		2·50	4·50 2·15		95·0	96·0 93·0	5·0	7·0 4·0	38·5

1. Where coals of generally different composition occur in the same field, they have been classified under A, B, etc.
2. The analyses of Kent coals refer to samples from borings.

TABLE XVIII.

Indian Coals.

Average composition and upper and lower limits calculated on the pure combustible (*i.e.* moisture and ash free).

District.	No. of samples.	Carbon.	Hydrogen.	Sulphur.	Nitrogen and oxygen.	Fixed carbon.	Volatile hydrocarbons.	Ash on dry coal.
Assam	3	81·1 82·9 80·1	5·8 6·21 5·50	4·24 1·13	10·2 13·1 6·7	53·8 55·8 52·8	46·2 47·2 44·2	4·8 1·3
,,	5	—	—	—	—	51·8 53·6 49·7	47·2 50·3 46·4	4·7 1·0
Baluchistan	2	79·8 81·3 78·4	5·92 6·39 5·46	5·30 0·85	11·1 11·46 10·84	— 54·5 47·2	— 52·8 45·5	10·9 5·4
Bengal	2	88·9 89·4 88·3	4·83 4·91 4·76	0·46 0·43	5·8 6·48 5·26	— 71·5 71·0	— 29·0 28·5	7·5 5·4
,,	3	83·5 84·0 82·4	5·45 5·58 5·20	0·63 0·33	10·5 11·7 9·8	60·9 64·8 56·8	39·1 43·2 35·2	14·1 9·4
,,	6	Fixed	carbon over	70 per cent.	—	71·3 73·0 70·0	28·7 30·0 27·0	15·9 5·4
,,	16	,,	,, 62·5	to 77·0 ,,	—	67·0 69·6 63·2	33·0 36·8 31·4	18·9 8·6
,,	12	,,	,, 55·0	to 62·5 ,,	—	58·0 60·8 55·7	42·0 44·3 39·2	29·2 7·6
,,	6	,,	,, 50·0	to 55·0 ,,	—	53·5 54·6 52·9	46·5 47·1 45·4	15·0 8·5
,,	6	,,	,, below	50·0 ,,	—	48·6 50·0 46·8	51·4 53·2 50·0	17·1 8·9
Central India	3	,,	,, over	70·0 ,,	—	75·8 78·0 73·8	24·2 26·2 22·0	23·6 16·0
,, ,,	3	,,	,, under	70·0 ,,	—	57·6 64·7 54·2	42·4 45·8 35·3	24·3 14·9
Central Provinces	1	81·4 —	5·25 —	0·52 —	13·83 —	54·2 —	45·8 —	10·5
,, ,,	1	Fixed	carbon over	65·0 per cent.	—	66·2 —	33·8 —	8·3
,, ,,	5	,,	,, under	60·0 ,,	—	52·0 56·1 47·8	48·0 52·2 43·9	24·3 8·3
Punjaub	3	—	—	—	—	43·8 44·1 43·5	56·2 56·5 55·9	13·1 10·0
Burmah	1	76·1 —	5·86 —	0·42 —	17·62 —	42·1 —	57·9 —	10·5
,,	4	—	—	—	—	45·5 48·6 42·0	54·5 58·0 51·4	21·7 1·9

large quantities, and in places where there has been great disturbance of strata and igneous intrusions the bituminous coal has been converted into a natural coke, there being various gradations between the extremes.

In a report on "The Coal Resources of New South Wales" (*Geol. Surv., N.S.W.*, 1912), proximate analyses of 194 representative samples are given. The following summarizes the results :—

Coal Field.	Northern.		Western.	Southern.
	Upper and Middle.	Lower.	Upper.	Upper.
Fixed carbon	59·7	54·4	62·2	73·0
Volatile hydrocarbons .	40·3	45·6	37·8	27·0
Ash on *dry* coal . . .	8·9	7·15	12·8	11·75

An analysis may also be quoted of a coal which appears to agree closely with the well-known Torbane Hill cannel—

Fixed carbon.	Volatile hydrocarbons.	Ash on dry coal.
28·5	71·5	31·8

Canada.—Coal is widely distributed in Canada, but many of the seams are thin, and frequently yield little coal worth working. Bituminous coals of the Carboniferous period are found, principally in Nova Scotia and New Brunswick. East of the Rocky Mountains, lying largely in Manitoba, there are immense deposits of lignite, which is the chief fuel of this colony, and is the parent substance from which bituminous coals and coals of anthracitic character, found to the west of the region, have been derived through disturbance of strata. In British Columbia deposits of excellent coal are found, many of which yield good coke, and to the south anthracites occur.

A Summary Report of the Mines Branch of the Canadian Department of Mines (1909) gives a preliminary account of systematic investigations on the Canadian coals. The estimated contents of the different fields are :—

1. Maritime Provinces (Nova Scotia, etc.): bituminous, 10,000 million tons.
2. Central Plains and Eastern Rocky Mountains: anthracite, 400 million tons; bituminous, 80,000 million tons; lignite, 80,000 million tons.
3. Pacific Coast and Western Mountains: anthracite, 10,000 million tons; bituminous, 2000 million tons; lignite, 1000 million tons.
4. Arctic Mackenzie basin: lignite only, 500 million tons.

The Nova Scotia coals closely resemble English and Scotch coals, but usually have a higher ash and sulphur.

The coals in section 2 are of very variable character and have high ash; some excellent coals are however found.

Very few analyses are available, but the following are typical :—

	Fixed carbon.	Volatile hydrocarbons.	Ash on dry coal.
Lignites	54	46	8·3
Bituminous coal (Nova Scotia) . .	63·5	36·5	1·8
	71·7	28·3	5·1
Coking coal (Bighorn, Alberta) . .	75·2	24·8	7·1

New Zealand.—The coals, which occur in both the North and South Islands, are of considerable importance. The main deposits are of lignitious character, but various gradations of bituminous coals, including coking and good quality steam coal to anthracite, are found, apparently all derived from lignites by intrusions. Large quantities of steam coal are shipped for Admiralty use in the East.

A very large number of proximate analyses of New Zealand coals, together with bomb determination of calorific value, are to be found in the Reports of the Dominion Laboratory, Mines Dept., Nos. 40, 41, 42, and in a paper by A. M. Wright (*J. C. S. I.* 1905, 1213). From these two sources the data of Table XIX. have been obtained :—

TABLE XIX.

COMPOSITION OF NEW ZEALAND COALS.

	Fixed carbon.	Volatile hydrocarbons.	Ash on dry coal.	Average moisture.
Lignites (4)	43·7 {47·5 40·0	56·3 {60·0 52·5	7·7 5·3	28 per cent.
Brown coals (3)	44·5 {46·3 43·5	55·5 {56·5 53·7	7·7 3·9	26 per cent.
Bituminous (12)	62·5 {69·0 53·0	37·5 {47·0 31·0	9·6 1·0	
Steam (4 typical) as shipped for Admiralty	89·0	11·0	10·0	
Anthracites (?) "Mammoth"	78·7	21·3	15·0	
—	82·8	17·2	5·2	
Anthracite (Wairo)	93·7	6·3	3·1	

In some New Zealand coals the sulphur content is unusually high.

South Africa.—Coal is distributed over a wide area, which includes Cape Colony, Natal, Transvaal, Southern Rhodesia, Zululand, and Swaziland. The output of the Transvaal is about 2·75 million tons, and of Natal 1·25 million tons. Most of the seams are thin, and frequently dirt bands are interspersed. The coals generally have a high ash, but the sulphur content is low.

Most of the coal is of a soft bituminous kind, but in Zululand and Swaziland anthracitic coals and anthracites are found. Some of the Transvaal coals are stated to resemble Welsh steam, but this appears to be based upon the composition when their high ash is included. When the composition on the combustible is considered, the volatile hydrocarbons are far higher than in the Welsh coal. One analysis of a Swaziland coal (see Table XX.) does closely agree with the best Welsh coals, and some of the Natal coals approximate to the second grade steam or bunker coals of South Wales, but the ash is somewhat higher. Only one complete analysis can be quoted:—

TRANSVAAL COAL (A. Whitby).

Carbon	85·2	Oxygen	6·87
Hydrogen	5·53	Fixed carbon . . .	68·0
Sulphur	0·53	Volatile hydrocarbons	32·0
Nitrogen	1·87	Ash on dry coal . .	11·0

TABLE XX.

PROXIMATE COMPOSITION OF SOUTH AFRICAN COALS.

	Fixed carbon.	Volatile hydrocarbons.	Ash on dry coal.
Transvaal—			
Steam coal (Transvaal and Delagoa Bay Collieries)	72·0	28·0	15·0
Koomati Poort	74·4	25·6	16·9
Natal—			
Navigation Collieries	81·4	18·6	11·5
Dundee.	77·2	23·8	8·7
Zululand—			
Indewa	85·2	14·8	21·4
Anthracitic coals	91·4 89·0	8·6 11·0	13·4 19·4
Swaziland—			
Steam coal	87·0	13·0	5·2
Anthracites (4)	95·4 95·6 95·0	4·6 5·0 4·4	8·3 7·4

The following limits are stated to include the composition of bituminous coals of the Transvaal, results being on the whole coals:—

Fixed carbon . . .	51·0–60·6	Ash	14·7–21·5
Volatile hydrocarbons	21·8–25·8	Sulphur	0·5–2·0
Moisture	1–5		

The coal production of the world has reached the enormous total of 1250 million tons. Whilst for many years Great Britain produced by far the largest quantity of coal, the output of the United States now greatly surpasses it. To the above output the British Empire contributes about 27 per cent.; the United States, 43 per cent.; Germany, 15·5 per cent. Of the British output the United Kingdom contributes over 86 per cent., the remaining 14 per cent. being distributed as follows: British India, 4 per cent.; Australia and Canada, each 3·5 per cent.; South Africa, over 2 per cent.; New Zealand, under 1 per cent.

PHYSICAL PROPERTIES OF COAL

Specific Gravity and Stowage Capacity.—The specific gravity of coal is dependent upon two variables—the character of the combustible portion and the proportion of ash; the latter being of much higher density than the coal substance, and consequently exercising considerable influence on the specific gravity of the whole coal. The specific gravity varies between 1·27 and 1·45; only in exceptional cases will it fall outside these limits. On an average anthracite is from 10 to 15 per cent. denser than bituminous coals.

The stowage capacity, or number of cubic feet per ton, will depend upon the specific gravity and size of the coal (relation of air spaces to solid). From the figures of the Admiralty Investigation on Coal it may be taken that:—

1 ton of Welsh coal . . . . = 40–42 cubic ft. per ton
1 ton of Newcastle or Lancashire coal = 45 cubic ft. per ton
1 ton of Scotch coal . . . . = 47–50 cubic ft. per ton

Coherence.—The resistance to breakage on handling is a most important factor; coals of otherwise excellent character are sometimes so soft that they are broken down during transport, with the production of so much small coal as to detract seriously from their value. Many of the Indian coals are of this friable character. The waste in mining such coals is also great, and much of the small can be utilized economically only by briquetting or in producers. In shipment by older methods of tipping great crushing frequently results, which besides giving so much small coal, has a most important influence on the liability to spontaneous ignition.

Calorific Value.—This is obviously one of the most important properties of a coal which is to be employed by direct combustion, and although in practice it is only possible, even under the best conditions, to utilize a portion of the heat units of the fuel, it has been demonstrated conclusively in the United States Fuel Tests that the practical heating effect under a boiler, when proper attention is given to the conditions of combustion, is strictly proportional to the calorific value as determined in a bomb calorimeter.

The calorific value of a coal or any fuel will be dependent upon the amount of combustible matter present and the calorific value of this combustible. Since the amount of non-combustible material present (ash and moisture, principally) varies over very wide limits for coals of the same type and having practically the same composition for the combustible, comparison of composition and calorific value between such coals can only be properly made when these variables are eliminated. In all examples given of the composition and calorific value, the results are calculated on the pure combustible, *i.e.* on the dry and ash-free coal. Where a comparison is required between individual coals for practical purposes, the ash and moisture necessarily must be included.

The calorific value of the combustible may be regarded as the sum of the heat units of the fixed carbon and volatile hydrocarbons; the calorific value of the former is practically constant for all coals (8000 calories; 14,400 B.Th.U.); but whilst for a large number the composition and heating value of the volatile hydrocarbons are also the same, this is not invariably the case, especially with coals of the same proximate composition but from different coal fields. Parr and Wheeler (*Univ. of Ill., Eng. Experimental Station*, Bull. 37, 1909) conclude that for American coals the composition of the coal substance from a given deposit is very uniform, and affords a basis for estimating the calorific value of any similar coal of the district, after the proximate composition has been determined and proper allowance made for the volatile constituents of the ash (combined water, carbon dioxide, etc.). This pure coal substance they term the "unit coal" of the district. Whilst for the majority of the British coal measures the data are insufficient for a comparison, the author believes that there is good evidence of this uniformity in certain of the Durham, Northumberland, and Clyde Basin measures.

The methods of determining and calculating calorific values and the reliance to be placed on the various methods are discussed in detail in Chapter XVIII.; here it is sufficient to point out that whilst a very large number of previously recorded values may be accurate, they are open to the suspicion of considerable error, owing to their having been arrived at either by calculation or by determination in calorimeters liable to grave errors. For scientific purposes some form of bomb calorimeter is essential, and only results obtained in this manner are included below, where the approximate range of calorific value of the pure combustible is given for the principal commercial classes of coal:—

	Calories.	B.Th.U.
Splint coals . .	7700–8150	13,850–14,650
Bituminous . .	8000–8700	14,600–15,300
Coking	8300–8600	14,940–15,480
Smokeless steam	8700–8900	15,650–16,000
Anthracite . .	8700–8800	15,650–15,800

The *ignition point* of coals has been given on p. 5.

Endothermic Character of Coal.—For many years it was considered that some of the heat of combustion of the coal was expended in breaking down the compounds into more simple forms before further combustion took place, and the frequent discrepancy between calculated and determined calorific values was also ascribed to this. From a comparison between the results actually obtained in a bomb calorimeter and those calculated from ultimate composition, the former being almost invariably the greater, and from the fact that the heat units available in the products of destructive distillation are less than those of the coal itself, there can be little doubt but that coal is an endothermic substance, and gives out on burning not only heat by the combustion of the coal substance but some additional heat, which may be regarded as rendered latent at the time of its formation. In general this excess of heat units is greater with high oxygen content, and has practically disappeared when the anthracite coals are reached. Sufficient data are not available for any exact statement, but with bituminous coals from 1·5 to 3 per cent. of the total heating value appears to be due to this endothermic property.

Chapter V

TREATMENT AND STORAGE OF COAL. BRIQUETTES AND POWDERED COAL

Preparation of Coal.—A thick clean seam may require no special treatment before marketing. If the coal is "holed" the small and dust may be considerable and require screening, and if the "holing" is in the dirt, and care is taken to clear this properly before the coal is allowed to fall, a good product is obtainable.

Where dirt bands, bone coal, pyrites, etc., occur, or when adjoining strata are inevitably mixed with the coal, some form of washing is very necessary. This is becoming more and more essential as the better class seams are worked out, and poorer seams, in which dirt is present, have to be mined to render an otherwise unmarketable or low-priced product remunerative. From the point of view of properly economizing our coal deposits the use of these poorer seams is an important question, the solution of which lies in the adoption of suitable methods of cleaning.

Space does not permit of a detailed description of washing plant, etc.; the reader is referred to two excellent papers by W. McD. Mackey (*J. S. C. I.* 1904, 431), and Professor H. Louis (*J. S. C. I.* 1911, 662). Screening is the first operation when the coal has to be treated, to separate the larger coal from the small, the latter being afterwards separately screened. With very tender coals ordinary methods of screening through the revolving or jigging screens lead to too much breakage, and a system of fixed bars alternated with moving bars independently operated, which throws the coal forward, is employed. Large coal goes directly to some form of travelling plane, a belt or rotating table, and as the coal is passed forward bad pieces are picked out by hand.

The small coal is sorted into various commercial sizes. According to Louis the following are usual, although there is some variation with locality :—

Cobbles	
Nuts	¾ to 1½ inch
Beans . . .	¼ or ½ to ¾ inch
Peas	down to ⅜ inch
Duff	

These smaller sizes alone are washed, the general principle of the operation being that owing to the difference of specific gravity between the pure coal (sp. gr. for bituminous averages 1·3) and the impurities, bone coal (sp. gr. 1·5 to 1·8), shale (sp. gr. 2·5), and pyrites (sp. gr. 5 or over), material of approximately the same size will, on treatment in a stream of water, be separated, the heavier particles settling under a given velocity, while the lighter coal is carried away. Obviously larger pieces of coal will settle at the same rate as much smaller pieces of dirt, hence the necessity for practically uniform size in a given washer; further, very small coal and dirt will not separate, owing to the effect of surface friction overwhelming the effect of difference of specific gravity.

The general classes of washing plant may be summarized as follows:—trough-washers with dams at intervals, the coal and water passing down the inclined trough, when the heavier dirt is retained by the dams; troughs in which movable dams are worked upwards, the coal usually being fed near the centre, when the water carries the coal downwards, the moving dams carrying the dirt to the upper end. Although the water is used several times the consumption with both types is high, and to obviate this pulsating washers or jigs are employed. An upward and downward movement of water is obtained by means of a plunger working in a cylinder forming part of the washer; the coal is fed on to a suitable screen in the water, and as the water pulsates up through the coal the latter is carried over at a suitable level, and the heavier dirt, passing through an opening, falls through the water in the lower part of the tank. The same result may be attained by causing a sieve to ascend and descend rapidly in water. For the finer coals feldspar is employed on the grid in the washer. Very fine coal forms slimes with water from which separation is difficult, and large settling tanks are employed. It is noted that such very fine coal mixed with coal for coking frequently improves greatly the quality of the coke.

The net result of washing, besides that of economy, is a great reduction in the percentage of ash and of sulphur derived from pyrites. Organic sulphur, being part of the coal substance, is not affected. Thorough draining of the washed coal must be allowed, otherwise the moisture content will be very excessive. Poole (*J. S. C. I.* 1901, 562) gives the following results:—

	50 ton samples, Cape Breton.								10,000 tons Dominion coal.	
	1		2		3		4			
	Ash.	S.	Ash.	S.	Ash.	S.	Ash.	S.	Ash.	S.
Raw . .	7·5	3·24	15·00	3·02	11·09	4·23	11·55	5·26	10·07	2·38
Washed .	4·37	2·38	7·05	2·87	5·50	3·12	6·01	3·15	4·82	1·79

The cost of washing naturally will vary greatly with the character of the coal, plant adopted, its water consumption, etc. It may be taken to average 2*d.* to 4*d.* per ton, and the value of the coal is generally enhanced by 6*d.* to 7*d.* per ton.

In order to determine in the laboratory the amount of coal likely to be obtained by suitable washing, 100 grams of the crushed and sized coal may be submitted to test with solutions of suitable gravity. Mackey recommends potassium carbonate solution of specific gravity ranging from 1·25 by increments of 0·1 to that of the saturated solution 1·53; Louis uses solutions of zinc iodide, specific gravity ranging from 1·4 to 1·7. The quantity of suspended material in the different solutions may be estimated by filtration (preferably with a filter pump), rapidly washing, drying and weighing, after which separate determinations of the ash may be made.

Combustion of Coal and Formation of Smoke.—The combustible elements of coal consist entirely of carbon, hydrogen, and a portion of the sulphur, and when their combustion is properly completed the flue gases should contain only carbon dioxide, water vapour, and sulphur dioxide, in addition to the large volume of nitrogen which accompanied the oxygen of the air used up in the process. The theoretical amount of air for fuel of any given composition can be calculated readily, but in practice it is found impossible to get the best results without considerable excess of air.

Combustion of coal is in practice a compromise; it means striking the best balance possible between losses of heat units through incomplete combustion on the one hand, and losses through heat units carried away in the flue gases by an excessive supply of air on the other hand. The calculation of the theoretical supply of air and the losses through the last-named causes are dealt with fully in Chapters I. and XIX. Here, it is only necessary to deal with the question of incomplete combustion, more particularly in its relation to the formation of smoke.

Theoretically, an average bituminous coal requires 11 lbs. of air or 140 cubic feet per lb., but perfect combustion under the best conditions cannot be attained without 20 per cent. excess, say 170 cubic feet. Incomplete combustion may exist without visible evidence when carbon is partly burned to carbon monoxide instead of the dioxide, and when hydrocarbon gases escape unburnt. Visible evidence of incomplete combustion is given by the formation of smoke. When carbon is burnt to carbon monoxide, out of the possible 8130 calories per kilogram (or 14,650 B.Th.U. per lb.) only 2490 calories (or 4480 B.Th.U.) are actually produced. With escaping hydrocarbon gases the losses may also be very high, since these gases have a very high calorific value. The conditions favourable to the formation of carbon monoxide are a thick fuel bed (see Theory of Producer Gas Reactions p. 208) and insufficient supply of air over the bed. The 20 per cent. excess air will ensure against both these losses with reasonable management, but by no means ensures absence of smoke when other very important factors are involved.

Smoke is formed from the distillation products of the coal, which, owing to imperfect systems of firing and furnace arrangements, escape before combustion is completed. Obviously, the smaller the amount of volatile matter commensurate with free burning properties, the less the liability to smoke, which explains the special characteristic of the Welsh smokeless coals. The production of smoke is best understood by following the sequence of events when a bituminous fuel is hand-fired. A layer of white hot solid carbon is on the firebars, with probably an excess of highly-heated air passing through; coal is thrown in and partially checks the hot air supply over a portion of the grate; there is a local sudden cooling due to cold coal and the evaporation of moisture from the coal, and a rush of cold air through the open door produces general lowering of temperature over the grate. Possibly the interaction between steam and carbon, which absorbs heat no matter whether producing carbon dioxide or the monoxide together with hydrogen, also exercises a minor cooling effect. Almost immediately the destructive distillation of the coal sets in, and with small coal this may be extremely rapid, with the evolution of large volumes of combustible gases and vapours over a small interval of time.

A ton of bituminous coal will yield 11,000 cubic feet of gas, and in addition large volumes of vaporized products (the tars resulting in gas manufacture), giving a total which may be taken approximately at 13,000–14,000 cubic feet per ton, or about 6 cubic feet per lb. of coal charged. With a moderate charge of 40 lbs. of coal this means that some 240 cubic feet of gases are set free; on an average each cubic foot will require 3 cubic feet of oxygen or 15 cubic feet of air, so that the air supply for complete combustion of these volatile products must be 3000 cubic feet.

For the perfect combustion of these gases there must be obviously no deficiency in oxygen; further, that as intimate a mixture as possible of combustible gas with the necessary oxygen must be made; and lastly, that as high a temperature as possible shall be maintained, otherwise combustion will be checked and smoke formed. The necessity for the last two conditions is well illustrated by the actions with a paraffin lamp. Lighted up without the chimney the flame extends itself greatly in its effort to obtain the necessary oxygen; owing to this diffusion it becomes so cooled that smoke is formed freely, and the flame towards its edges is of a red colour with little luminosity, due to its low temperature. With the chimney the air supply is directed properly on to the flame, which is greatly reduced in size, the increase in the intensity of its combustion is manifest by the disappearance of the red colour and the increase of luminosity, and no smoke is formed. If the conditions of combustion of coal under any boiler fails in one of these points, smoke will result.

The supply of the large number of cubic feet of air during the first few minutes after firing is the first consideration. It is well known that keeping the door open for a short time, or providing for sufficient air inlet through suitable louvres in the door arranged so that they may be gradually closed, is effective in preventing smoke, if the other conditions named are satisfied, but a good draught is essential. When a boiler is working for some time below its maximum, the chimney damper being partly in, there may be difficulty in getting the requisite air over the grate unless an ash pit damper is provided. Obviously, the provision of sufficient air at any and every moment will be simplified and better opportunity of proper mixture ensured if there is no rush of combustible gases at any time. This will be best attained by a continuous feed of fuel, as with mechanical stokers, or, if necessarily intermittent, as in hand-firing, by the adoption of either a "coking" or "alternate" system of firing. By charging the fuel on a dead plate just inside the door with suitable air admission above the grate, distillation proceeds slowly, the products passing with the necessary air over the highly incandescent fuel on the bars, where they meet with further excess of air at high temperature. When distillation is completed the coked mass is distributed over the grate. The objection to the method is mainly that it is frequently impossible to burn the quantity of fuel requisite, but it is certainly the most scientific method of hand-firing.

Alternate firing may be either in sections over the front and back of the grate, or sections to the right or left. In either case proper admixture with air and maintenance of the necessary temperature are assured, if the furnace construction is a proper one. Necessarily the more frequent opening of the doors with the accompanying losses through excess air are involved, and success with either coking or alternate systems is dependent on the skill of the fireman.

The question of mechanical stokers and their operation is outside the scope of the present volume, but brief reference to one or two points may be made. All are dependent upon the principle of practically continuous feed, with its advantage of uniform evolution of the smoke-producing elements. It is therefore easy to adjust the air supply so that, whilst ensuring complete combustion, no unnecessary excess is employed, whereby the highest efficiency is secured, providing the arrangement is such that towards the back of the grate air is not able to pass freely in through a residue of nearly completely consumed fuel. The amount of fuel which can be burned per square foot of grate area is higher under these uniform conditions, and consequently the duty of the boiler is increased, which often leads to a reduction in the number requisite for a given output. Again, it is frequently possible to use a cheaper grade of fuel than with hand-firing, and saving in labour costs is also effected.

The second essential for smokeless combustion is efficient mixing of the gases and air. This will reduce the length of the flame and increase its calorific intensity, enabling the combustion to be completed before an inordinate space, with possible contact with cool surfaces, has been traversed. A suitable direction to the in-going air may be given at the door by plates, etc., and sometimes a steam jet or jets can be effectively employed. In an internally-fired boiler there is seldom any difficulty as regards mixing, owing to the rapid sweep of the gases and air towards the firebridge.

The third condition of maintenance of a high temperature is of equal importance to the supply of sufficient air. In the domestic fire there can be no question of any deficiency of air, but its smoke-producing powers are obvious and are due primarily to cooling, and to a minor extent to insufficient mixture. In boiler practice it is essential that the mixture of gases, vapours, and air in a state of incomplete combustion shall not come in contact with any surface at a comparatively low temperature, such as that at which the boiler plates and tubes are. With an internally-fired boiler there must be sufficient space between the grate and plates, which will be governed largely by the character of the fuel to be generally employed, that is, its percentage of volatile hydrocarbons. With cross-tubes it is impossible to avoid this contact. Beyond the grate and divided from it by a firebridge a capacious combustion chamber of firebrick reduces the speed of the gases, and enables combustion to be completed before the gases are drawn into the flues. In a water-tube boiler the incompletely burned mixture must be prevented from contact with the lower tubes, either by suitable arches, baffles or fireclay covering to the tubes.

The partial failure of one or other of these conditions will exercise an important influence on the character of the smoke. The researches of Burgess and Wheeler indicate that on distillation at low temperatures coal yields chiefly tar-forming bodies and rich hydrocarbon gases, while at high temperatures, after the former have distilled off, other bodies break up, yielding gas very rich in hydrogen. The tarry bodies (existing partly as heavy vapours and gases in the furnace, and possibly even as liquid vesicles) and the hydrocarbon gases will differ very much in their combustion. It will be more difficult to ensure complete admixture of the former with air, especially if liquid vesicles are present, and they will escape with very little alteration beyond combustion of the more volatile portions, giving a *brown* tarry smoke. The hydrocarbon gases will mix more readily with air, and if intensity of combustion is maintained, will undergo complete combustion, but should this be checked by cooling, dense clouds of *black* smoke, consisting largely of free carbon, will be produced. Should this free carbon once be produced no excess of highly heated air will cause its combustion, a result which has frequently given trouble in burning liquid fuel. The high-temperature gaseous products of distillation, consisting mainly of hydrogen, will offer no difficulties in combustion; it is the low-temperature products, given off with a rush on firing, and the character of these products which are wholly responsible for smoke. Deficiency of air and improper mixing will result chiefly in brown (tar) smoke with little free carbon; checking of combustion will be the primary factor in the production of black smoke.

A great deal is made of the losses of fuel due to the formation of smoke, and results are quoted frequently showing the great saving in fuel which has resulted when the boiler plant has been remodelled, primarily to overcome the smoke difficulty and to satisfy the local authority. These very great savings are, however, dependent far more upon avoidance of heavy losses through excess air and bad flue gases than upon heat units saved by utilization of the smoke. Under the old system very large excess of air was general in the attempt to avoid dense smoke; with the modernized system it has been possible to reduce greatly the air supply and still attain much better combustion. What percentage of the heat units in the fuel actually escapes in smoke it is impossible to ascertain directly. From an approximate estimate by Cohen and Ruston (see *Journ. Gas Ltg.* 1910, **112**, 201), the amount of soot collected by filtration of the air in the manufacturing district in Leeds is equal to 0·5 per cent. on the coal consumed. They state the quantity to be over 5 per cent. for domestic fires, and therefore that the estimate for industrial smoke is probably low. The composition of the combustible portion showed 85 per cent. carbon and 15 per cent. tarry matter, and on this basis it would have a calorific value of 8500 cals. (15,330 B.Th.U.). Allowing 1 per cent. of the coal escaping as smoke, with average bituminous coal the percentage of heat units escaping would be 1·2 per cent. By raising the carbon dioxide in the flue gases only 1 per cent., twice this saving of heat units could be effected, and fortunately the means taken to overcome the smoke trouble, usually the installation of mechanical stokers, are just those which enable better economy to be obtained through generally better conditions of combustion, and the economy found is ascribable only to a limited extent to heat units recovered from the smoke itself.

Harmful and objectionable in every way as smoke is, it must not be overlooked that the sulphur dioxide which accompanies it is one of its most injurious features, and that whilst the visible smoke may be reduced or abolished, this sulphur dioxide will still pass into the atmosphere.

THE DETERIORATION, HEATING, AND SPONTANEOUS IGNITION OF COAL

These phenomena are all intimately connected with each other, the degree to which spontaneous oxidation of the coal proceeds alone determining whether simple deterioration in quality results, or whether overheating and finally spontaneous combustion are set up.

It is well recognized that freshly mined coal frequently undergoes a rapid loss in calorific value during the first week or two after its removal from the pit, and old pillars of coal in the pit have been found to have an appreciably lower calorific value than the coal as freshly cut from around them. Parr and Wheeler found that American bituminous coals lost from 1·3 to 3·4 per cent. of their calorific value in ten months, but that the loss is confined nearly wholly to the first two or three weeks. Such loss usually is ascribed to escape of hydrocarbon gases (methane, etc.), which are of relatively high calorific value, but the loss in most instances appears to be greater than is probable from such causes alone, and absorption of oxygen must be a contributing factor.

Absorption of Oxygen by Coal.—Many bituminous coals contain unsaturated compounds which are capable of absorbing oxygen from the air. For this absorption to take place the physical condition of the coal will be the primary controlling factor; its size, as governing the relations of surface to mass; its hardness; its porosity. Demstedt and Biinz (abs. *J. S. C. I.* 1908, 929) show that absorption is dependent upon unsaturated oxygen-containing compounds, that these compounds are not present in any quantity unless the coal has a high oxygen content, and establish their unsaturated character by the response of such coal to the iodine absorption test and Maumène test, as applied to oils containing unsaturated compounds. The work of Boudouard and others confirms this view, and also that by further oxidation the products are humic acid and similar substances. Freshly mined coal placed in air-tight vessels absorbs oxygen at first without the formation of carbon dioxide ; it is only at a subsequent stage that this gas is evolved, showing that a process of slow combustion is set up, the heat from which is usually disseminated rapidly.

In a very large number of cases these actions proceed no further, but the practical results on the qualities of the coal are most important. Reference has been made to the loss of coking power of some coals on exposure to air and, above, to the loss of calorific value ; the ash is said to be raised, evidently through the escape of coal constituents as gases or vapours, the gas yield lowered, and more heat demanded for gas manufacture. When large stocks of coal have to be maintained, as in the gas industry, these results are of great importance. Grundmann has shown that Rühr coal gives from 1 to 7 per cent. lower gas yield after 14 days' exposure; from 3 to 12 per cent. after 150 to 180 days, and from 8 to 17 per cent. after 370 to 380 days' exposure. With an English coal at the Königsberg gas works the following yields were obtained :—

Coal as discharged . .	10,870	cub. ft.	per ton of	dry coal
„ after 3 months . .	10,815	„	„	„
„ after 7 months . .	9,930	„	„	„

Gas coals are not usually strongly caking coals, so that it would be expected that after exposure of the coal the coke would be less coherent, that is, that the proportion of breeze would be increased. That this is the case is shown by results from the Breslau gas works :—

	Fresh screened lump.	Fresh unscreened.	Weathered.
Large coke	93·3	86·06	52·63
Small coke	4·45	8·77	18·91
Breeze	2·27	5·17	28·36

Storage of Coal.—There is a general consensus of opinion that some deterioration ensues with most bituminous coals, which affects their value for practically all purposes. When large quantities have to be stored, the reduction of this to the minimum is obviously desirable, if it can be accomplished at a cost commensurate with the saving. The first idea would be the avoidance of oxidation by exclusion of air, either in air-tight chambers, which is impracticable, or by storage under water. It is well known that experiments on these lines have been made at Portsmouth, and the Twin City Rapid Transport Company of Minneapolis have stores for 12,000 tons of screenings in four reinforced concrete tanks. Coal removed from water and properly drained should not contain more moisture than washed coals; but storage under water is probably only justifiable under exceptional circumstances.

Storage under conditions which limit the amount of weathering, which includes the effect of moisture and oxidation, is more practicable. Moist coal is primarily more readily oxidized, and water exercises a disintegrating action, especially in winter, so that the coal becomes more open and porous. When properly stacked in the open, whilst the outer portions are undoubtedly affected, this, on the whole mass, is not serious, especially if the outer pieces are of fair size. The smallest area exposed in relation to the whole mass will give the best results, but this entails deep stacks with accompanying liability to heating and ignition. Good results follow the use of covered stores for soft friable coals, but generally the expense entailed is proportionately high to the preservation effected. With hard coals the weathering is not great.

Spontaneous Heating and Ignition of Coal.—Where oxidation proceeds to a more advanced stage it may lead to considerable heating and possibly spontaneous ignition of the coal. At one time heating was confidently ascribed to the oxidation of iron pyrites, but the evidence against pyrites playing more than a very minor part is overwhelming. The serious losses which may occur through spontaneous ignition in stores or coal cargoes render it necessary that the conditions through which heating may arise should be carefully studied, if proper measures are to be taken for its avoidance.

Modern views on the changes involved, largely based on the work of Parr and Kressman (*Univ. of Illinois: J. Ind. & Eng. Chem.* March, 1911), are, that after the coal has been broken out and the evolution of occluded hydrocarbon gases has practically ceased, the absorption of oxygen commences, which is accompanied by a slow rise of temperature, when the conditions of sufficiently rapid absorption (fineness of division chiefly) and prevention of escape of heat are present. It is not until a temperature of about 120° C. is reached that carbon dioxide and water vapour make their appearance, indicating that a slow combustion has started. Under suitable conditions the process accelerates until a temperature of 140° to 160° C. is reached, when the rate of increase of temperature becomes much greater, until between 200° and 275° C. a self-sustained process of combustion sets in with very rapid rise of temperature until the ignition point, which may lie between 300° and 400° C., is attained, when active combustion is set up.

It is evident that for coals to undergo this process certain chemical and physical conditions must exist. The chemical condition is the presence of unsaturated easily oxidized substances, but of the nature of these practically nothing is known. Demstedt and Biinz (*loc. cit.*) have proposed testing the finely divided coal by packing in a tube, with thermometer, passing carbon dioxide through the tube heated to 100–115° C. in an oil bath, to dry the coal, then raising the temperature to 135° or 150°, while dry oxygen is passed through at the rate of 2 to 3 litres per hour. Coals which heat up slightly above the bath temperature, and will heat up more rapidly and perhaps ignite on increasing the oxygen supply, are dangerous.

The physical conditions must be such that oxidation with accompanying generation of heat must be sufficiently rapid in relation to the cooling factors. Large surface—fineness of division—is essential to heating. It has always been noted that fires in coal cargoes start invariably under the hatchways, where there is great crushing, and that large coal never heats if free from smalls and particularly dust. For the heat generated by this oxidation to become serious it is obvious that the action must be cumulative, that is, that the heat shall not become dissipated to any great degree. A solid mass of coal is of a low order of thermal conductivity, and, when broken up, the air spaces further greatly lower its conductivity. Given a sufficiently large mass of coal with generation of heat taking place some distance from the surface, the escape of heat is prevented and the temperature at the affected part will rise until the self-sustained stage of oxidation is reached, ultimately resulting in firing if the supply of oxygen is sufficient to sustain rapid combustion. If this is not the case oxidation will proceed only to the limit of available oxygen, the rate will fall practically to zero, and the heated portion gradually cool off.

Experience shows that a large mass of coal in which conditions are favourable is far more likely to heat and finally ignite than smaller masses. In the case of coal cargoes this is particularly noticeable, statistics over one period showing that whilst the casualties for cargoes between 500 and 1000 tons were 1 per cent., with cargoes of over 2000 tons they amounted to 9 per cent. Again, there is a safe depth to which a coal may be stacked without risk, but it does not always follow that shallow stacks are safe, and fires have occurred within a few feet of the surface in deep stacks. It is difficult to see that mass alone should have any effect, provided there is sufficient to properly heat-insulate a zone where conditions of size, etc., are favourable to heating; rather should it retard that free accession of oxygen essential to the process. The explanation of this apparent effect of mass arises most probably through the greater quantity of smalls and dust produced in handling these large quantities.

Another important consideration is the effect of moisture in promoting heating, and very contradictory opinions are held on this point, due doubtless to the lack of distinction between moist coal and wet coal. In the Report of the New South Wales Commission on Spontaneous Ignition (1900), there appears an account of experiments with two bins 21 feet square loaded with the same coal, one kept dry and the other saturated from a hose until water ran off in a small stream. The dry coal heated, but the wet did not. The result was said to prove conclusively that dry coal was most dangerous, and that the view of the British Commission (1876), supported generally by evidence before other Commissions, that wet coal was most dangerous, should be abandoned. The experiment really proved only that when sufficient water was present to prevent appreciable access of oxygen to the coal surface, it would not heat. If the moisture present is not sufficient to exclude oxygen from the surface there is every reason for still believing that it will materially assist chemical action. Doane (*Eng. News*, 1904, 52, 141) states that the amount of moisture in an air-dried bituminous fuel is a measure of the risk from spontaneous ignition, and that bituminous coal with over 4·75 per cent. is most dangerous. There is little reason, however, for believing that moisture *per se* can be such an important factor. In the oxidation of pyrites it plays undoubtedly an important part.

The prevention of heating and ignition in coals liable to these changes evidently is primarily dependent upon prevention of oxidation at any centre being sufficiently rapid to more than counterbalance the natural cooling effect of the surrounding masses of coal. It is only in places where the surface area of a considerable quantity of coal in relation to its mass is very great, that is, where there is an accumulation of fine and dust surrounded by sufficient material to give the necessary heat insulation without cutting off the supply of oxygen, that heating can ever arise. With larger coal slow oxidation of the exterior faces alone is possible, and beyond slight deterioration can do no harm; it is the accumulation of masses of small coal which must be avoided. In loading cargoes with the usual tips such accumulation under hatchways is unavoidable; the distribution of such crushed material has been suggested, but obviously this would be a matter of difficulty in the hold of a ship, and the adoption of more modern methods which lessen the crushing is the correct solution of the problem. In stacking coal this distribution can be conveniently arranged, and small coal amongst larger sizes checks to a great degree the access of air to the mass; further, by building up in sections, or simultaneously, in more than one stack, a period may be allowed to elapse before successive layers are added, so that the initial oxidation may have made considerable progress in the top layer before another is added.

The "safe" depth to which coal may be stacked is dependent upon so many variables, such as length of time since mined, the character of the coal substance, and the proportion of "smalls," that it is impossible to give exact figures. One writer says the depth may be 20 feet in the open and 16 feet under cover, whilst an average depth of 13 feet and a maximum of 15 feet is frequently taken. A screened coal obviously may be stacked to a greater depth than one containing slack, and the above figures are frequently greatly exceeded without bad results following.

The question of providing ventilation to the coal in store is important. On the one hand, if air cannot penetrate with sufficient rapidity the oxygen gets slowly used up, the coal may heat a little, but will cool off slowly by conduction. On the other extreme, if the air supply could be sufficiently great, whilst oxidation would occur to the maximum extent possible for the temperature attained, the good air current would carry off the heat and again cool the mass. The whole difficulty in a stack or cargo is to provide this large excess of air, for if insufficient for any reason it will evidently promote ignition by freely supplying the necessary oxygen. It is a striking fact (1876 Commission Report), that in four vessels laden with between 1500 and 2000 tons of the same coals shipped at the same time at Newcastle for Bombay, only one arrived safely, and that the one in which no attempt was made at ventilation. It may be safely asserted that it is next to impossible to provide such adequate ventilation as to keep a stack or cargo cool, so that attention must be given to other methods indicated.

A careful record of the temperature in various parts of the coal should be taken by means of iron pipes bedded in, down which maximum recording thermometers may be inserted, and if the temperature is found to rise unduly, the upper layers should be removed. Any external source of heat, such as contact with warm pipes or bulkheads, must be carefully guarded against, since heat in the initial stages quickly results in the attainment of the dangerous heating stage. It is well recognized that a cargo shipped in the summer, especially after exposure to the hot sun, is far more liable to ignition for the same reason.

In view of the New South Wales results referred to above, it has been suggested that water from a hose should be played upon the coal accumulated beneath the hatchways when loading. It is estimated that 10 per cent. of water prevents heating, and assuming the coal as shipped contains from 2 to 3 per cent. of water, the additional water demanded would be 8 per cent. on approximately one-fifteenth of the whole cargo, equal to only a half per cent. on the total cargo (Threlfall, see *J. S. C. I.* 1909, 759). If the quantity of water could be maintained located in the crushed coal, it would, no doubt, be effective, but under the conditions existing in the hold it would almost certainly become more evenly distributed throughout the rest of the coal, when the net result would be the absence of a wet, safe, and limited mass of coal, and the presence of a *moist*, finely divided mass in a condition peculiarly liable to oxidation.

Lewes (*J. Gas Ltg.* 1906, 94, 33) recommends placing cylinders of liquid carbon dioxide at points where heating is probable, the cylinders being sealed with a fusible alloy melting at about 93° C., the valve being opened before the cylinder is placed. On rise of temperature the alloy would melt and allow the escape of the gas, which would quickly put an end to oxidation.

Coal Briquettes (Patent Fuel).—The necessity for utilizing the large quantities of small coal and slack obtained when the softer bituminous coals are worked and prepared for the market has led to great developments in the production of briquettes, and this will become an even more important question as the supplies of the better grades of coal become reduced. The world's production of this class of fuel is fully 30 million tons, of which nearly three-fourths are made in Germany; the output in Great Britain in 1910 was 1·6 million tons.

Although all bituminous coals will cohere under pressure when in a finely divided state, the blocks are too fragile for commercial use, so that some binding material is requisite. A large number of substances have been patented for this purpose, but in practice pitch, either from wood, petroleum, or coal tar, especially the latter, is always employed. The demand for pitch for this purpose on the Continent has greatly increased of recent years, and exercises considerable influence on the price of tar. The suitability of various binders has been fully investigated in the United States at the St. Louis Fuel Testing plant (*U. S. Bureau of Mines, Bulls.* 343, 385), and comparative steaming tests between the natural and briquetted coal carried out (*U. S. Geol. Surv., Bull.* 363).

The pitch used, whether from wood tar or coal tar, should be residues after all products distilling below 270° C. have been removed. Free carbon in any quantity is objectionable, and the quality is dependent largely upon a high percentage being soluble in carbon disulphide; those examined vary between 63 and 85 per cent. It should not flow below 70° C., and up to the limit at which the working of the machines is impeded, the higher the flowing point, the better, as the blocks then stand the fire best. Softening with heavy tar oils boiling above 270° C. is recommended for pitch so hard as to give trouble in the machines, or which does not possess the necessary spreading power to cover the coal particles. 6·5 to 8 per cent. of pitch (calculated on the coal) was found to give good results. Water gas, producer gas, blast furnace and coke oven tars were found to yield satisfactory pitch.

In the manufacture of briquettes the coal is reduced to a coarse powder, which, if wet, is dried in a suitable oven, and then incorporated with the broken pitch, first by passing them together through a disintegrator, and secondly in a suitable mixer, such as a pug mill. In order that the binder may be softened, the mixture is heated during incorporation either by "dry" or "live" steam, and then passed on to the press. According to Colquhoun (*Min. Proc. Inst. C. E.* **117**) the cost of briquetting, including capital charges, is approximately 2*s*. 7*d*. per ton additional to the cost of the fuel. The United States cost at the experimental plant was 4*s*. 2*d*. per ton.

The calorific value of the briquettes is slightly higher than that of the coal from which they are produced; the French Admiralty standard briquettes range between 8200 and 8500 calories. The specific gravity of the blocks averages 1·2, and the stowage capacity about 50 pounds per cubic foot; owing to the regular shape of the blocks it is possible to store a far greater number of potential heat units per cubic foot of space, a matter of considerable importance, especially in locomotive practice, for which briquettes are largely employed on the Continental and American railways. With careful firing the density of the smoke is less with the briquetted fuel, doubtless due to the more steady evolution of the smoke-producing elements, and within the practical limit of the variation of the binder the quantity of the latter has little influence on the smoke. The advantages gained by briquetting a given fuel do not appear to be commensurate with the cost if the fuel can be employed in any other way, but briquetting offers undoubtedly an economical means of employing fuel which otherwise would have little commercial value.

Powdered Coal as Fuel.—By the reduction of coal to a fine state of division, and carrying the powder forward into a furnace by an air blast, it is possible to obtain the most perfect combustion with entire absence of smoke, when using the smallest possible excess of air, and therefore with very high efficiency under a boiler. This method of using coal is employed largely in firing rotary cement kilns, in which a flame of great intensity and length is obtained, much resembling a large oil fuel flame, and considerable success has attended the application of powdered fuel in boiler practice.

From a large number of tests it is proved beyond question that high economy is obtained when powdered fuel is used for steam raising, that smoke is abolished, and that frequently an inferior fuel may be economically utilized. In one case Welsh coal at 27*s.* 6*d.* per ton was replaced by coal at 12*s.* 6*d.*; owing, however, to the inferior calorific value of the latter the consumption was increased.

The question resolves itself largely into the cost of an installation and its operation; but one difficulty requires special mention, namely, the deposition of dust (ashes) in flues, etc. It is usual to provide a large expansion chamber in which the heavier dust settles. The ashes frequently fuse at the high temperature attained, forming a vitreous glaze on iron-work and firebrick linings. Hughes (*Min. and Eng. World*, April 20th, 1912) says that this may be prevented by the incorporation of limestone dust.

Starting with a cheap bituminous slack, this is all reduced to a coarse powder through rolls, and before further reduction in size is practicable, is dried and then pulverized in some form of disintegrator or a ball mill. According to one authority (*Proc. Inst. C. E.* 1902, 147, 517) the best results are obtained when 90 per cent. of the powder will pass a sieve of 150 meshes to the inch.

A plant for dealing with 75 to 100 tons in 24 hours is estimated to require 25 H.P.—less than 1 per cent. of the power produced when coal is burnt under a boiler. The following data refer to power required to operate "Cyclone" pulverizers:—

18–20 cwt. per hour, 19 H.P.
25–40 ,, ,, 24 ,,
over 60 ,, ,, 40 ,,

and the cost at from 1*s.* to 1*s.* 2*d.* per ton.

Eustace Carey (*J. S. C. I.* 1905, 369), from practical experience with a 500 H.P. Stirling boiler, gives the following estimate, based on 500 tons ground per week by electric power, costing $\frac{1}{4}$*d.* per unit (a charge which will certainly be exceeded in general):—

	Day of 12 hours.		Day of 24 hours.	
	Capital charges and labour.	Power.	Capital charges and labour.	Power.
Drying and grinding	5·35*d.*	1·33*d.*	3·5 *d.*	1·33*d.*
Burning	4·12	0·27	2·58	0·27
	9·47	1·60	6·08	1·60
Total costs per ton	11·07		7·68	

In the Schwartz-Kopff plant the coal is distributed by a brush revolving at 800–1000 revolutions per minute on to a firebrick lining extending some 6 feet into the furnace. Carey also found that some kind of firebrick retort into which the dust-laden blast was sent was a good arrangement.

Dust-firing offers undoubtedly great advantages in boiler practice, especially over hand-firing, and is almost an ideal system for the combustion of coal; but as compared with a good installation of mechanical stokers, capable of dealing with a cheap class of fuel, its advantages are not so apparent. A comparison between cost of installation, renewals, and running costs for both systems does not appear to favour dust-firing, if one takes as a criterion the relative progress made in the introduction of the two systems.

C. A. King (*J. S. C. I.*, 1917, 114) records tests with a Bettington boiler, which is a vertical boiler; the coal is fed from a storage hopper into a pulverizer, which also acts as a fan for the air supply. Heated air for the injection and combustion of the coal is drawn from a tubular heater which is placed above the boiler in the smaller sizes and separately in larger installations. This acts as a "regenerator" and at the same time dries the coal passing through the disintegrator, and prevents clogging of a sieve placed between it and the water-cooled nozzle through which the dust is injected. The high temperature of the furnace converts the ash into a semi-liquid spray which coalesces on the fire-brick lining, slowly trickles down, and drips from the bottom edge into the ash-pit. Low fusibility of the ash would appear advantageous, but there would be risk of inclusion of unburnt carbon.

The following results may be quoted from the paper:—

	At normal load.	At 30 °/o overload.
Coal per hour	1,344 lbs.	1,736 lbs.
Water evaporated from and at 100° C.		
Total	12,300 lbs.	16,544 lbs.
Per lb. coal . . .	9·15	9·53
Boiler efficiency	76·9 per cent.	80·0 per cent.

The boiler was not credited with heating the water from main (12° C.) to the temperature of the feed-water tank (mean 44° C. at normal load), nor debited with power consumed in pulverizer. (29 E.H.P. — equal to 3 per cent. of the steam raised, assuming 15 lbs. of steam per K.W.)

Tests by Messrs. Burstall and Monkhouse with a poor quality slack, 16·2 per cent. ash on the *dry* coal, and 14·4 per cent. moisture as fired, gave an evaporation from and at 100° C. of 7·55 lbs. per lb. of coal, the boiler efficiency being 75·6 per cent.

Chapter VI

COKES AND COKING. SPECIAL FORMS OF COKE

Coke

For many generations charcoal was a fuel of great industrial importance and used entirely for the production of iron, for which it is particularly suitable by reason of its high calorific intensity and great purity. As the supplies were becoming depleted, restrictive legislation on its production was imposed, and it became necessary to find some efficient substitute. A fuel poor in volatile matter and with a rapid rate of combustion is essential for the high calorific intensity required, and this is best furnished by coke, the porosity of which ensures sufficiently rapid burning; anthracite, poor as it is in volatile matter and yet of good calorific value, fails by reason of its density. Consequent upon the introduction of coke, with its high resistance to crushing in the furnace and its good combustion with a hot blast at high pressure, it has been possible to increase greatly the size and output of the blast furnace.

By submitting a bituminous coal to a temperature of well over 1000° C. it loses practically the whole of its volatile constituents, which escape as gases and vapours, leaving behind a more or less hard cellular mass of coke. The hard, dense but cellular coke essential for metallurgical operations is yielded only by certain classes of coal, in which a perfect fusion takes place; owing to the escape of hydrocarbon gases and vapours a cellular structure is developed, which becomes fixed and hardened at the final high temperature attained, the finished mass retaining none of the characteristics of the parent coal. Reference already has been made (p. 38) to the probable nature of the constituents of coal on which coking is dependent and to the composition of coking coals. When coals contain less of these fusible constituents, as they approach the semi-bituminous coals on the one hand and lignitious coals on the other, the coke pieces retain more or less the original shape of the coal masses, and the material lacks strength.

Whilst the coke produced may for practical purposes be regarded as carbon together with the mineral matter of the coal, it is always found that hydrogen, oxygen and nitrogen are present, and it is possible to extract gases — principally carbon dioxide, carbon monoxide and hydrogen—from it on further heating in a vacuum. Coke, like all forms of carbon, possesses considerable absorptive power for gases and vapours, which accounts for the presence of some of these gases, and, in addition, some of the complex hydrocarbon bodies are extremely resistant to high temperatures. A well-carbonized coke should not yield more than 1 per cent of volatile matter (other than moisture) on submitting to strong ignition in a powdered condition.

Accompanying the hydrocarbon gases and vapours and their decomposition products is a portion of the sulphur and nitrogen of the coal. The escape of these volatile constituents necessarily leads to concentration of the mineral matter of the coal in the coke. Since a high ash is detrimental, the selection of a coal originally low in ash, or the reduction of the mineral matter by suitable picking and washing, is highly essential, and these processes have the further advantage of reducing the sulphur content of the charged coal (see Coal Washing, p. 70). During the process of carbonization a large proportion of the organic sulphur is driven off, together with some of the pyritic sulphur, and on quenching the hot coke there is a further escape of sulphur compounds. It is frequently assumed that the sulphur content of the coke is one-half that of the parent coal, but it is seldom found that less than 70 per cent. of the original sulphur is retained. The actual amount removed is not directly related to the total sulphur present, but depends mainly upon the relative proportions of organic sulphur, iron pyrites and sulphur as mineral sulphates. At the high temperature of the ovens the latter are probably reduced to sulphides, and remain as such in the coke.

Lowthian Bell gives the following figures for a coal yielding 74·4 per cent. of coke:—

	Before washing.	After washing.	Finished coke.
Ash	10·42	6·42	8·18
Sulphur	1·71	1·30	1·03

According to Fulton the percentage of residual sulphur in tests with American coals ranged from 85·25 to 42·08, with an average of 61·5. Andrew Short (*J. S. C. I.* 1907, 585) gives the following distribution of sulphur in the products from a Durham coal worked in an Otto-Hilgenstock oven :—

In coke	72·5 per cent.
In tar	1·45 ,,
In gas and liquors	25·72 ,,

The distribution of nitrogen among the products is also of importance in view of the recovery of by-products. The following data are given by Short (*loc. cit.*) :—

Observer	Foster.	Knublauch.	McLeod.	Short.
Nitrogen in coke . .	48·68	50·0	58·3	43·31
,, tar . . .	35·26	30·0	3·9	2·98
,, gas . . .			19·5	37·12
As ammonia compounds	14·50	12–14	17·1	15·16
As cyanogen compounds	1·56	2·0	1·2	1·43

It is important to note that the nitrogen retained in the coke is greater with quick carbonization. It may be fairly assumed that half the nitrogen remains in the coke, and in view of the profitable recovery of sulphate of ammonium and the economic aspects of recovery, the utilization of this residual nitrogen in coal gas coke, which is largely possible by gasifying in producers, the gas being used for the retorts, is receiving attention.

The calorific value (absolute heat value) of the combustible of coke will be practically that of pure coke carbon—8137 calories (14,645 B.Th.U.), so that the calorific value of a thoroughly carbonized dry coke will be given by

$$\frac{8137 \times (100 - \text{ash})}{100}$$

The value of coke, however, is more dependent upon its pyrometric heating effect, that is, the temperature attainable on combustion. This will depend principally upon the coke being sufficiently dense to enable a large number of heat units to be available in a small space ; on its being sufficiently porous for rapid combustion, *i.e.* on its offering a large surface ; on the resistance of the surface not actually undergoing proper combustion to the action of carbon dioxide, leading to the formation of carbon monoxide, the action absorbing heat. The presence of moisture will necessarily decrease the calorific intensity greatly. Increase of the air blast will intensify the effect up to a certain point for a given coke ; beyond this the large excess of nitrogen will lead to cooling, and similarly the use of a hot blast also increases the pyrometric heating power, since more air can be blown through without chilling.

Properties of Blast Furnace Coke.—*Hardness* is necessary to resist losses in drawing ovens and in handling, and in the furnace itself. Smalls favour the formation of stoppages, and by exposing great surface to the action of the hot ascending gases rich in carbon dioxide valuable carbon is lost as the monoxide in the furnace gases. Weill (*Re. de Metall.* 1905, 557) calculates the crushing stress in a 20 metre furnace as 1·7 kilos per square centimetre (Wedding had previously calculated 3·0 kilos per square centimetre for a 30 metre furnace). Since the resistance of coke to crushing ranges from 60 to 175 kilos per square centimetre, an average of 120 kilos being generally taken, breakage in the furnace is not due to simple crushing, but is the effect of intermittent slides and shocks.

Weill recommends a test in a drum of considerable diameter, rotating on a horizontal axis at 10 revolutions per minute for 15 minutes, the debris being afterwards graded and weighed. This certainly is superior to the usual crushing test on cubes of 1 centimetre, the results of which would appear of little value unless breakage by attrition can be correlated with absolute resistance to crushing, and these tests are open to the difficulty of obtaining and preparing representative cubes, and particularly cubes free from flaws.

The hardness of coke is increased by high temperatures and by the length of time of exposure to heat. It is consequently highest near the upper portion of the beehive product and near the walls of retorts. A narrow oven will yield harder coke generally than a wide one, unless the carbonization period in the latter is proportionately extended.

Density and Porosity.—In a blast furnace it is essential to maintain an atmosphere rich in carbon monoxide in the reduction zone, and a high temperature in the smelting zone. The latter is assured by the combustion of carbon to carbon dioxide, the former by the action of carbon dioxide on further masses of red hot carbon, according to the equation:

$$CO_2 + C = 2CO$$

The production of these conditions will be dependent largely on the porosity of the fuel and the resistance or otherwise of the cell walls to gaseous action. A highly porous fuel, such as wood charcoal, gives a high calorific intensity, burning practically at twice the rate of coke, but hot wood charcoal is converted into carbon monoxide by the dioxide at approximately twelve times the rate of coke. The relative porosity of the wood charcoal and coke may be taken as 2·6 to 1. High porosity and ease of attack by carbon dioxide would mean large losses of fuel in the upper portions of a furnace. High density means least liability to formation of carbon monoxide, and providing the blast is sufficient to ensure the requisite rapid burning to carbon dioxide, such dense coke will be the most efficient for foundry purposes, where it is obviously desirable to burn the maximum of carbon to the dioxide. In former days high porosity of the coke was essential to the formation of the necessary carbon monoxide by the secondary reaction of carbon dioxide on carbon in the blast furnace, and beehive coke with its hard cell walls, and frequently a ratio of cell space to cell wall of 1 to 1, was an ideal fuel. Under modern blast furnace conditions all coke is sufficiently porous to burn well, and the general tendency is in favour of denser cokes. Weill shows that a diminution of 20 per cent. in the volume of coke means an effective increase of 10 per cent. in the capacity of the furnace, when the volume of coke is assumed to equal half the volume of the charge.

Fulton states that the most desirable ratio of cellular space to cell wall is 44 to 56 (0·8–1), and that of average standard Connellsville (beehive) coke is 39·53 to 60·47 (0·67–1).

The *real specific gravity* of coke is that of the carbonaceous elements together with that of the ash. It is the specific gravity of the coke substance exclusive of the pores. The *apparent specific gravity* is the ratio of the whole coke, inclusive of pores, to that of an equal volume of water. This value is one of the most practical importance, and lies between 1·2 and 1·9. The porosity or volume occupied by the pores is found from—

$$\frac{(\text{real specific gravity} - \text{apparent sp. gr.}) \times 100}{\text{real specific gravity}}$$

For the determination of the real specific gravity all air has to be removed and replaced by water. If this is attempted in the unbroken material, water-tight cells will obviously lead to considerable error.

Ash.—Not only is high ash detrimental from the point of view of calorific value and possible influence on metal smelted, but its presence involves expenditure of additional flux in order that it may be removed properly as slag, and also entails an extra consumption of carbon to provide the necessary heat for fusion of this slag. Weill concludes that each per cent. extra ash lessens the value of coke per ton by 0·45 fr. Lürmann estimates that each per cent. difference means about half a ton greater or less consumption of coke for the daily operation of a furnace.

Water.—The amount present will be dependent primarily on the method of quenching; 4 to 5 per cent. is common, but in good Durham coke it seldom exceeds 1·5 to 2 per cent. Its presence entails expenditure of heat in evaporation. Lürmann estimates the daily consumption for a furnace to be increased or diminished by 0·125 ton for every per cent. of water. Weill, on the assumption that 1 lb. of water requires for its evaporation 0·2 lb. of carbon, estimates that each per cent. additional water entails an increased expenditure of 0·35 ton of coke, and this, together with the charges for water at coke prices, lowers the value per ton by 0·35 fr. (3*d.*) for each per cent.

Sulphur.—The extent of removal of this element during carbonization and quenching has been referred to already, and the effect of sulphur in promoting the formation of hard white brittle iron is well known. The extent to which iron takes up sulphur from the fuel is not definitely known, and much depends upon working conditions. Under the best conditions it should be combined with lime as calcium sulphide and sulphate ($4CaO + 4S = 3CaS + CaSO_4$), and pass off in the slag; but the slag will retain only a certain amount, largely dependent upon its other constituents. If this amount is exceeded, a greater proportion of fluxing material per ton of pig must be used. Assuming 1 per cent. as the normal sulphur in coke, Weill estimates that to convert this sulphur in 150 tons to calcium sulphide 3·3 tons of limestone are required, and for fusion and expulsion of carbon dioxide a consumption of 1·1 tons of coke. An additional 0·5 per cent. of sulphur is estimated to reduce the value of the coke 0·12 fr. per ton.

Most good cokes contain less than 1 per cent. sulphur. English cokes give a range from 0·75 to 1·3 per cent.

Phosphorus.—The importance of this element in coke is great, since it is generally agreed that the bulk of the phosphorus finds its way into the iron. For pig irons to be used for fine castings phosphorus is not detrimental, but in general its bad effects on iron and more particularly steel are well known. According to Weill, Durham cokes contain about 0·012 per cent.; South Wales, 0·022 to 0·05 per cent. In Pennsylvanian coke the average is 0·01 per cent.

Alkali Chlorides.—Weill regards alkali chlorides as particularly corrosive to furnace linings, although of no influence on the character of the iron. For this reason coke quenched with brine water may produce serious damage.

Production of Coke.—In the manufacture of metallurgical coke the object is to attain the highest possible yield of serviceable coke from a given coal, *i.e.* to fix as much of the carbon of the coal as possible in the coke at the sacrifice of the gas, which is virtually a by-product. Coke is also obtained in coal gas manufacture, but in this case it is a by-product, the primary object of the gas-maker being to obtain as much of the carbon as possible in the gas in the form of hydrocarbons of high illuminating or calorific power. Gas coke does not possess those properties so essential in metallurgical coke; it is less dense and more fragile, and has not that resistance to the action of furnace gases, largely by reason of the roughness of the cell walls and lack of the carbon "glaze" characteristic of good metallurgical coke.

The small shallow charges in ordinary gas retorts necessarily fail to yield fine largely developed coke masses, such as are obtained in coking ovens, and again the coal for gas making is not selected with regard to its suitability for yielding high-class coke. With the recent introduction of large chamber processes in the manufacture of gas the conditions closely resemble those in retort coke ovens, and the coke from a suitable coal can be made to approach closely to good metallurgical coke, but the higher temperature needed for this detracts largely from its value for general purposes, for which the great bulk of gasworks coke is sold.

The earliest methods of obtaining coke were similar to those in vogue for charcoal burning, the restricted combustion of the coal in piles or in stacks with brick flues, this partial combustion furnishing sufficient heat to carbonize the remainder; but such wasteful methods are practically obsolete. The natural development was combustion of the volatile constituents in a dome-shaped oven, arranged for suitable and easily-regulated air admission, above the surface of the coal, so that the heat slowly penetrated downwards and effectually coked the mass. These beehive ovens are still employed very largely in Great Britain and the United States, the "fat" coking coals in both countries being eminently suitable for use in them and yielding a coke of the highest quality, frequently unequalled by more refined processes.

The beehive ovens are from 12 to 13 feet in diameter, 7 feet high; the coal is charged to a depth of 2 feet 6 inches to 3 feet. To economize heat the ovens are built in two rows, back to back, with a common flue arranged down the centre, the waste heat passing off under boilers. A false door is built up above the level of the coal, and air is admitted to the evolved vapours in the upper space, where combustion takes place, and steady carbonization from above downwards proceeds. Modifications of the beehive oven have been made to permit of the more easy discharge of the coke, and in some cases recovery processes have met with some success, flues being arranged below the floor through which the evolved gases and vapours are drawn off.

For successful results in such ovens the coal must have good coking properties, as the temperature at which coking commences is low, and the rise of temperature not rapid, since the previous charge has been cooled in the oven by water, and the oven has usually been standing two or three hours before recharging.

The slow initial rate of heating promotes the formation of well-developed cell structure, and the final high temperature attained ensures a dense hard character to the product. Low temperatures lead to irregularity in coking, lack of coherence and inflated cell development. In beehive ovens it is impossible to prevent loss of carbon by burning from the coke substance itself, so that the yield for a particular coal is lower in these ovens than in retort ovens, and another consequence is that the upper layers have a higher ash content than the mass. A coal rich in volatile constituents ("fat") will derive sufficient heat from this source, but with a drier coal some of the heat for proper carbonization is derived from a portion of the coke substance.

The natural development to avoid the loss of coke substance was the introduction of ovens from which the combustion products could distil through suitable orifices in the walls, and meet the air necessary for combustion only in an exterior space. By the use of long horizontal rectangular ovens, closed by doors at the ends (Coppée), the coal could be charged conveniently and the coke pushed out by mechanical means; or in vertical ovens with a slight taper (Appolt) the coke could be dropped when the lower doors were opened. With the beehive ovens or ovens of the above pattern far more gas was utilized for heating than necessary, and although the waste heat was to some extent recovered by passing the gases through boilers, the losses were great, and further all the valuable by-products were lost.

The average yield of a retort oven as compared with a beehive oven working on the same coal will be approximately 10 per cent. higher. For a coal yielding 67 per cent. of coke in the beehive oven, the following products may be expected in a closed oven recovery plant:—

Coke	73–74	per cent.
Tar	4–6	,,
Ammonium sulphate	1–1·25	,,
Gas	10,000	cubic feet

The value of recovering these by-products and economically employing surplus gas is generally recognized, and the displacement of the old wasteful methods of carbonizing is rapidly taking place. Recovery plant coke was at one time regarded as inferior to beehive coke, and doubtless this was the case with the earlier product, but it is now generally admitted that an equally good and economical fuel can be obtained; the rapid replacement of beehive ovens by recovery plant would obviously have been impossible if the fuel were appreciably inferior.

Practically all modern ovens consist of long rectangular chambers, 30 to 35 feet long, 6 to 7 feet high, and 18 to 24 inches wide, closed by doors at either end, so that charging is performed at one end, the coke being pushed out by suitable discharging machinery and quenched at the other end. A number of ovens are built up side by side to form a battery, the bottoms being heated by combustion of the gas in sole flues, and the sides by a suitable arrangement of flues between adjacent ovens. The main differences between the numerous forms of coking plant are to be found in the arrangement of the flues in order to secure the most effective and uniform heating; on this the success of the operation is entirely dependent.

The discussion of these various forms of construction is outside the scope of this volume; in the earlier forms the side flues were horizontal, the hot gases passing from end to end two or three times (Simon-Carvè, Semet-Solvay, Hüssner, etc.); but now these are not so favourably regarded, preference being given to vertical flues (Coppée, Otto-Hoffmann, Otto-Hilgenstock, Koppers, new Simon-Carvè, Collin, etc.), since it is more easy to obtain uniform heating.

Modern recovery plants are constructed for working on the "waste heat" or "regenerative" principle. In the waste heat type the hot gaseous products of combustion pass through boilers where they meet any surplus gas, which undergoes combustion, so that steam is raised for works purposes. The temperature of the flue gases is from 920° C. to 1100° C. (1700 – 1950° F.), and with water-tube boilers two pounds of steam have been raised from and at 212° F. per lb. of coal carbonized; with Lancashire and similar boilers from 1 to 1·25 lbs. can be obtained.

In the regenerative system continuous or alternate methods are employed; with the first, the hot gases pass through suitable firebrick channels to the chimney, and the air for combustion passes in the reverse direction through parallel channels, and so becomes heated. In the alternate method, the arrangement is similar to that of Siemens, at least two chequers of firebrick being used; during the heating up of the one the other is imparting its heat to the incoming air, necessitating reversals at frequent intervals, so that the oven flues are at times acting as heating flues, and at others as exhaust flues. If the sections affected by the reversals are large, this leads to considerable trouble with brickwork through its alternate expansions and contractions, and the heating is never uniform. All modern improvements aim at the multiplication of the number of sections; in the most recent ovens reversals are confined to alternative vertical flues. In the latest Koppers plant each oven has its own regenerator beneath the sole flue.

With regeneration only a portion of the distillation gases are required for heating the ovens, so that there is considerable surplus gas which may be employed very profitably in gas engines for power production. Naturally this surplus entirely depends upon the character of the coal, and with "fat" coals frequently reaches

50 per cent. Much of this gas is available for illumination purposes, which, together with the composition of the coke-oven gas, is fully dealt with under Gaseous Fuel (p. 191), and estimates of the power available by its use in gas engines on p. 192.

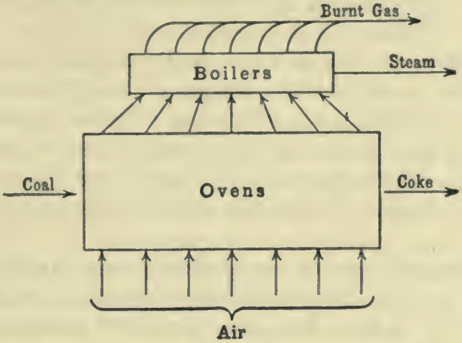

Fig. 3.—Coke oven plant, non-recovery of by-products.

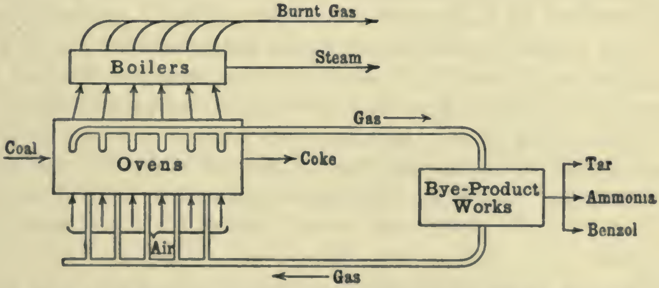

Fig. 4.—Coke oven plant, by-product recovery, waste heat type.

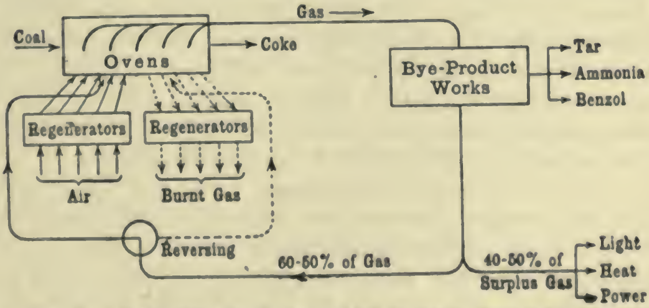

Fig. 5.—Coke oven plant, by-product recovery, regenerative type.

The distinctive arrangement of the three types, non-recovery plant and recovery plant with waste heat and with regeneration will be made clear by the diagrammatic plans shown in Figs. 3, 4 and 5.

In coking the best results are obtained with coal of small size, which enables small coal, fine washings, etc., otherwise of little value, to be utilized economically. Larger coal for coking is usually crushed. In modern plants the crushed coal is compressed in a stamper and charged into the oven in a solid mass slightly smaller than the inner dimensions of the ovens. From 10 to 12 per cent. of moisture is usual in the crushed coal, and this ensures sufficient binding for the mass to retain its proper shape when the retaining walls of the compressor are let down. The moisture also prevents the loss of fine coal dust in the gases evolved, which takes place with dry fine coal. By compression a charge some 25 per cent. heavier can be got into each oven, and the coke produced is firmer and more dense.

The charges and time of carbonization vary greatly with the type of oven and to some extent with the nature of the coal. Beehive ovens take from 5 to 7 tons, the period of carbonization running respectively to 48 hours and 96 hours. Six tons with 72 hours' carbonization is fairly general. The coal carbonized per oven per week averages 20 to 24 tons; the output of coke necessarily varies with the volatile constituents of the coal and the losses in the carbonization, 60 to 65 per cent. is a fair average. Modern retort ovens deal with some 40 tons per oven per week, this with a 72 per cent. yield giving 29 to 30 tons of coke. A modern battery of Koppers ovens in South Wales, working on a coal with 19·5 per cent. of volatile matter, takes an average charge of 6·8 tons of coal, and carbonizes it in 28 hours, with a coke yield of 81·75 per cent. (on the dry coal).

Influence of Conditions on the Coke.—The suitability of modern recovery plant coke and its efficiency as compared with beehive coke is no longer questioned. The poorer results with earlier retort cokes were due probably to an insufficient temperature being attained, with consequent lack of hardness in the cell walls. A. J. Moxham records a maximum temperature in a beehive oven of 1520° C. (2770° F.), but this is probably excessive. In the flues of earlier recovery plants 1100° C. to 1200° C. (2010–2190° F.) have been recorded.

The beehive oven is sometimes stated to be the only suitable one for the "fat" coals of the northern counties, but Professor O'Shea (*J. S. C. I.* 1911, 938) gives statistics for 1909 showing that in Yorkshire over 28 per cent. of by-product ovens were in use, carbonizing coals with an average volatile matter of 32·6 per cent. Generally, statistics show the steady replacement of beehive ovens by recovery plant, and in view of the larger weekly output per oven the actual amount of "fat" coking coals treated must be considerable. Many "lean" coals fail to yield a serviceable coke, unless treated in a retort oven with quick heating, and the more general introduction of recovery plant on the Continent is due largely to the fact that the bulk of the coals yield a satisfactory coke only in such ovens.

In beehive ovens practically the whole heating effect is from above downwards, the upper layers being carbonized first, and then maintained at a high temperature. As successive layers undergo distillation the hydrocarbon gases and vapours have to pass through these superimposed incandescent layers of carbon. It is well known that under these conditions the hydrocarbons break up and deposit their carbon on heated surfaces, and to this is usually ascribed the peculiar light grey and highly glazed surface of beehive coke, to which it owes largely its valuable property of resistance to the action of carbon dioxide in the upper regions of the blast furnace. The chances of penetration of these gases through intact cell walls is, however, so remote that this explanation seems improbable, except for exposed surfaces. It is more probable that the earlier noted differences in appearance and the character of the cell walls between beehive and retort cokes were due to different conditions subsequent to carbonization. Beehive coke was quenched in the oven, and there was no chance of access of air to hot surfaces of coke. In retort ovens the coke is pushed from the furnace and then quenched. That minimum chance of oxidation and rapid cooling are essential to good appearance is recognized, and in modern plants sprinklers are arranged to spray the coke immediately and thoroughly as it leaves the oven. The best results are said to be obtained with steam quenching.

One authority states that 1 cubic metre (220 gals.) is requisite for quenching each ton of coke. Dirty water will detract certainly from the appearance, and the possible action of alkali chlorides from the water has been referred to already.

When any portion of the charge does not reach a sufficient temperature the coal is imperfectly carbonized, and "black-heads" appear in the coke. With beehive ovens this was found to take place at the bottom, and the withdrawal of the products through bottom flues was the remedy. In retort ovens such black-heads are found at the doors.

For the development of good cell structure the fused coal must be free to "rise" as the gases are evolved; it is found that the lower portions of beehive coke are more dense than the upper; similarly, with the relatively thin bed of some 2 feet 6 inches in these ovens the coke from a given coal is less dense than that produced in a retort oven, where the depth of fuel is some 5 feet.

The best conditions of treatment for a coal can be arrived at only by proper works trials, but in general, for good cell structure to be developed, the viscosity of the decomposing mass must be either inherently high enough, or by decomposition become so, to remain in the distended condition until the walls harden by subsequent heating. If less viscid the walls will again collapse, and the cell development be poor. Many "fat" coals give a viscous mass at moderate temperatures, and inflated cell structure results; at higher temperatures a more fluid condition is attained, so that by quick heating through the pasty stage a denser coke results. With fairly dry coals prolonged heating at moderate temperature leads to volatilization or decomposition of those constituents essential to the production of the viscous bodies, and here again satisfactory coke can be produced only in quick ovens, such coal often failing to yield good coke in beehive ovens.

Recovery of By-products.—The system universal until quite recently and still most generally employed was exactly similar to that in the gas industry—condensation of the tar and ammonia liquor, and water-washing to abstract ammonia from the cooled gases. For gas engine use the gases are afterwards cleansed by filtration; in some cases iron oxide purification from sulphur compounds is also practised. Where benzene is to be recovered the gases are washed with creosote oil, from which the benzene is removed by distillation.

Several improved systems of treatment have been introduced which simplify and cheapen the process and do away with objectionable effluents. In the Otto and Simon-Carvè systems the idea is to remove the tar at a temperature above the dew point of the gas (70° C.), in the first case by a tar spray and in the second mechanically, and then to pass the warm moist gases through the usual sulphuric acid saturators to form ammonium sulphate. In the Koppers and one or two other systems the gases are cooled to about 20–25° C., passed through a mechanical tar separator, the cooled gases re-heated to 70° C. by the waste heat from the hot crude gases, and then delivered into the sulphuric acid saturator. To recover benzene in either of these processes the gases must be again cooled after the acid saturators; much water separates but contains no objectionable solids, and the benzene is recovered by the usual oil washing.

Most ingenious processes are attaining importance, whereby the sulphur in the coal is made to furnish the necessary sulphuric acid—by a series of intermediate reactions which need not be detailed—for the conversion of the ammonia into sulphate. The cost of sulphuric acid is ordinarily a fair charge on the working of ammonia plant, but all coal contains more than enough sulphur to satisfy the ammonia evolved, and by the utilization of this sulphur great economies should be possible. In the Burkheiser process that portion of the gases burnt under the ovens yields sulphur dioxide among its products; the sulphur compounds in the gases not burnt (or in coal gas) are removed by a special form of iron oxide, which yields sulphur dioxide when a blast of air is subsequently sent through it, and regenerates the active iron oxide, the sulphur dioxide forming with ammonia its sulphite, and finally the sulphate.

Further information on these modern processes may be found in the following articles:—

"Coke Manufacture," Andrew Short, *J. S. C. I.* 1910, 926.

"Koppers Plant," *Jour. Gas Ltg.* 1911, **113**, 777.

"By-product Coking Process," Ernest Bury, *Jour. Gas Ltg.* 1911, **113**, 917.

"The Burkheiser Process," *Jour. Gas Ltg.* 1911, **113**, 369.

"Direct Ammonia Recovery Processes," *Jour. Gas Ltg.* 1911, **116**, 607.

"Recovery of Benzol," D. G. Bagley, *Iron and Coal Trades Review*, August 18th, 1911.

Economic Aspects of By-product Recovery.—The recovery of the valuable by-products, tar and ammonia, and the effective utilization of the gases are questions of enormous national importance, when consideration is given to the limited supplies of coal and the enormous waste in its conversion into coke. Suitable small coal, otherwise of little value, may be converted most profitably into a good-priced coke, so offering considerable economies; if by-products are at the same time recovered, these economies are greatly enhanced, both from the larger yield of coke and the value of the by-products.

The amount of coal carbonized annually in Great Britain is approximately 35·5 million tons, yielding 19 million tons of coke, 7·5 millions of which are from gasworks and 11·5 to 12 million tons from special coking plant. Statistics show a steady replacement during recent years of beehive ovens by retort ovens, and a steady increase in the number of by-product recovery plants. W. H. Coleman states that of the total coke used for metallurgical processes, in 1906 the by-product recovery coke was 17 per cent., in 1910 it was 34 per cent. The amount of ammonium sulphate recovered from coke oven plant is an excellent guide to the progress made, and reference to the diagram (Fig. 45, p. 256), giving the production from various sources during recent years, shows the rapid increase from this first source. In spite of the total increase in production the price has risen rather than declined, and there seems no reason for supposing that, even were all the available nitrogen recovered as ammonium salts in the various processes for gasifying coal, any great depreciation in the market price would result.

A fair working yield of ammonium sulphate per ton of coal may be taken as 18 lbs., and from the latest returns it would appear that on this basis about 8 to 8·5 million tons of coal are at present coked in recovery plants (excluding gas works), representing nearly half the total amount carbonized. The recovery of sulphate from the remainder would yield about £1,200,000, and to this must be added the value of the tar. The development of the Diesel engine has rendered crude tar available as a fuel, and for this purpose there is likely to be a considerable demand. Further, the greatly increased importance which benzene is likely to assume for high-speed internal combustion engines must also be taken into consideration. In addition to the economic value of the by-products themselves, the direct saving of coal which is possible through an increase in the quantity of surplus gas and the better utilization of the waste gases is very large.

The estimates of power available per ton of coal carbonized given in Table XXI. are based upon figures commonly obtained in practice—

TABLE XXI.

HORSE-POWER PER TON OF COAL CARBONIZED IN COKING OVENS.

Steam.			Gas.	
Steam raised per lb. of coal carbonized . .	1·25 lbs.		Surplus gas per ton of coal carbonized .	5000 cu. ft.
	Reciprocating engines.	Turbines.		
Steam required per B.H.P. (or S.H.P.)	15 lbs.	11 lbs.	Heat units required per B.H.P. . .	9500 (27 p.c. eff.)
H.P. per ton . . .	$\frac{2240 \times 1{\cdot}25}{15}$ $= 187$	$\frac{2240 \times 1{\cdot}25}{11}$ $= 255$	$\frac{5000 \times 500}{9500}$ $= 266$	

Results of tests on coke oven gas at the Cockerill Company's works showed that for 1 KW. at the terminals, the consumption of gas was 35·3 cu. ft. of a calorific value of 450 B.Th.U.—approximately 9000 B.Th.U. per B.H.P. on the gas engine with 95 per cent. efficiency of the generator. H. G. Colman gives the consumption of 458 B.Th.U. gas in a Nurnberg engine of 1200 H.P., working at 100 revolutions, as 21·3 cu. ft. per B.H.P., equal to 9750 B.Th.U. per H.P.

It may be estimated that a coke oven plant carbonizing 400 tons per day and giving 50 per cent. surplus gas, will with large modern gas engines consuming 21 cubic feet per B.H.P. operate a power plant of 4000 B.H.P. per hour.

Coke oven gas is dealt with under Gaseous Fuels, Chapter XI., and further reference made to the by-products.

SPECIAL FORMS OF COKE

Coalite.—This special form of coke was introduced primarily with the idea of providing a smokeless fuel capable of being burnt easily in the ordinary domestic grate, and ignited directly in the usual manner with wood. To obtain these results, distillation at a low red heat (about 400° C. or 750° F.) was employed, and at this temperature the fully carbonized coke was comparatively soft and porous, and still contained a considerable proportion of volatile matter, which characters rendered it easy of ignition and free burning. In an open grate a more perfect fuel has never been employed. In the more recent form of the several systems experimented with, the retorts were long cylindrical iron tubes with a slight taper from the top downwards, eight of these being cast in two rows side by side. The distillation products were led off at the top, and passed through the usual condensers and washers for the recovery of tar and ammonia, and the purified gas was led into holders. The quantity of gas yielded was approximately half that obtained in gasworks practice, 5000 cubic feet per ton, and it differed widely in composition from ordinary coal gas, being rich in methane and other hydrocarbons and relatively poor in hydrogen. Its candle power was therefore high, frequently amounting to over 20 candles. The yield of tar averaged 21 gallons per ton, and its character was widely different from that of ordinary gasworks tar, being of lower density, and poor in aromatic hydrocarbons (benzene, etc.); naphthalene and anthracene were practically absent, but a fair proportion of liquid paraffin hydrocarbons and hydrocarbons of the hydro-aromatic series were present. Phenol or carbolic acid was practically absent, but the higher tar acids—cresylic, etc.—were present in far greater quantity than in coal tar.

The average proximate composition of a large number of samples examined by the writer gave, in the dry state—

Volatile matter	10·37 per cent.
Coke	89·63 „

Calculated on the pure combustible, the results were—

Volatile hydrocarbons	11 per cent.
Fixed carbon	89 „

In the production of a successful fuel of this nature it was essential to have a uniform character, *i.e.* the amount of volatile matter in the core should be but little greater than that on the outside. This could be accomplished in a reasonable carbonization period only by treating in thin masses, which led to the introduction of narrow tubes. The choice of coal was thus restricted owing to difficulties in getting the coalite to drop out, or, in other samples, the swelling at the low temperatures was so pronounced that serious trouble at the mouthpiece was experienced. In a narrow tube the escape of the gas upwards from the botton portions of the charge was greatly impeded by the semi-fused coal above. The disposal or economic utilization of the gas was another difficulty.

S. H. Parr and H. L. Olin (*Bull.* 60 (1913) *Eng. Exp. Station, Univ. of Illinois*) record experiments in coking coal at low temperatures (450° C. or 840° F.) by means of superheated steam, which has no chemical action on the coal at this temperature. The following yields are given :—

Coke	75 – 80 per cent.	Ammonia	0·8 lb. per ton
Tar	8 ,,	Gas	1100 cu. ft. ,,

The exclusion of oxygen is stated to be essential for obtaining good coke in low temperature carbonization, and pressure must be applied during the process to obtain firm blocks.

Charco and Coalexld.—In these forms of fuel attempts were made to overcome the drawbacks to the domestic use of gas coke either by special conditions of cooling (Charco), or by the addition of small—almost infinitesimal—amounts of chemicals to the retort charge (Coalexld). By preventing the access of air to the coke by means of a 6 to 8 inch layer of coke breeze, the resulting coke was said to burn without the crackling noise of quenched coke, and to remain alight with ordinary draught. It is difficult to see why this method of cooling should give better results as far as burning when compared with coke which had not been treated with an undue excess of water; it was claimed that the slow cooling was more of the character of "annealing" and considerably modified the character of the product.

Coalexld.—Coalexld was produced by the addition to an average coal of 14 ounces of potassium chlorate, 6 ounces of potassium nitrate, and a quarter ounce of potassium permanganate to 1 ton of coal before charging the retort; in all 20·25 ounces in 35,840 ounces. This minute quantity of chemicals, which on decomposition by heat can only evolve oxygen, was claimed to improve the coke, making it burn better and give out more heat and prevent clinkering. With very inferior coking coal a larger quantity of the mixture was claimed to make the coke of a good character.

Carefully conducted tests on Coalexld are recorded by Mr. H. Kendricks before the Manchester District Institution of Gas Engineers, 1910 (*Jour. Gas Ltg.* 1910, 109, 580), on the effect of the process on the gas, tar and coke. So slight are the differences that they fall well within the range of slight variation in conditions and unavoidable experimental error.

Through the kindness of Professor Vivian B. Lewes, samples of coke, Charco, and Coalexld, produced as nearly as possible under the same conditions from the same coal, were obtained and examined by the author with the results given in Table XXII.

TABLE XXII.

ANALYSES OF COKE, CHARCO AND COALEXLD.

	Ordinary coke.	Charco.	Coalexld.
Proximate analysis on the dry sample—			
Volatile matter	4·36	2·52	2·40
Ash	6·00	5·53	6·08
Analysis on the pure combustible—			
Carbon	94·45	96·09	95·82
Hydrogen	1·26	0·69	0·88
Sulphur	0·50	0·42	0·46
Oxygen and nitrogen	3·79	2·80	2·84
Calorific value on the pure combustible (Mahler bomb)—			
Calories per kilo	8,450	8,150	8,240
B.Th.U. per lb.	15,200	14,670	14,840

It is impossible to arrange that carbonization is carried just to the same point in each case on a large scale, but with all possible allowance for the higher volatile matter in the ordinary coke, there appears no ground for believing that these special cokes are an improvement on ordinary coke, unless in a manner undiscoverable by chemical analysis or determination of calorific value.

A large sample of ground Coalexld was extracted with water, and its calorific value in the Mahler bomb compared with that of the original. The results obtained were—

Coalexld	7140 calories	12,880 B.Th.U.
Coke residue	7154 „	12,850 „

the difference being well within the limit of experimental error.

PART II

LIQUID FUEL

CHAPTER VII

COMPOSITION AND CHARACTER OF FUEL OILS

UNTIL within the past decade it was generally understood that a liquid fuel was a heavy oil capable of being burnt for steam-raising or for heating operations in metallurgical or other furnaces, but the term has acquired much wider significance since the introduction of the internal combustion engine. Within recent years the marvellous development of such engines and their application to the motor-car, the submarine, the dirigible balloon and aeroplane, which have completely revolutionized our ideas of locomotion, and rendered possible that mastery of the sea in submerged craft and the conquest of the air so long sought by man, have been possible only by reason of the suitability of light oils or spirits for such engines, enabling the maximum of heat units to be carried in minimum space and efficiently employed in the engine.

Liquid fuel for external combustion must now be relegated to the second place in importance for power purposes, and fuels suitable for internal combustion engines regarded as the principal liquid fuels, and these are increasing daily in relative importance with the application of heavy oil-fired engines of the Diesel type. Heavy fuel oil, however, has played no small part in the development of our maritime power; to the splendid results obtained by oil-firing in conjunction with the use of turbines the marvellous power and speed of battleships of all types must be ascribed in a large measure.

The consideration of liquid fuels is, for convenience, divided into two sections; in the first, fuels suitable for external combustion are dealt with; and in the second, fuels for internal combustion engines, but no hard and fast line can be drawn actually between the two, for an oil of suitably high flash-point for burning is equally applicable for use in engines of the Diesel type.

Liquid Fuel for Steam-raising.—The advantages of liquid fuel for steam-raising as compared with coal are very great, and may be summarized as—

High Calorific Value: 1 lb. of oil fuel averages 19,500 B.Th.U. as compared with 12,500 B.Th.U. for average coal. This is due to the inherent high calorific value of the hydrocarbon constituents, and to the high purity of oils, the non-combustible matter usually being almost negligible.

The theoretical evaporative value of petroleum fuel oil is thus about 20 lbs.; one eminent firm will guarantee 16·5 lbs. from and at 212° F. when the rate of evaporation does not exceed 4–5 lbs. per square foot of surface, and 14 lbs. with evaporation at the rate of 16 lbs. per square foot.

Low Stowage Value: 1 ton of oil averages 38 cubic feet as against an average for coal of 43 cubic feet.

The high calorific value and low stowage value enable a greater number of heat units to be carried or stored per cubic foot of space than for coal in the ratio of 1·7 to 1.

Further, oil can be stored on shore in tanks below the ground level, thus economizing in space, or on board ship stored in fore or aft compartments or the double bottoms, situations impossible for solid fuel, the bunkers for which must be situated conveniently in relation to the stoke-hold.

These properties, in the case of vessels of the mercantile marine, leave valuable space free for cargo; in battleships, they add enormously to the radius of action of the vessel.

Easy Control of Consumption: this being effected by opening or closing the valve, or by putting into or out of action additional burners, is a simple operation, and any desired rate of steam production can readily be ensured; further, a steady steam pressure can be assured.

Economy in Staff: control being so easy and the heavy labour in coal-trimming and handling abolished, great reductions of stoke-hold staff are possible. This is important in the mercantile marine from the point of view of wages and provisions. In the Navy it means a reduction in the crew, with less loss of life in the event of a vessel being sunk in action, and a greater proportion of the crew available for fighting the ship.

Many examples of reduction in staff might be quoted; all show that one man with oil may reasonably replace six to eight with coal. Kermode estimates that the firemen on a large liner (*Lusitania*), numbering 312, could be replaced by 27 men if oil-firing were adopted, and with wages at 28*s.* per week, a weekly saving of £256 would be possible.

Cleanliness: Bunkering with coal, especially on board ship, must be always an extremely dirty process, and result in valuable time being spent in cleaning up. Since oil can be pumped through suitable hose directly into the tanks no dirt is distributed. Further, in the case of battleships, the practicability of taking in oil supplies in this manner while under way at sea is an important matter.

Again, oil burns without residue, so that the handling and disposal of ashes, clinker, etc., are obviated. The amount of inert matter in the form of ash carried with coal is often overlooked; 2000 tons of bunker coal with 5 per cent. of ash means shipping no less than 100 tons of useless material. The absence of ash, moreover, leads to better efficiency, as the opening of the doors for cleaning the fires is rendered unnecessary.

Other minor advantages are the non-deterioration of oil in storage; the absence of danger from bunker explosions with oil of satisfactory flash-point, lower stoke-hold temperatures, no corrosion of the bunker plates, and the abolition of the excessive physical exertion in stoking.

The advantages of liquid fuel are not confined to steam-raising; its high intensity of combustion, and the ease with which a steady temperature can be maintained over a long period, and the facility of control are very favourable to its use in many metallurgical and other industrial operations. For many purposes the absence of ash and the low sulphur content of most oils are greatly in favour of its employment.

The advantages to be derived from the use of liquid fuel in place of coal are unquestionable, and the matter resolves itself largely into considerations of supplies and price. In the British Dominions generally, and in Great Britain in particular, the bulk of oil suitable for fuel must always be imported, and the continuity of supplies, which has even under peace conditions suffered interruption, with consequent great advance in price, demands careful consideration. The economic aspects of oil fuel are deferred for discussion in a later chapter.

Characters necessary in a Fuel Oil.—The oil should have a high calorific value; the highest will be found with those oils consisting almost entirely of pure liquid hydrocarbons. Oils containing any quantity of oxygen compounds, such as tar oils, have necessarily a lower calorific value. For safety in use the oil must not give off inflammable vapour until a temperature well above any likely to be attained in use is reached, that is, its *Flash-Point* must be high. In the mercantile marine the flash-point must not be lower than 150° F.

(close test), and for Naval use below 200°F.[1] In order that the oil may flow readily through pipes it must not be too viscous at ordinary temperatures. Many natural oils and residues contain so much solid hydrocarbon in solution that on lowering the temperature they become semi-solid. The oil should be as free from water as possible, or there is a risk of the burners being extinguished, and free from solid matter, otherwise the fine orifices of the burners will become choked.

The following abstract of the oil fuel specification drawn up by the United States Bureau of Mines (Technical Paper, No. 3, 1911), summarizes admirably the desirable characters and other important points:—

Fuel oil should be either a natural homogeneous oil or a homogeneous residue from a natural oil; if the latter, all the constituents having a low flash-point should have been removed by distillation, but not at such high temperature as to produce free carbon; it should not be a mixture of a light and heavy oil mixed to give the right gravity.

Range of Specific Gravity.—0·85 to 0·96 at 15° C.: rejection is above 0·97.

Flash-point.—In Abel-Pensky or Pensky-Marten, 60° C. (140° F.).

Mobility.—It should be mobile, free from solid or semi-solid bodies; should flow readily at ordinary temperatures under a head of 1 foot of oil through a 4-inch pipe, 10 feet in length.

It should not congeal or become too sluggish to flow at 0° C.

Calorific Value.—Not less than 18,000 B.Th.U. per lb.; 18,450 B.Th.U. to be the standard. Bonus or penalty clauses are inserted in the contracts.

Water.—Reject if above 2 per cent.

Sulphur.—Reject if above 1 per cent.

Sand, Clay and Dirt.—Not contain more than a trace.

All particulars as to source of oil, where distilled, nature of oil, must be stated.

Sampling.—Sampled on delivery, and from the bulk of samples another shall be drawn which should represent fairly the bulk.

Care is required that samples from a tank, etc., shall be fair. Sampling by dipping must be from all parts.

A good method is to take a 1-inch tube long enough to reach to the bottom of the tank. A conical plug is fitted to the bottom, and a stiff, strong wire runs up through the tube. The plug is allowed to hang below the bottom end, and the tube is slowly pushed down into the oil, so as to cut a core. When the tube is nearly at the bottom, the wire is pulled to get the plug into the end of the tube, which is

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[1] For Admiralty specification, see page 109.

then struck firmly on the bottom of the tank, this driving the plug well home.

It may be desirable to take cores at several points.

Weight from Volume.—Observed specific gravity for each degree above or below 15° C., add or subtract 0·0006.

Weight of 1 gallon[1] in lbs = 8·3316 × (correct specific gravity).
" 1 cubic ft. " = 62·3425 × (" " ").

The following is a copy of the specification issued by the Admiralty (1913):—

1. *Quality.*—The Oil fuel supplied under this Contract shall consist of Liquid Hydrocarbons, and may be either :—

(*a*) Shale Oil; or

(*b*) Petroleum as may be required; or

(*c*) A distillate or a residual product of petroleum; and shall comply with the Admiralty requirements as regards flash-point, fluidity at low temperatures, percentage of sulphur, presence of water, acidity and freedom from impurities.

The *flash-point* shall not be lower than 175° F. close test (Abel or Pensky-Martens). [In the case of oils of exceptionally low viscosity such as distillates from shale, the flash point must be not less than 200° F.]

The proportion of *sulphur* contained in the Oil shall not exceed 3·00 per cent.

The Oil fuel supplied shall be as free as possible from *acid*, and in any case the quantity of acid must not exceed 0·05 per cent., calculated as oleic acid, when tested by shaking up the Oil with distilled water, and determining by titration with decinormal alkali the amount of acid extracted by the water, methyl orange being used as indicator.

The quantity of *water* delivered with the Oil shall not exceed 0·5 per cent.

The *viscosity* of the Oil supplied shall not exceed 2000 seconds for an outflow of 50 cubic centimetres at a temperature of 32° F., as determined by Sir Boverton Redwood's Standard Viscometer (Admiralty type for testing Oil fuel, p. 310).

The Oil supplied shall be free from earthy, carbonaceous, or fibrous matter, or other impurities which are likely to choke the burners.

The Oil shall, if required by the Inspecting Officer, be strained by being pumped on discharge from the tanks, or Tank Steamers, through filters of wire gauze having 16 meshes to the inch.

The quality and kind of Oil supplied shall be fully described. The original source from which the Oil has been obtained shall be stated in detail, as well as the treatment to which it has been subjected, and the place at which it has been treated.

The ratio which the Oil supplied bears to the original crude oil should also be stated as a percentage.

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[1] This refers to the United States gallon, of which there are 42 to the barrel of oil; equal to 35 Imperial gallons. The weight of the Imperial gallon of oil will be the corrected gravity × 10, since there are 10 lbs. to the Imperial gallon of water.

Available Oil Fuels.—The available oil fuels are heavier portions of natural petroleums and shale oils, tar oils derived from coal distillation, blast furnace tar, water gas tar, and tar from gas producers.

PETROLEUM

As crude petroleum is the source from which the bulk of oil fuels —ranging from petrol to heavy oil—is obtained, its general characters and distillation may be described conveniently here, the individual distillates being considered more fully later.

Petroleum occurs widely distributed throughout the world, but the two greatest oil-producing regions are those of America and the Russian fields. Within recent years the oil fields of California, Texas, and Mexico have assumed considerable importance. In the East, oil is found in quantity in Burma and the Eastern Archipelago, notably Borneo. The British Empire does not contain any important oil fields, but there are small outputs of oil in Canada, Australia, New Zealand, Newfoundland, Trinidad, and Barbadoes. Table III. (Appendix) shows the world's output in barrels of 42 gallons (United States Geological Survey).

Physical Characters.—The origin of petroleum is still a matter of debate and need not be considered here. As obtained from the borings it varies in colour from a light yellow to almost black; some oils are highly mobile, whilst others are thick and viscid. Sir Boverton Redwood found the lowest specific gravity (0·771) in samples from Washington, U.S.A., and Sumatra, and the highest (1·06) in a Mexican sample. According to the same authority, the range for American oils is between 0·785 and 0·945, and for Baku oils 0·85 to 0·90.

The *flash-point* may be from below the freezing-point of water up to 320° F.

The *coefficient of expansion* (the ratio of the increase in volume for 1° to the original volume) with rise of temperature is an important property, and due allowance must be made for this in estimating deliveries under different temperature conditions. The lower the specific gravity of the oils the greater is the rate of expansion. For heavy oils, this is 0·0007 per ° C. (0·00039 per ° F.), and for lighter oils 0·00072–0·00076 per ° C. (0·00040–0·00042 per ° F.). For Roumanian petroleum Petroni gives—

Specific gravity.	Coefficient of expansion per °C.
0·730 — 0·820	0 0009 — 0·0010
0·830 — 0·870	0·0008 — 0·0009
0·870 — 0·910	0·0007 — 0·0008

Sir Boverton Redwood states that the following values may be taken in practice for expansion per degree Fahrenheit:—

Oils lighter than kerosene	0·0004–0·00048
Kerosene	0·0004
Gas oils	0·00036
Lubricating oils	0·00034

The *viscosity* of petroleum oils varies greatly even with oils from the same district. It increases with rise of specific gravity, the higher value for both being dependent mainly upon the presence of heavier hydrocarbons, possibly solid paraffins held in solution by the higher liquid paraffins, but no connection can be traced between viscosity and specific gravity, oils of the same specific gravity varying widely in viscosity. Increase of temperature causes a rapid decrease in the viscosity, and a rise of a few degrees will often cause a sluggish oil to flow freely.

The *specific heat* is frequently important, since it is often necessary to heat fuel oils before use. The specific heat decreases almost *pro rata* with a rise in specific gravity. Mabery and Goldstein (*Amer. Chem. Jour.* 1902, 28, 67) give the following values for crude oils:—

	Specific gravity.	Specific heat.
Pennsylvania	0·8095	0·5000
California	0·9600	0·3980
Texas	0·9200	0·4315
Russia	0·9079	0·4355

Determinations made by the author for fuel oils give the following results:—

	Specific gravity.	Specific heat.
Russian	0·914	0·448
Burma	0·897 0·924	0·433 0·406
Texas	0·927	0·436
Shale	0·880	0·460

The calorific value of petroleum and heavy oil fuels is dealt with at the end of the present chapter.

Chemical Composition of Petroleum.—Petroleum consists almost entirely of the elements carbon and hydrogen, together with small and varying quantities of oxygen, nitrogen and sulphur. According to Veith, the proportions are—

Carbon	79·5–87·1	average	84·5
Hydrogen	11·5–14·8	„	12·5
Oxygen, etc.	0·1– 6·9	„	2·0

The sulphur in petroleum seldom exceeds 1 per cent., but over 2 per cent. has been recorded in samples from Texas. Average American petroleum contains about 0·5 per cent.

Sulphur is objectionable in fuel oil, especially for use in internal combustion engines, by reason of the corrosion its products of combustion set up. The objectionable odour of many oils is due partly to sulphur compounds, which occur mainly as organic sulphides, but it is frequently found that after the objectionable smell has been removed by chemical treatment, there is no great reduction in the sulphur.

Hydrocarbons Present in Petroleum.—By a combination of chemical treatment and refined methods of fractional distillation a large number of hydrocarbons have been isolated from petroleums, and it has been established that all natural oils consist of mixtures of numerous hydrocarbons belonging to various well-recognized series, and at least members of eight such series have been identified. By a "series" is meant a succession of definite compounds, the individual members, as one ascends in molecular weight, showing a regular difference in the number of carbon and hydrogen atoms present, and it is therefore possible to write a general formula for the members.

Of these eight series of hydrocarbons the following are the principal:—

Paraffins	Olefines	Naphthenes or pseudo-olefines	Benzene or aromatic
C_nH_{2n+2}	C_nH_{2n}	$C_nH_{2n-6}+H_6$	C_nH_{2n-6}

The lower members of a series are frequently gases, soon passing into easily condensible liquids, and finally through more and more stable liquids until solid substances are reached. Increase in molecular complexity is then accompanied by rise in boiling-point in the case of liquids, or of melting-point in the case of solids, and the rise in these properties is also associated with a rise in specific gravity and viscosity. Thus, in the case of the paraffin hydrocarbons, the first four members are gases; at C_5H_{12} (pentane) we have a very volatile liquid; the subsequent liquid members increase in boiling-point and density until about $C_{18}H_{38}$ (octdecane) jelly-like hydrocarbons (mineral jelly or vaselin) are reached, and these finally are succeeded, about $C_{21}H_{44}$, by solids, which in various mixtures constitute paraffin wax.

The character of a natural oil and the proportion of different commercial constituents (petrol, illuminating oil, etc.) which it will yield will vary principally according to the different proportions of the members of a given series present, but also through the varying proportion of hydrocarbons of the different series. It is found that American petroleum consists mainly of paraffin hydrocarbons, whilst Russian oil is composed chiefly of naphthenes, in some cases to the extent of 80 per cent. For a given range of boiling the hydrocarbons of the latter have a higher density than paraffins, consequently a fraction from Russian oil is of higher density than the corresponding fraction from American oil. Solid paraffins are said to be absent in Galician oils, and these oils (together with Roumanian) differ from most others in that the portions distilling below 150° are rich in aromatic hydrocarbons.

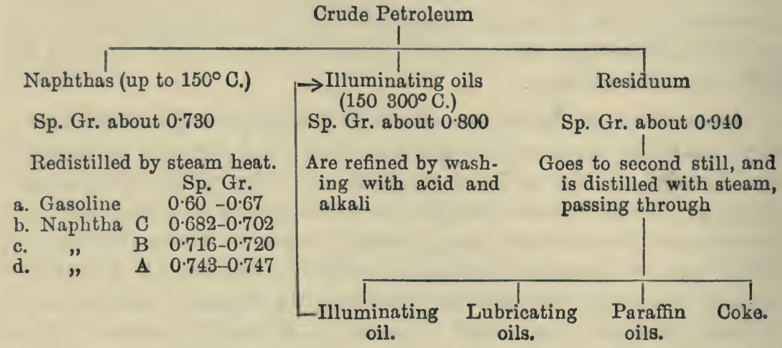
Distillation of Petroleum.—Natural petroleum is found occasionally containing so small an amount of lower hydrocarbons that it can be used directly as lubricating oil, etc., after clearing by subsidence or filtration; with rather more of the volatile constituents, by spontaneous evaporation from shallow layers or slight distillation, these may be recovered, giving a residue ("reduced oil") suitable for oil fuel, etc. In general, however, systematic distillation is necessary to yield the various important commercial fractions. The method of carrying this out varies in different oilfields, and with the character of the oil and the fractions it is most profitable to obtain, so that only a general description is given here.

The stills are heated by a fire beneath, and usually so fitted that steam may be admitted. The distillation is generally divided into two operations; in the first the crude oil yields as distillates the naphthas and illuminating oils, leaving in the still a residue which is run off into another still and further fractionated, yielding lubricating oils and oils rich in solid paraffin. Between the illuminating oils and the oils suitable for lubrication more or less "intermediate" oil is obtained. It is found that higher oils of this type on strongly heating break down into lower boiling oils, so that by allowing them to condense and fall back into the much hotter oil below, or distilling under higher pressures, a considerable increase in the lower boiling oils is obtained. This breaking down is known as "cracking." The fuel oils for burning will consist of the portions remaining after lighter distillates have been removed sufficiently for the residue to have a satisfactorily high flash-point. In Russia these residues are known as Ostatki or Masut. Such fuel oils are not themselves distilled over, consequently they are very dark in colour and may contain particles of free carbon.

The schemes shown on p. 114 indicate the general course of refining in America and Russia.

General Schemes illustrating Petroleum Distillation

America



Crude Petroleum

Naphthas (up to 150° C.)
Sp. Gr. about 0·730
Redistilled by steam heat.

	Sp. Gr.
a. Gasoline	0·60 –0·67
b. Naphtha C	0·682–0·702
c. „ B	0·716–0·720
d. „ A	0·743–0·747

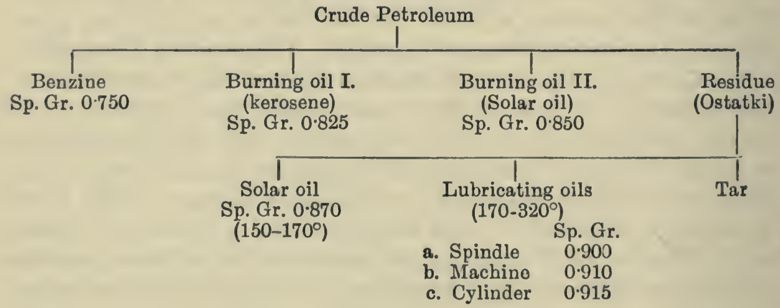
Illuminating oils
(150 300° C.)
Sp. Gr. about 0·800
Are refined by washing with acid and alkali

Residuum
Sp. Gr. about 0·940
Goes to second still, and is distilled with steam, passing through

Illuminating oil.
Lubricating oils.
Paraffin oils.
Coke.

Russia

A continuous system of distilation is generally employed.



Crude Petroleum

Benzine
Sp. Gr. 0·750

Burning oil I.
(kerosene)
Sp. Gr. 0·825

Burning oil II.
(Solar oil)
Sp. Gr. 0·850

Residue
(Ostatki)

Solar oil
Sp. Gr. 0·870
(150–170°)

Lubricating oils
(170-320°)

	Sp. Gr.
a. Spindle	0·900
b. Machine	0·910
c. Cylinder	0·915

Tar

Yield of Different Commercial Fractions.—Owing to the wide variation of the crude oils in different fields in the same country and the consequent difference in the process of distillation, which is governed both by the character of the oil and by the markets for the products, it is difficult to give more than rough approximations for the yields of the various products. Table XXIII. has been drawn up from either average or typical oils.

TABLE XXIII.

Composition of Crude Petroleum Oils.

	Pennsylvania.	Canada.	Texas.	Baku.	Malkop.	Argentine.	Trinidad.
Naphthas (benzine, petrol, etc.)	15	5	11	6	16	3	12–20
Lamp oil (kerosene)	50	40	54	20	36	5	30–50
Intermediate oil (solar, gas oils, etc.)	12	10		6		10	30–45
Lubricating oils	15	—	—	—	—	28	
Residue and loss	8	45	35	58	48	56	5

The yields of different commercial fractions (residues and loss in working omitted), as given by Kessler, are shown in Table XXIV.

TABLE XXIV.

Composition of Crude Petroleums (Kessler).

	Specific gravity.	Benzine.	Burning.	Intermediate.	Lubricating.
Pennsylvania	0·812	11	48	13	27
Galicia	0·856	12	34	22	31
Roumania	0·852	15	41	19	24
Sumatra	0·775	38	48	6	7
Borneo	0·850	17	51	14	18
Germany	0·881	3	29	27	40

The yield of heavy fuel oil for burning may be taken approximately as—

American	20 per cent.
Russian	60 ,,
Borneo, Texas, and California	75 ,,

Shale Oil

The production of shale oil is an important consideration in view of this being the only fuel oil of high quality which is produced in Great Britain. The bituminous shales which are employed are confined to a narrow strip of country between Edinburgh and Glasgow and on the Firth of Forth in the neighbourhood of Edinburgh. Shales employed for distillation are also found in New South Wales and New Zealand. The distillation was established in Scotland originally by Young in 1849 for the production of burning and lubricating oils.

The process of distillation is a continuous one, the shale being fed into vertical retorts; the upper part of the retort is of iron, and this is heated to about 480° C. (900° F.), and the lower part of firebrick, this portion being heated to 700° C. (1300° F.). The hydrocarbons are all driven off before the residue, which amounts to 70–80 per cent. of the charge, passes into the firebrick part. This residue still contains from 9 to 14 per cent. of carbon and much nitrogen.

Steam is blown through the retort during distillation, and performs three important functions. The use of steam was intended primarily to prevent decomposition by heat of the valuable paraffin wax; it also plays an important part in the efficient recovery of ammonia, and in the gasification of the carbon present in the residue below the iron portion of the retort. Shale contains from 1·16 to 1·45 per cent. of nitrogen, and a notable proportion of this is in the above-mentioned residue, and without steam could not be recovered.

Passing from the still are the oil vapours, the steam, and about 2000 cubic feet per ton of non-condensible gases. After condensation of the oil and steam these gases are generally utilized, together with producer gases, for heating the retorts.

Shale yields a very varying quantity of crude oil—from 18 to 40 gallons per ton, the average being 23 gallons. The specific gravity of the oil is between 0·860 and 0·890, and it usually solidifies at 90° F. The oil is afterwards redistilled and submitted to chemical treatment. From the higher boiling portions paraffin wax is obtained by cooling and pressing. The products are similar to those obtained from petroleum-naphthas, a proportion of which is available for motor spirit, burning oils, intermediate and lubricating oils. It is these heavier oils, freed from paraffin, which are so eminently suitable for fuel purposes.

It is only by the remarkable fuel economy practised in the distillation of shale and the good recovery of ammonium sulphate that the industry has been able to hold its own against the supply of natural oils, and it is noteworthy that in recent years it has undergone considerable extension. In 1909 three million tons of shale were treated, with an average yield of 23 gallons per ton. The quantity of the different commercial products obtained was—

68,000,000 gallons crude oil

4,000,000 gallons naphtha	22,000,000 gallons lamp oil	40,000 tons intermediate or gas oil	40,000 tons lubricating oil	60,000 tons ammonium sulphate

yielding 25,000 tons of paraffin wax.

Brown Coal Tar Oils.—There being no deposits of brown coal in this country, such oils are of no importance here, but with the large deposits in many parts of the Empire such fuels may at some time become of value, although only a certain class of such coals is capable of yielding the desired products, and this can be ascertained only by actual distillation. Generally, the character of the distillates obtained from suitable brown coals is similar to the shale products.

TAR OILS

These are of considerable importance in Great Britain, forming the only possible native supply of fuel oils, with the exception of the shale distillates. With the adaptation of the Diesel engine to such fuels as crude tar, and the increasing importance of benzene as a substitute for petrol in high-speed internal combustion engines, tar oils will assume increased value from the fuel point of view.

The more common forms of tar are those resulting from coal distillation in gasworks and coke ovens; in addition, considerable quantities are produced from blast furnaces working on hard coal, and minor quantities, which are important only locally, from all gas-producer plants working on bituminous fuels. The following is an approximate estimate of the tar produced annually:—

On 15 million tons of coal in gas works, yielding 4·5 per cent. of tar	700,000 tons
On 8·5 million tons of coal in coke ovens, yielding 5 per cent of tar	425,000 ,,
From blast furnaces	200,000 ,,
	1,325,000 ,,

The physical characters and chemical components of tar are dependent largely upon the conditions of distillation of the coal. With high temperatures and the subjection of the products of distillation to a high temperature before escaping from the retort, as with the usual type of horizontal gas retort, the tars are very viscid and are highly charged with naphthalene and free carbon. With low temperature tars, such as are obtained in blast furnaces and in distillation for coalite, the tars are fairly fluid, contain little naphthalene and anthracene, and practically no free carbon. In the modern vertical retorts the heat penetrates more slowly into the charge, and the distillation process is more or less intermediate between the above extremes, so that the tars are fairly fluid and do not contain so much of the objectionable naphthalene and free carbon.

For burning, tar is employed in the crude state, or, in some cases, after the lighter portions (benzene, etc.) have been removed by distillation. There are certain essential differences between coal tar and petroleum and shale oils. In the first place, a much higher proportion of oxygen-containing compounds, mainly constituting the tar acids, carbolic acid, cresylic acid, etc., are present. The effect of their presence is twofold; they detract seriously from its calorific value and produce exceedingly pungent fumes during combustion, which may be troublesome in a badly ventilated stokehold. The ultimate composition of crude tar is approximately—

Carbon	77·5
Hydrogen	6·3
Sulphur	1·0
Nitrogen	0·6
Oxygen	14·6

In the second place, many tars contain a high proportion of free carbon, which may prove troublesome in practice. According to E. F. Hooper (*Jour. Gas Ltg.* 1911, 113, 100), the following quantities are present:—

Kind of tar.	Free carbon per cent.
Coalite	0·15
Vertical retort	2·50
Dessau retort	4·00
Inclined retort	16·5
Horizontal retort (mean)	19·0

The amount of water in tar is important, for if separated into fair-sized globules it may lead to trouble with the burners. It is seldom as low as 1 per cent., and is frequently as high as 5 or 6 per cent. The more fluid the tar the better will the ammoniacal liquor produced simultaneously separate.

Tar oils for use in Diesel engines should not contain more than a trace of material insoluble in xylol, and 50 to 60 per cent. should distil below a temperature of 300° C.

Physical Properties of Tar.—The *flash-point* of crude tar is, according to Allner, for horizontal retorts from 160°–190° F., and for vertical retorts from 100°–115° F. The *viscosity* is very much lower for vertical retort tar, so that it is more easy to deal with it both when burning or in internal combustion engines of the Diesel type. The *calorific value* of coal tar is about 8,800 calories (15,840 B.Th.U.). The *coefficient of expansion* per degree Fahrenheit of different tars is—

Water gas	0·00036
Coal gas, average	0·00031
Coke oven, average	0·00032

TABLE XXV.

COMPOSITION OF CRUDE TARS.[1]

Tar.	Specific gravity.	Free carbon.	Tar acids.	Distillation temperatures and volume of fractions.			Amount of pitch.	Authority.
				To 170° C.	170°–270°.	270°–350°.		
Blast furnace	0·954	—	—	2·9 (to 230°)	6·97 (230–300°)	33·0 (300–350°)	55–60	Hooper.
Coalite	1·070	—	—	10·8	20·0	30·0	39·2	Warnes.
,, (average)	1·061	—	20·0	3·8	30·6	21·0 (to 320°)	51·4	Brame.
Water gas	1·092	Trace	—	1·4	15·4 (to 230°)	43·4 (230–250°)	18·2	Tutweiler.
Horizontal retort	1·220	17·25	3·0	4·9	18·4	9·0	60·6	Hooper.
Inclined retort (Bueb) . . .	1·095	2·60	—	4·4	28·5	19·2	47·5	Warnes.
Vertical retort	1·100	2·40	—	5·85	12·3	26·9	49·7	Lunge.
,, ,, (Dessau) . . .	1·113	4·00	5·3	13·0	24·0	9·0	50·0	Hooper.
,, ,, ...	1·084	3·6	—	6·7	21·7	22·5	48·5	Lunge.
,, ,, (Glover-West) .	1·034	3·6	—	8·5	25·2	24·1	48·5	Colman.
Chamber retort	1·180	11·1	—	0·4	10·2	30·1	53·9	Warnes.
Coke oven (Otto-Hilgenstock) .	1·198	10·5	3·0	9·4	9·8	24·8	51·0	Hooper.

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[1] Mainly from a table by E. F. Hooper on "The Present Position of the Coal-tar Industry," *J. S. C. I.* 1910, 1437.

The commercial distillation of tar for the production of its valuable by-products need be dealt with only briefly, since it has no further bearing upon the production of fuel than for the recovery of benzene. After separation of the ammoniacal liquor floating on the surface, the tar is distilled from iron retorts, usually in complete charges, although continuous systems are sometimes employed. The following scheme represents generally the fractions obtained, and the range of temperature over which they are collected:—

Crude tar

Light oils	Carbolic oil	Creosote oil	Anthracene oil	Pitch
(up to 170° C.)	(170°–225°)	(225°–270°)	(270°–320°)	

The general character and composition of various tars are given in Table XXV. (page 119). In some cases different distillation temperatures were taken, in which case the range is included in brackets.

COMPOSITION, FLASH-POINT, AND CALORIFIC VALUE OF CRUDE OILS AND HEAVY FUEL OILS

Information relating to these important properties is summarised in Tables XXVI., XXVII., XXVIII., and XXIX.

TABLE XXVI.

COMPOSITION AND CALORIFIC VALUE OF CRUDE OILS
(W. Inchley. *The Engineer*, 1909.)

Source.	Specific gravity.	Composition.				Calorific value.	
		Carbon.	Hydrogen.	Oxygen.	Sulphur.	Calories.	B.Th.U.
American .	—	86·89	13·11	—	—	10,912	19,650
Russian .	0·871	86·90	13·10	—	—	10,833	19,500
Caucasian	—	84·90	11·63	1·46	—	10,328	18,600
Canadian .	0·859	86·92	12·87	—	0·35	10,797	19,420
Texas . .	0·947	86·62	11·80	—	0·63	10,517	18,945
Java . .	0·867	87·10	12·7	—	—	10,654	19,180

TABLE XXVII.

FLASH-POINT, CALORIFIC VALUE, ETC., OF ARGENTINE PETROLEUMS
(W. Mecklenburg).

Source.	Specific gravity.	Flash-point, °F.	Sulphur.	Calories.	B.Th.U.
Yacuiva	0·898	158	0·07	10,860	19,550
Salta (Tartagal) .	0·909	185	—	10,715	19,300
,, (Arguaray .	0·927	194	0·16	10,525	18,950
Neuquén . . .	0·915	302	0·85	10,510	18,920
Comodoro Rivadavia	0·957	176	—	10,520	18,940

TABLE XXVIII.

Specific Gravity, Calorific Value (Bomb Calorimeter), etc., of Heavy Fuel Oils (Brame).

Source of oil.	Specific gravity at 15° C.	Flash-point, °F.	Sulphur per cent.	Calorific value.	
				Calories.	B.Th.U.
Russia-Ostatki (1) . .	0·914	—	0·16	10,990	19,780
,, ,, (2) . .	0·920	—	0·35	10,580	19,040
Texas (1)	0·928	185	1·40	10,750	19,350
,, (2)	0·927	—	0·71	10,730	19,310
,, (3)	0·934	250	—	10,900	19,630
Burma (1)	0·924	280	0·20	10,520	18,950
,, (2)	0·900	—	0·14	10,610	19,100
,, crude oil . .	0·873	120	0·16	10,650	19,160
Borneo	0·915	—	0·52	10,780	19,400
Argentine	0·942	220	—	10,680	19,220
Shale oil (1)	0·880	310	0·36	10,570	19,030
,, (2)	0·803	—	—	11,150	20,070
Low temperature heavy coal-tar	0·998	190	0·81	9,050	16,300
Ditto, after soda washing	0·989	180	0·99	9,720	17,490

TABLE XXIX.

Composition and Calorific Value of Masut (Ostatki) from Galician Petroleums. (Wielczynski, *Petroleum*, 1908, **3**, 507.)

Calculated from Mendeléeffs' formula: $81C + 300H - 26(O - S) = \text{Calories}$.

Source.	Sp. gr. at 15° C.	Composition.			Calorific value.	
		Carbon.	Hydrogen.	Oxygen.	Calories.	B.Th.U.
Uryez (1) .	0·933	85·53	12·96	1·56	10,675	19,200
,, (2) .	0·940	86·75	12·09	1·16	10,625	19,150
Boryslau .	0·925	85·23	13·27	1·50	10,845	19,500
Orou . .	—	87·02	12·98	—	10,940	19,680
Harklowa .	—	86·56	12·54	0·90	10,750	19,350

According to Heck, the average composition of Ostatki or Masut of sp. gr. 0·91 is: carbon, 87·5 per cent.; hydrogen, 11·0 per cent.; oxygen, 1·5 per cent.; and its calorific value 10,700 calories (19,260 B.Th.U.). The coefficient of expansion per degree Centigrade is given as 0·00091 (or 0·0005 per °F.), which is somewhat higher than usual for heavy fuel oil.

It is important to note that the calorific value of a hydrocarbon oil is lowered by 13·14 B.Th.U. per lb. of oil for every per cent. of water, in addition to the lowering due to less combustible matter. The calorific value of a wet oil will therefore be found from

$$\frac{\text{Cal. value of dry oil} \times (100 - H_2O\,\%)}{100} - (13{\cdot}14 \times H_2O\,\%).$$

Gas Tars.—The following calorific values are stated to be the average for dry tar by the authorities named: 9,000 cals. (16,200 B.Th.U.), Godinet; 8,800 cals. gross (15,840 B.Th.U.) and 8,530 cals. net (15,400 B.Th.U.), Mahler; 8,510 cals. gross (15,350 B.Th.U.), Euchêne. The German Gas Association takes a value of 8,800 cals. (15,840 B.Th.U.).

The following particulars of the physical properties of coal tars are due to Allner:—

Flash-point.	Horizontal retorts.	160° F. to 190° F.
	Vertical retorts.	100° F. to 115° F.
Viscosity.	Engler's degrees =	$\frac{\text{seconds for tar}}{\text{seconds for water at } 20^\circ \text{C.}}$

Temperature.	English horizontal. (1)	English horizontal. (2)	English vertical. (1)	English vertical. (2)	English vertical. (3)
20° C. (68° F.)	114·4	550·0	75·9	39·3	7·8
50° C. (122° F.)	16·0	51·0	4·5	3·9	2·5
70° C. (157° F.)	7·2	23·0	2·2	2·2	1·5
Calorific value. Cals.	8,770	—	8,990	—	9,180
B.Th.U.	15,780	—	16,175	—	16,530

From a number of determinations of the calorific value of horizontal and vertical retort tars it would appear that the latter, besides being less viscous and containing less water and free carbon, have the higher calorific value, the mean figures for the dry tars being: horizontal, 9,115 cals. (16,430 B.Th.U.); vertical, 9,300 cals. (16,740 B.Th.U.).

CHAPTER VIII

SYSTEMS OF BURNING OIL FUEL

General Arrangement of Oil Supply to Burners.—The oil should be almost free from suspended water and solids, but most installations provide for the contingency of this not being wholly the case. When the oil is supplied by gravity from tanks it is usual to employ a pair of supply tanks into which the oil is pumped; here it is heated by a steam coil to promote the separation of water and increase the fluidity of the oil.

At ordinary temperatures the separation of finely divided water is very sluggish, since the difference of gravity is but slight, and with the high viscosity of the oil these globules remain suspended almost indefinitely. On heating the oil two distinct changes occur—first, its viscosity is reduced very rapidly, and secondly, the oil expands at a greater rate than water, so that the difference in specific gravity is considerably increased. The relative coefficients of expansion of heavy oils and water are approximately per degree Centigrade 0·00070 and 0·000476; or per degree Fahrenheit 0·00039 and 0·000264.

For the supply of oil to the atomisers in the steam or air systems it is only necessary to have a feed tank or tanks at a sufficient height to give the necessary flow, and a pump for lifting the oil. The general arrangement in the Holden system is illustrated in Fig. 6. In the pressure jet systems provision is made for warming and filtering the oil on the suction pipe: the oil then passes to the pumps, and is forced into a second heater with a suitable air chamber, and then led off to the burners. To provide for the proper regulation of the oil pressure a loaded valve on a connection between the pressure side and the suction side of the pump is fitted, and lifts when the maximum is reached. For the oil to attain the necessary working temperature it is circulated through suitable heaters by piping leading from the oil supply pipe to the burners (which are shut off) back to the suction side of the pump.

The general arrangement in the different systems is very similar, and is illustrated in Fig. 7 for Körting plant, and in Fig. 8 the Kermode apparatus as applied to marine boilers is shown.

It is important to note that condensed water from these heating coils must not be allowed to return into the boiler feed until it has passed through a suitable separating tank, owing to the risk of oil being carried into a boiler should a leak occur in the heater.

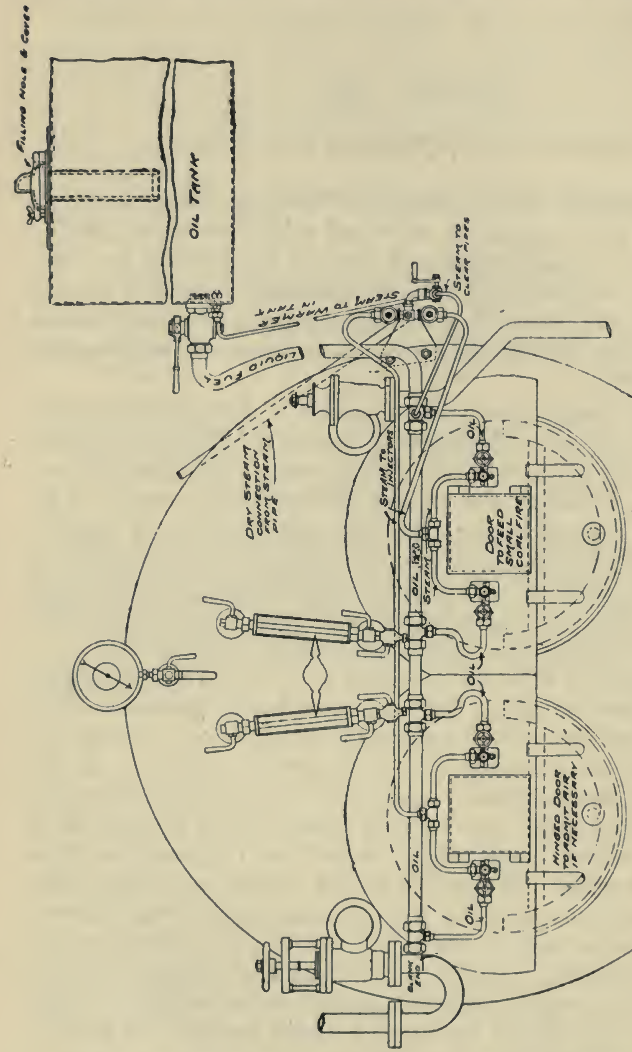


FIG. 6.—General arrangement of oil fuel system (Holden).

The temperature to which the oil may be heated safely before delivery to the burners is limited obviously to some degrees below the flash-point, and it is very essential to the attainment of smooth working, with the least necessity for alteration of the oil or atomising agent valves, that the temperature shall be fairly uniform and the pressure of the oil supply constant. To this end thermometers should be placed in the supply pipe.

Experiments were carried out by the Wallsend Slipway Co., of Newcastle-on-Tyne (*Eng.* 1908, 85, 805), on mixtures of oil with

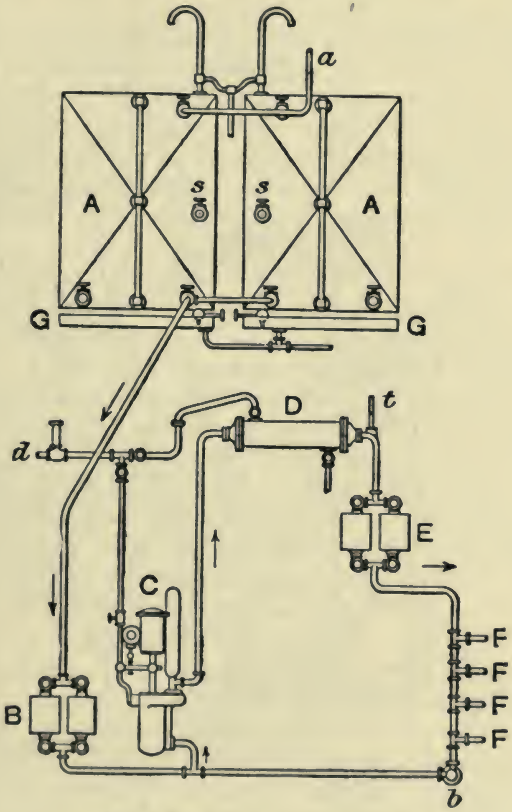


FIG. 7.—Körting pressure system.

A A, Oil settling tanks.	E, Duplicate discharge strainers.
a, Oil supply pipe.	F, Pipes to burners.
G G, Drip trays.	*b*, Bye-pass valve.
B, Duplicate suction strainers.	*t*, Thermometer.
C, Oil pump with air pressure vessel.	*d*, Steam supply to pump and heater.
D, Oil heater.	

water to ascertain the temperature requisite for proper separation. At 90° F. separation would not take place with a mixture of 60 gallons of oil with 20 gallons of water; at 150° F. only 75 per cent. of the water settled out; separation was perfect in 4 hours at 180° F.

The tank should be provided with a good air vent pipe leading to the open.

Vaporizing and Spraying the Oil.—For the perfect combustion of the oil it is essential that as perfect a mixture as possible with air shall be attained. In theoretical grounds this is accomplished most easily with the oil vapour, but it is not practicable to vaporize properly the heavier fuel oils, since the temperature requisite leads to "cracking" of the oil and the formation of carbonaceous deposits in the vaporizer and burning of the metal. The system however is applicable with low boiling oils, such as kerosene and intermediate oils,

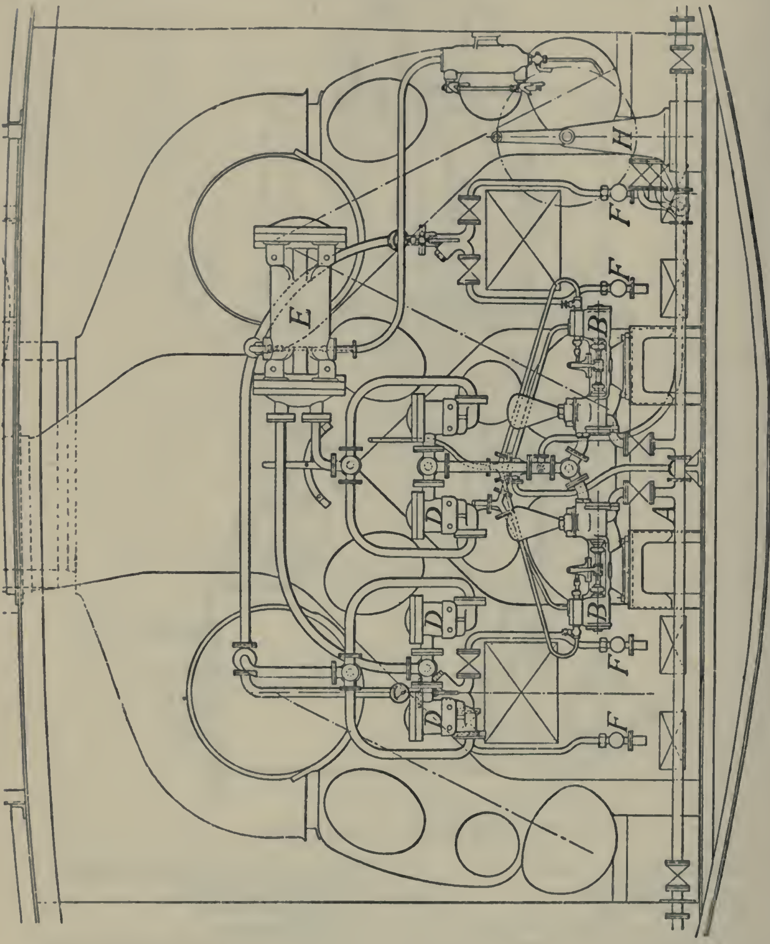


FIG. 8.—Kermode pressure system.

and little trouble is experienced if the vaporization takes place in presence of a good volume of air.

With the heavier oils such as are generally employed, conversion into as fine a mist of oil globules as possible enables proper admixture of air to be attained, and various forms of sprayers or atomisers, working with either steam or air under pressure, or the forcing of the heated oil under pressure through suitable orifices, are employed universally. All the well-known types of atomisers may be relied on to give the necessary disintegration, and as far as this effect is concerned there is but little to choose between the steam, air or pressure systems. It is upon other considerations, dealt with later, that the selection of the particular system mainly depends. Whilst an efficient atomiser is essential, attention to the details of the installation as a whole, and more particularly furnace construction, is the most important factor for good results.

The number of atomisers of the three main types which have been designed is legion, and only typical examples of atomisers of established efficiency on the three systems are described below, but here it may be mentioned that with any pattern it is essential that the burner should not get heated unduly over any great part of its length. It is usual to arrange the atomisers on a swinging arm so that they may be turned clear of the furnace, the oil and steam or air supply being cut off at the same time. This enables inspection and cleaning of the burners to be made, or, where solid fuel is sometimes employed as an alternative, the burners to be turned out of the way without the necessity of dismantling.

STEAM ATOMISERS

The fact that a convenient working fluid under steady pressure is at hand for atomisation of the oil in boiler practice with this fuel accounts for its extensive employment and the large number of successful steam atomisers which are in use. Broadly, these may be divided into two groups—those in which the oil and steam escape through concentric circular orifices, and those in which straight slots are employed. In many of the former elaborate arrangements are made for further heating the oil in the burner by suitable jacketing. It does not appear that any great advantage arises from this; indeed, some of the simplest burners give the best results in practice, and complication of design is to be avoided. According to H. B. MacFarlane, with the Santa Fé Booth burner irregularity in combustion was noted at 140° F. and higher, and that the greatest uniformity was attained with oil between 90° and 95° F.

The steam for atomising should be dry and is preferably superheated, and should be at as high a pressure as possible.

The Holden Injectors.—The successful application of liquid fuel to many purposes in this country, more especially in locomotive practice, owes much to the inventive genius of Mr. Holden, when in charge of the Great Eastern Railway Company's engines. The general principle of all burners of this design is that of injection through concentric orifices, and a supplementary oil feed, for use when extra fuel has to be employed, is arranged, so that the main oil valve requires little or no alteration. For the diagrams of the most recent modification, suitable for general steam-raising and heating, the author is indebted to Messrs. Taite and Carlton, Queen Victoria Street.

The oil is fed by gravity into the outer annular ring of the burner, the atomising steam being led in immediately inside this. Owing to the injector action of the whole burner air is drawn in through the central tube. Oil spray, steam, and air become thoroughly mixed in the larger chamber at the fore-end of the atomiser, and the mixture is forced out at high velocity through orifices bored at different angles through the front plate. These angles are so arranged that the different jets impinge on each other, and a secondary supply of steam is led through a branch pipe on the under side of the burner, escaping from two small orifices in such a direction that it assists the thorough mingling of the oil and air escaping from the other jets. It will be seen that most complete admixture is possible with this arrangement.

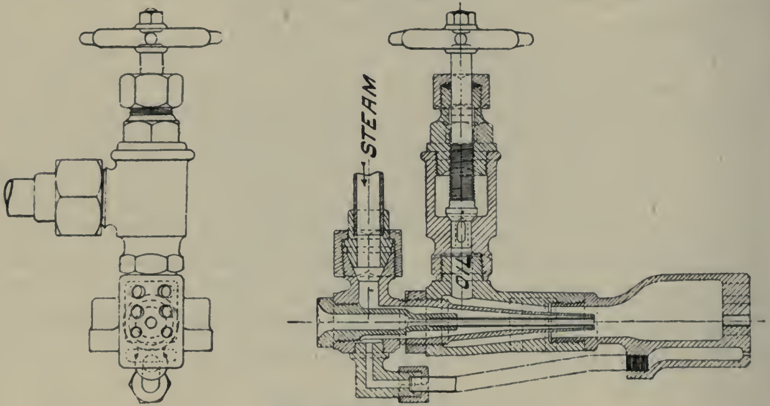


Fig. 9.—Holden atomiser.

The Field-Kirby Atomiser is of the type where jacketing of the fuel and induced air by the atomising steam is employed. The burner was designed more particularly with a view to the utilization of heavy tars, and has proved very successful even when several per cents. of water are still retained. The results of some trials with this atomiser when using tar are given later (p. 178).

The tar is led in through A (Fig. 10) to the central chamber, down which passes the spindle B, which has a hollow end perforated by a series of holes arranged spirally. By the withdrawal of the spindle any number of these orifices may be uncovered, so regulating the passage of the fuel. The steam enters through C and passes into two circular chambers E and F, so that the air induced through G is jacketed on both sides and the fuel on the outside. The steam issues at the two circular orifices and effectively sprays the fuel, at the same time mixing it with the induced air, which issues between the two annular steam orifices.

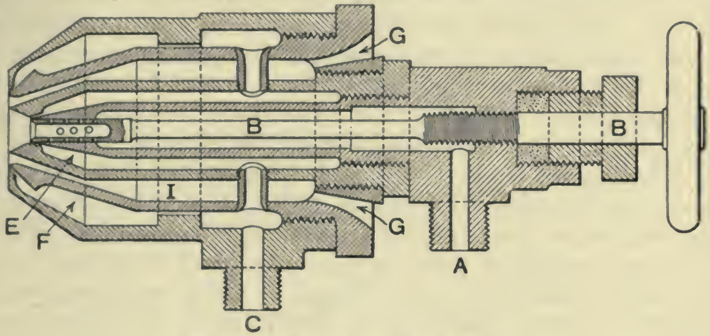


Fig. 10.—Field-Kirby atomiser.

"W. N. Best" Atomiser.—This is of the slot variety, and is noteworthy because the steam is delivered from the upper slot downwards on to a horizontal surface of oil, an arrangement claimed to prevent any carbonaceous deposit occurring. This pattern is selected for illustration (Figs. 11 and 12) because of the highly favourable opinion

Fig. 12.—Plan of mouthpiece.

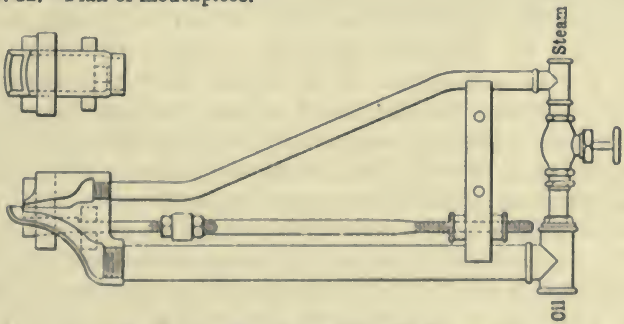


Fig. 11.—Steam atomisers—W. N. Best.

expressed on its performance by the United States Naval "Liquid Fuel" Board, who carried out a most exhaustive series of trials with many forms of atomisers.

It will be noted that the oil orifice is curved on the two long sides Arrangements are made for quickly unshipping the nose-piece of the steam jet should an obstruction occur, and by closing the oil supply valve and opening the steam valve between the steam and oil pipes, the steam may be blown through the oil tube to clear any obstruction.

The Booth (Santa Fé Railway) Atomiser.—This again is of the simple slot pattern, arranged as is general in such burners, with the oil supply above the steam orifice. The success of this atomiser is substantiated by the number of locomotives running on oil fuel on this railway; Mr. H. B. MacFarlane (Cassier's "Railway Number," March, 1910, p. 610) gives this as 685, and mentions that great advantages arise from the fixing of the burners at the *forward* end of the firebox, leading to the abolition of the usual brick arch necessitated when the common arrangement of fitting the burner at the firedoor is adopted. This arch is costly in bricks and expensive to maintain.

This atomiser is illustrated in Fig. 13. The sizes of the respective orifices are: oil, $2\frac{1}{2}$ inches by $\frac{7}{16}$ inch; steam, $2\frac{3}{4}$ inches by $\frac{1}{32}$ inch.

FIG. 13.—Santa Fé atomiser.

Steam Consumption for Atomising.—Owing to the great variety of steam atomisers which have met with success in practice, the steam consumption for atomising purposes, of which there are records, shows a wide divergence. It is indeed difficult to estimate the amount in ordinary practice where all the steam is from one boiler, and the most reliable figures are without doubt those of the United States Report on Liquid Fuel for Naval Purposes, 1902. In these extensive and valuable tests a separate boiler was installed for supplying the atomising steam, and on an average 0·6 lb. at 274 lbs. pressure was required per lb. of oil. Allowing an evaporation of 14 lbs. of water per lb. of oil, this is equivalent to 4·4 per cent. of the total steam generated. According to Bohler 0·85 lb. and to Grébel 0·80 lb. are required per lb. of oil. Much smaller quantities have been stated to have been utilized in some trials, but it is unlikely that over an extended period much less than 4 per cent. will be attained.

For heavy tar oils a greater quantity is required; much will depend on the viscosity of the tar, and the temperature at which it comes in contact with the steam. Echinard, as the result of a large experience with French tars, gives the consumption as 1·5 lbs. per lb. of tar, but this probably refers to practice with the thick carbon-laden tars produced in high temperature distillation of the coal in thin layers. There seems to be no adequate reason for suspecting that the more fluid tars from modern bulk distillation would require appreciably more steam than a heavy oil residuum.

AIR ATOMISERS

The Carbogen.—This simple form of atomiser, the invention of Mr. S. F. Stackard, has met with wide success in practice both for steam-raising and for general industrial purposes, notably for glass furnaces, where it is imperative that a flame of high intensity which will not deposit free carbon shall be employed. Many of these furnaces have been running continuously for months on oil fuel with these burners, and the combustion is absolutely smokeless; indeed, in some annealing furnaces no smoke stack or outlet, other than from the ordinary openings to the furnace, is provided.

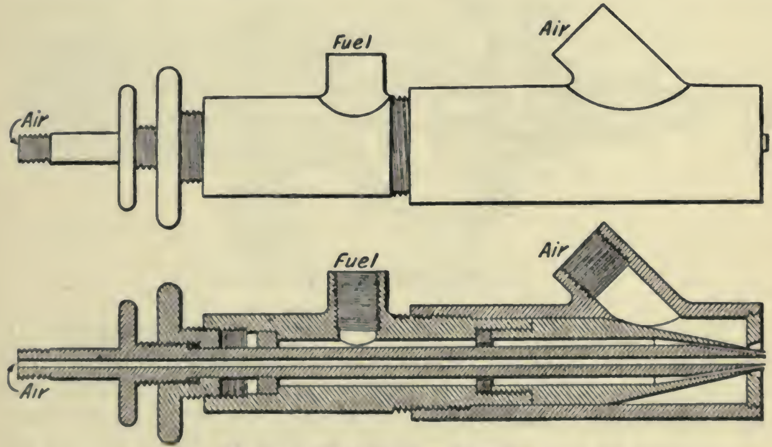


FIG. 14.—The Carbogen atomiser.

The illustration, Fig. 14, shows clearly the essential feature of the Carbogen burner. It will be noted that two air streams impinge on the oil; these are both supplied from the same air pipe which is branched a little distance from the burner. The interior supply has doubtless much to do with the excellent combustion obtained.

An inner stream of oxygen has been employed when specially high intensity was required. Two standard sizes are made, one passing from 0·5 to 3 gallons per hour; the other from 2 to 20 gallons.

Mr. Stackard informed the author that 8 cubic feet of free air per minute are required at 18 lbs. pressure to spray 1 gallon of oil in the glass furnaces. This is approximately equivalent to just over 4 lbs. air per lb. of oil (or 52 cubic feet). In the American Trials (1902 Report) with the Oil City Boiler Works atomiser, 50 cubic feet were required.

Kermode Air Atomiser.—In the burner illustrated in Fig. 15, either air or steam may be used as the atomising agent. When air is employed it is highly heated by passing through pipes in the furnace, or uptake in the case of marine boilers, and is stated to vaporize the oil completely in the central chamber of the burner.

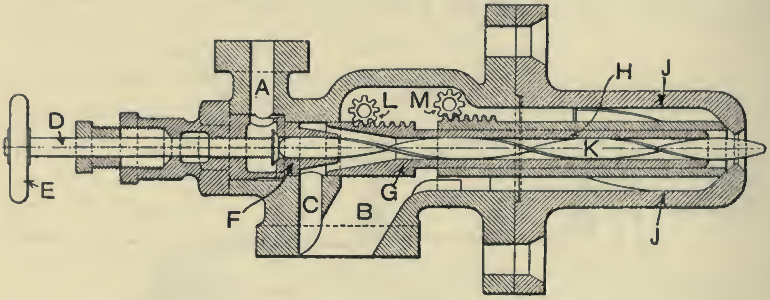


FIG. 15.—Kermode air atomiser.

The oil enters at A, and the flow is regulated by the spindle D, which operates the coned valve F. The air supply is divided between the two channels C and B, and the amount passing respectively into the inner space, to commingle with the oil, and into the outer space is regulated by the rack and pinion movements L and M. In the inner section a spiral blade K is fixed, which serves to mix up efficiently the air and oil as the latter vaporizes more or less, and another shorter helix is provided in the outer air channel to impart a rotary motion to this supply. The air is supplied at from 0·5 to 4 lbs. pressure.

Air required for Atomising.—In the United States trials (1902 Report) the average amount of air for 1 lb. of oil on 9 complete tests was 50 cubic feet, entailing an average consumption of steam (indirectly) of 0·4 lb., or 3·2 per cent. of the total steam generated. Analysis of the flue gases shows that very considerable excess of air was present, and the above amount is unnecessarily high. Other American tests on air sprayers showed that approximately 1 cubic foot of air was required per lb. of steam raised. Assuming an evaporation of 13 lb. of water per lb. of oil, then 13 cubic feet of air, or 1 lb., are required per lb. of oil.

The pressure required for air atomisers varies greatly with the pattern. Kermode states that it need never exceed 3 lbs. with his burners, and in a successful Russian installation the pressure is only $\frac{7}{10}$ths of an inch with the oil at 70° F. At low pressure air is very economical, but as the steam consumption in compressors goes up rapidly as higher compressions are made, and the atomising power of the air does not rise in anything like the same proportion, it will be seen that an atomiser requiring air at low pressure offers considerable advantage. With a good air atomiser the steam consumption should not exceed 1·5 to 2 per. cent. of the total generated.

PRESSURE ATOMISERS

The action of these atomisers is based upon either a jet of fluid oil at high velocity impinging upon a fixed knife-edge, which causes it to break up into spray, or imparting a sufficiently powerful centrifugal action to cause disintegration. The Swensson atomiser is on the former plan, and the better-known Körting, Kermode, and White atomisers on the latter.

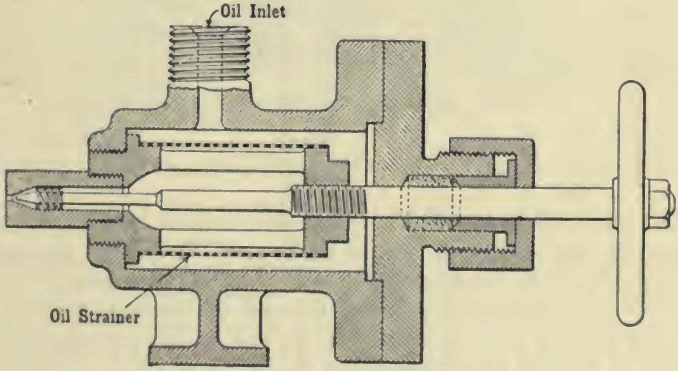


FIG. 16.—Pressure atomiser—Körting.

Körting Atomiser.—In this atomiser, which has been very successful in marine and other installations, the oil is forced through a channel in which a spindle having a deep thread cut out on the outside works, the coned part of the spindle opening or closing the small orifice through which the oil escapes from the nozzle. The hot oil, under pressure of at least 30 lbs., thus has a sufficiently rapid rotary motion imparted to it to break up into a fine spray.

The Körting atomiser is illustrated in Fig. 16, through the courtesy of the Editor of *Engineering*. Surrounding the atomiser chamber is an arrangement for the final filtration of the oil, which effectively prevents any clogging of the spraying device.

Kermode Pressure Atomiser.—This is certainly one of the most efficient atomisers of the pressure type, and is illustrated in Figs. 17 and 18.

The oil enters the burner through the supply pipe A, and is forced through the annular space between the fixed inner part B and the outer walls D. At the nozzle end, B makes a perfect fit with the outer wall D. and cut in the metal of B are a number of grooves parallel to the central axis of the burner; these grooves connect with similar ones cut in the end of B at right angles to the axis of the burner, so that they come against the cap nut E. These grooves are cut tangentially to the cone end of the spindle C, as shown in Fig. 18, and this cone serves to enlarge or contract the opening through the cap nut E, the movement of the spindle being indicated on the graduated wheel F by its position in relation to the fixed pointer G.

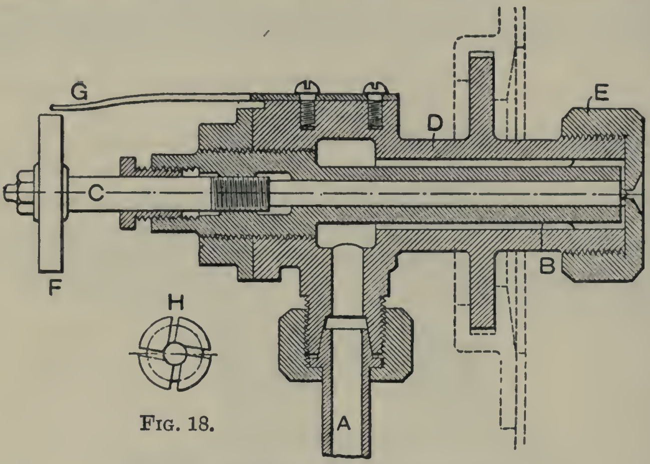


FIG. 18.

FIG. 17.—Pressure atomiser—Kermode.

Owing to the powerful rotary motion set up by these tangential grooves and the oil striking the cone at the end of the spindle C, it is thrown out in a perfectly atomised form.

The White Atomiser.—This pressure atomiser, made by Messrs. Samuel White & Co., of Cowes, the licensees being the Babcock and Wilcox Boiler Co., is one of the most recent patterns, and introduces novel features. In most pressure atomisers it is necessary to get the oil up to the proper temperature for spraying before the atomisers can be put into action. In the White burner (Figs. 19 and 20) provision is made for lighting up on cold oil, and by a simple movement of the regulating valve spraying with hot oil may be made when the necessary temperature is attained. The cold spraying is effected by forcing the oil under pressure through a narrow orifice against a metal disc on the end of a spindle, the spray issuing as a wide angle cone, and in a very finely divided condition, which would not be possible with cold oil by any other method than an interference one. For the hot spraying the spindle is drawn inwards, and the oil now issues with a powerful centrifugal motion through the same orifice and is effectively atomised, the cone of spray in this case being more narrow and more concentrated. Adjustment of the oil supply is affected by spiral passages *a* in the coned piece C, which can be regulated in area and in number by turning the hand wheel A. The coned piece is kept in position by the coiled spring. For altering the position of the sprayer *d* in relation to the small orifice, the small wheel B is rotated. Illustrations of the burner in action under both conditions are given in Figs. 21 and 22. From the clear appearance of the background in the photographs, it will be evident that in each case the atomisation is very perfect.

FIG. 20.

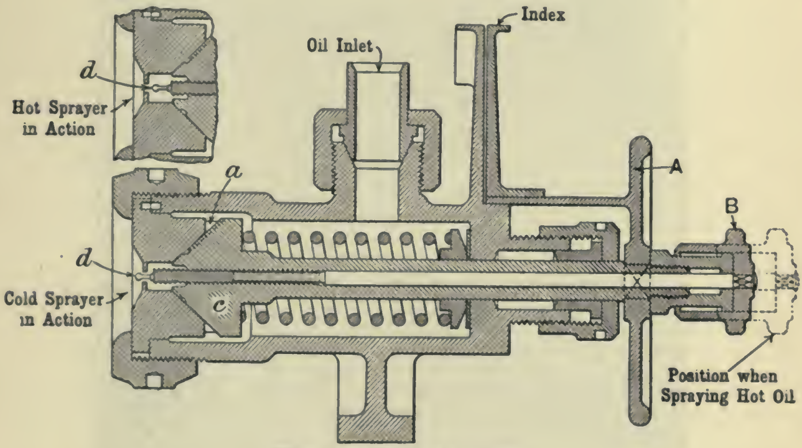


FIG. 19.—White atomiser.

Comparison of Systems of Atomising.—Each of the foregoing systems offers certain advantages, but on the whole the efficient atomising powers of the pressure burners, and the general convenience of the whole arrangement are in their favour, and certainly for steam-raising generally, but especially on board ship, this system offers so many advantages that it is superseding other systems. It is no secret that this is the system entirely employed in the Royal Navy, after exhaustive trials of the three.

Steam atomisers hold the advantage that the atomising agent is always to hand in unlimited quantities and under good pressure when one boiler at least is working, and further, the space occupied is less than with the other systems. On the other hand, in starting up steam must be raised in one boiler of a set or in an auxiliary boiler with solid fuel. Further, all steam used in atomising is lost, and has to be replaced by feed water. This is of no moment in shore work, but on ship, where the supply has to be obtained by distillation, the loss of 4 to 5 per cent. at least of the steam is too serious a question.

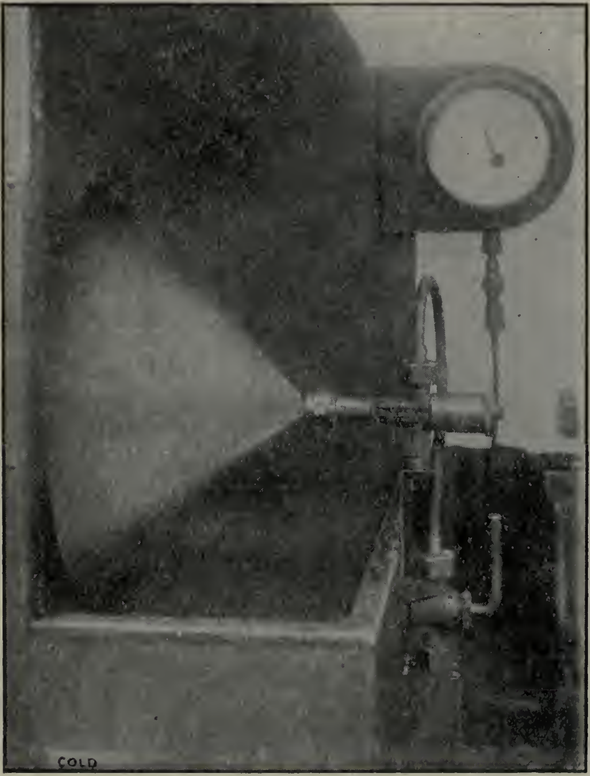


Fig. 21.—White atomiser spraying cold oil.

According to the United States Report, steam atomisers do not lend themselves so readily to forcing as air atomisers.

Air atomisers are advantageous, first, in that the steam consumption for the compressor need be about only one-half of that for direct steam atomisation, and, secondly, the whole of this steam may return to the boiler through the condensing plant. Air is the natural agent for atomising, since in the act of disintegrating the oil it must become properly mingled with the globules, ready to carry on the combustion. Steam, on the other hand, must displace a certain amount of air, and although there may be chemical interaction between the oil and steam which promotes the final combustion with air, results do not show any gain in efficiency. Any interaction between the steam and oil must be endothermic (absorb heat), and this, together with the displacement of air by steam, will extend the zone of combustion further into the furnace.

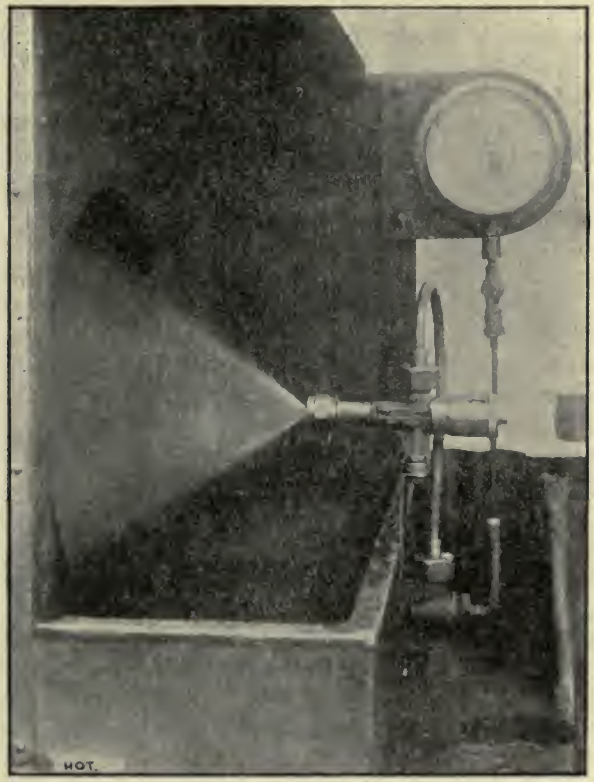


FIG. 22.—White atomiser spraying hot oil.

The space occupied by suitable compressors, especially those of the rotary type, is not great, and in starting up a small internal combustion engine can be usefully employed.

For metallurgical work, glass furnaces and other industrial operations, air atomisation is the most applicable system.

With the pressure jet system very perfect atomisation may be effected, and no difficulty is experienced in getting perfect air admixture. Oil pumps have to be installed with either system, and as they are usually in duplicate, one pump can be set aside conveniently for getting the oil under proper pressure. It is more particularly in competition with steam atomisation in boiler practice, and here there is no question as to the great superiority of the pressure system.

With both air and pressure systems, starting can be arranged for hand, motor, or internal combustion driven pumps or compressors.

According to Kermode, the relative efficiency of the three systems is: steam, 68 to 75 per cent.; air, 78 to 83 per cent.; pressure, 70 to 75 per cent.

Combustion of Oil Fuel.—Special consideration has to be given to the furnace arrangements for the combustion of oil fuel for steam-raising. Little difficulty is experienced in obtaining perfect combustion and high efficiency where the duty of the boiler is low, but it is otherwise when a high duty is demanded and a large quantity of oil has to be consumed. It is for this reason that the solution of the problem of the smokeless combustion of oil fuel was established at a much earlier date in the mercantile marine and in shore practice than under the conditions existing in a warship.

The conditions for perfect combustion differ radically from those existing in the case of solid fuel. As Lewes has pointed out, when an average coal is burnt beneath a boiler, by destructive distillation, some 11,000 to 12,000 cubic feet of gas, as measured at ordinary temperatures, and about 10 gallons of tar in the form of vapour are evolved per ton, whilst 75 per cent. of the coal is burnt as solid fuel on the grate, and the relationship between heating surface and grate area is of importance.

On the other hand, if oil is largely gasified prior to active combustion, as it must be in practice, every ton yields some 20,000 cubic feet of gas at ordinary temperature, and there is in addition some considerable volume of vaporized oil-gas tar. The whole of the oil is in fact burnt as gas or heavy vapour, and considerations of grate area are quite irrelevant; the essential factor is cubic feet of combustion space. Unfortunately, in the majority of reports on oil fuel installations, the useless factor "grate area" is given, and the useful factor of cubic feet of combustion space in relation to oil consumed is omitted.

Not only is the question of generous provision of combustion space indicated by the above considerations, but also by reason of the greater amount of air theoretically demanded per lb. of oil fuel as compared with coal. Taking average compositions for the two classes of fuel, the following comparison between the theoretical air supply is possible:—

	Weight of air per lb.	Volume of air in cubic feet	
		at 0° C.	at 60° F.
Coal	11·5	140	147
Oil	14·0	172	181

In the series of American trials, in endurance tests of 116 hours' duration and a combustion space of 121 cubic feet, the following relative results for coal and oil (air-atomised) were obtained:—

	Natural draught.		Forced draught.		
	Lbs. per cub. ft.	Evaporation from and at 212° F.	Pressure inches.	Lbs. per cub. ft.	Evaporation from and at 212° F.
		lbs.			lbs.
Coal	8·3	10,000—11,000	3·00	30	30,150
Oil	7·6	15,000—16,000	3·75	27	35,560

The guiding principles for the ensuring of complete combustion and absence of smoke have been laid down already, namely, sufficient air, proper admixture and maintenance of temperature.

The air supply in the case of oil fuel may be divided into *primary air*, the injection air where this system is used, or air drawn in by the injector action of the atomiser, and *secondary air*, or air supplied to complete the combustion partially carried out by the primary air or of any oil spray or vapour not yet attacked. For smokeless combustion not only must the air supply be efficient, but it must be mingled as intimately as possible with the escaping spray, and there must be no local cooling. Primary air does not need heating, as combustion in the region of its action will always be sufficiently vigorous to maintain a high temperature, but when special provision is made for secondary air to be introduced, such air is best supplied at as high a temperature as possible. There is no tendency for smoke production during the first 18 inches or 2 feet of the flame; smoke is produced by the less rapidly moving portions constituting the further end of the flame. Here it is that the proper admixture of hot secondary air is best arranged for. Attention may be again directed to the case of the oil lamp flame with and without the chimney (p. 73).

The United States Navy Fuel Board laid down the following as the essential conditions for the production of a short hot flame: the fuel should be a pure carbon-hydrogen oil, there should be initial heating of the air, intimate diffusion of the fuel and air, and a large surface of fuel exposed to the impact of the air.

Suitable arrangement of firebrick plays an important part in the successful combustion of oil fuel in most installations. In some pattern water-tube boilers, where there is ample space between the banks of tubes on either side, or where the lower rows are situated fairly high above the combustion space, the burners may play directly into the space. Where, however, there is any risk of flame impinging directly on the tubes, these should be protected by firebrick; the bottom and sides will be necessarily of firebrick. Suitable firebrick arches and baffles, however, are in many cases essential to success, for they may perform several important functions; heavier particles of oil falling on them are vaporized; they form efficient radiating surfaces (the inefficiency of flames in this respect has been pointed out already); lastly, properly arranged baffles prevent long tailing flames where combustion is often incomplete, and smoke forms by reason of the difficulty of mixing the air properly without some such arrangement. These baffles serve the purpose of admixture, and they maintain the high temperature at just the point in the system where checked combustion, with smoke formation, would otherwise probably result. Further, they may be easily constructed to enable the highly heated secondary air to be introduced effectively just where most required.

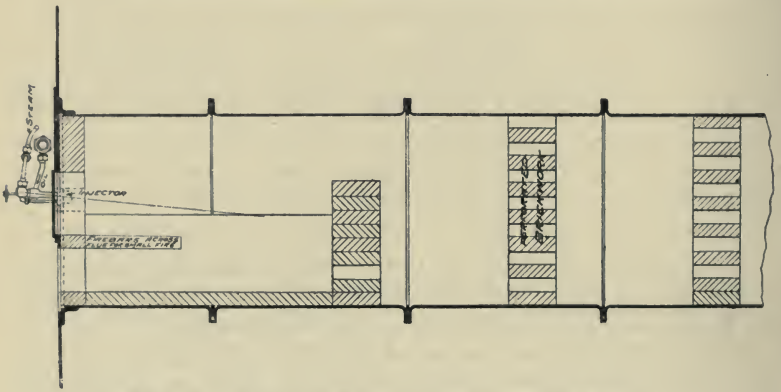


FIG. 23.—Furnace arrangement in Lancashire boiler.

One or two examples of furnace arrangements will now be given to illustrate the application of these principles in practice. In Fig. 23, the firebrick baffles, etc., in the Holden system applied to a Lancashire boiler are shown. This is an excellent arrangement; it will be seen that the hot gases and air at the outer end of the flame first strike a chequer work of firebrick extending halfway up the furnace; they are further thoroughly mixed by the two succeeding baffles, which extend completely through the combustion space. A short "grate" of firebrick extends immediately beneath the burners and serves for lighting up, and when fairly running would vaporize any heavier oil particles which might settle, although this is not a likely occurrence with such efficient atomisers. During the coal strike of 1912, boilers were fitted hurriedly on this plan with Holden injectors, and worked with most successful and economic results on gas tar, which had been prepared for road-spraying.

In Fig. 24, the furnace arrangements with the W. N. Best burner in the United States trials is illustrated. Firebrick air channels were provided beneath each of the burners and served for the heating and proper introduction of the secondary air supply at the most suitable point.

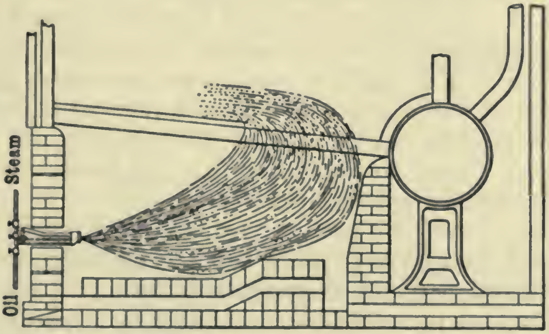


FIG. 24.—Furnace arrangement in W. T. boiler.

A hollow wall at the back of the combustion chamber built over somewhat towards the burner is also an effective way of providing highly heated secondary air in the case of water-tube boilers.

Liquid Fuel for other Purposes than Steam-raising.—Liquid fuel has been employed most successfully for a large number of industrial operations, amongst which may be mentioned melting metal for casting, etc., in glazing kilns, muffles for enamel ware, rivet heating, glass melting and annealing, carbonizing electric light filaments, etc. Not only has it been employed where high temperatures are desired, but, since the temperature attained is so well under control, it has been used successfully for the delicate operation of tea-drying and for drying bagasse preparatory to its use for animal foods.

The high intensity which is attainable, the ease of control of the temperature, the absence of ash and, with good oils, of more than traces of sulphur, render it particularly suitable for many metallurgical operations. Further, once the proper adjustment of air supply has been made, the nature of the combustion is constant, there being no opening and closing of fire-doors admitting varying quantities of air. In all such applications the conditions of use are far more favourable to easy combustion than in steam-raising, since the temperature of the furnace or material generally is not greatly removed from the flame temperature. For good results firebrick should not be spared. There appears good reason to believe that hot surfaces of firebrick act catalytically in promoting combustion. Heavier oil particles are gasified readily, and the atomisation need not be nearly as perfect as for boiler work. A simple type of burner in which a regular drip of oil is picked up by an air blast is frequently sufficient, and low air pressure is all that is required if a good type of atomiser is employed.

The air seldom requires pre-heating for metallurgical furnaces. In many cases it is advisable to install a pre-combustion chamber as an extension of the furnace; into this the atomiser is directed, and combustion partially carried out by the air used for injection. Secondary air should be supplied around the junction of the pre-combustion chamber and the main furnace.

Furnaces of the reverberatory type may be arranged easily for oil-firing, and although the system is not so generally advantageous for metallurgical purposes in comparison with producer gas with regeneration, tank furnaces of a similar type for glass melting have been in continuous successful operation for periods of over two years without the burners being turned off. The temperature required is about 1500° C. (2730° F.), and the following comparisons of cost and output obtained:—

	Coke-firing.	;Oil-firing.
Glass output	86·5 cwts.	458 cwts.
Total fuel costs	£13 4*s.* 0*d.*	£48 6*s.* 0*d.*
Fuel costs per cwt. . .	3*s.* 0*d.*	2*s.* 1*d.*

The output being so greatly increased, considerable economy in space is effected, and more men can be employed working the glass at each furnace.

Metallurgical operations in which oil fuel is employed for melting purposes are conducted usually in tilting furnaces of the Bessemer type, in which the oil is sent directly into the furnace, or in crucible furnaces of a tilting pattern, the crucible being fixed in a fireclay lined furnace mounted on trunnions. This system has many advantages (equally true when gas-fired) in that lifting the pots, with consequent liability to fracture and loss of metal, is avoided, larger pots and greater charges may be employed, and consequently considerable saving on fuel costs is possible. The description of such furnaces is outside the scope of the present work, but the reader is referred to the excellent series of articles in *Engineering*, 1910.

Illustrations are given in Figs. 25 to 28 of forms of oil fuel installations for industrial purposes which present novel features. The various heating furnaces, of which there are a large number of patterns, by Messrs. John Burdon & Sons, have an upper gasifying tube, into which the sprayed oil is carried by the air blast. As will be seen in Fig. 25, the hot products of combustion escape upwards from the heating chamber through suitable ports, which can be controlled by dampers.

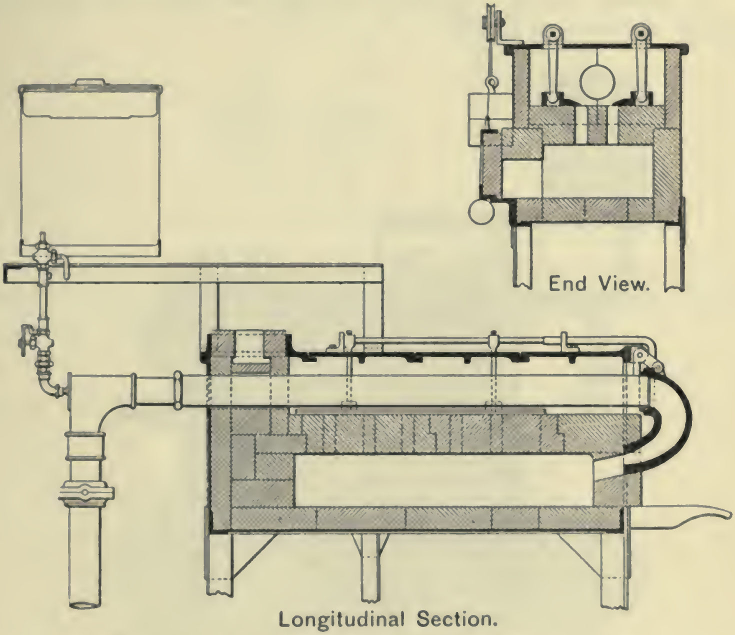


FIG. 25.—Section of oil-fired furnace—Burdon system.

The oil is supplied from an overhead tank to a special atomiser injecting into the air tube. The blast may be supplied either by a blower, attached to the framework of the furnace, or from a convenient blast main. The air supply can be regulated by a slide valve.

The oil is converted into oil gas of very high calorific value and mixes with the air blast, so that a powerful flame may be obtained, and control of the flame to almost any character is possible by regulating the oil or air supply, or both.

In the most recent patterns a number of minor details have been altered slightly; instead of the perforations shown through the crown bricks for heating the carburettor, the waste gases now pass through flues, and from there into the upper chamber. The smaller pattern furnaces are mounted on a framework carried on wheels, the larger being constructed on strong standards to any convenient height.

A general view of a Burdon Portable rivet, small bar and plate furnace is shown in Fig. 26.

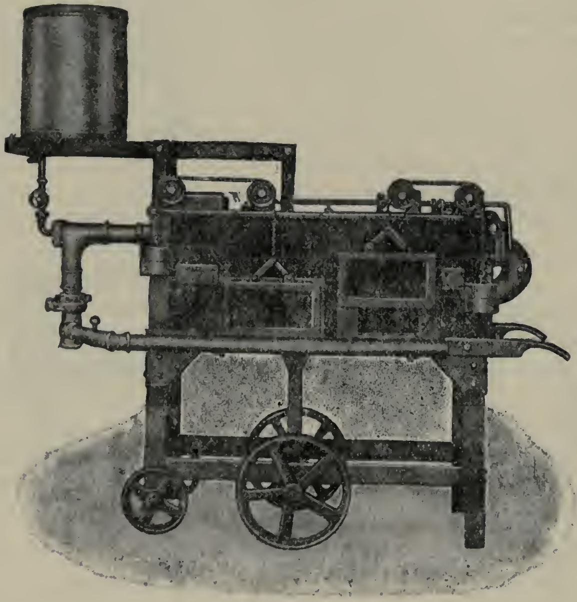


FIG. 26.—General view of Burdon oil-fired furnace.

The form of burner, illustrated in Fig. 27 is one devised by the Brett Patent Lifter Co., of Coventry, for adaptation to any existing furnace. It will be noted that the oil jet, under low pressure, strikes against a revolving propeller D actuated by the air blast, and thus becomes broken up. By means of a baffle plate in the lower part of the vertical hollow column support A, a portion of the air is sent round the space B surrounding the pre-combustion chamber E, and in this way becomes highly heated before rejoining through the pipe C the other portion at a little distance below the slide valve shown. The position of the connecting pipes will be followed from Fig. 28 (p. 146), which also shows how the waste heat from a pair of heating furnaces fired by this system is employed for raising steam in a water-tube boiler, an arrangement which frequently might be applied with larger installations of this type.

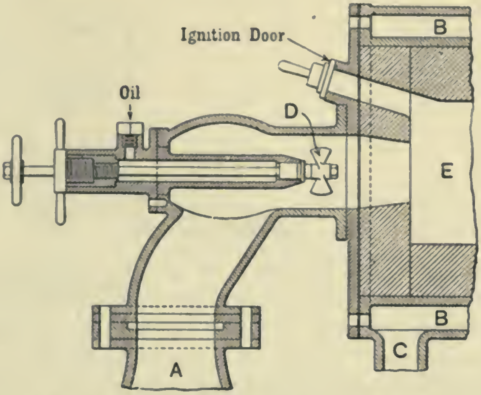


FIG. 27.—Brett oil sprayer for furnaces.

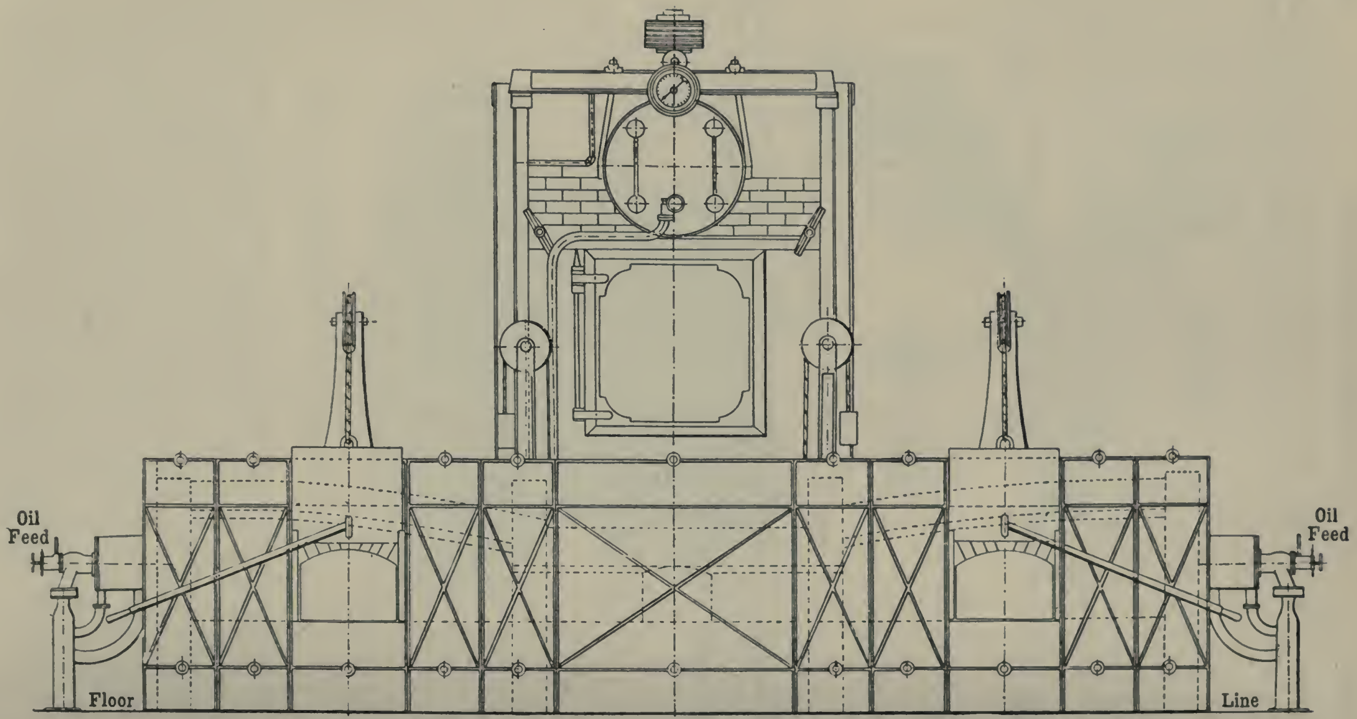


FIG. 28 —Arrangement of heating furnaces with Brett sprayers, with Babcock boilers fired by waste heat.

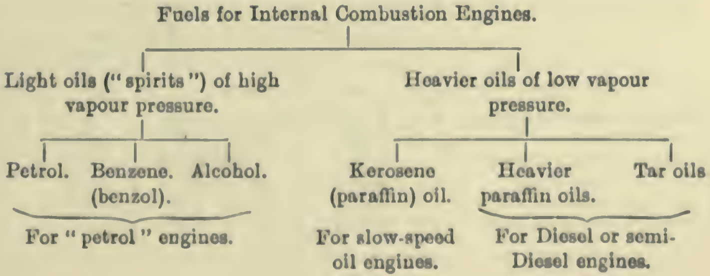
CHAPTER IX

LIQUID FUEL FOR INTERNAL COMBUSTION ENGINES

INTERNAL combustion engines may, for a consideration of the various fuels, be classified as high-speed engines, requiring an easily vaporized spirit or oil, and slow-speed engines, in which the oil is either vaporized by heat before entering or in the cylinder, or injected as a spray into the cylinder after the temperature of the air has been raised by compression, as in the Diesel engine. In these the temperature attained by this compression is sufficient to ignite the oil; in the more recent semi-Diesel type of engine, some oil is vaporized and ignited in a special extension of the cylinder and serves to ignite the main oil spray as it is pumped in.

The suitability of the various oils and distillates for the different types of engines is dependent largely on their vapour tension or pressure. For a high-speed engine (petrol motor) the fuel must have a high vapour pressure at ordinary temperatures, so that it may readily give an explosive mixture with air in the carburettor. When the vapour pressure is low, then the oil must be more or less highly heated to give off sufficient vapour, and in general is injected into the cylinder as the liquid and there vaporized by a more highly heated extension of the cylinder, so that it may form a combustible mixture with air in the cylinder. In engines of the Diesel type the ignition point of the oil is the controlling factor, and the influence of composition on this will be referred to later.

The following classification of such fuels is a convenient one :—



PETROL

This important fuel is obtained by the redistillation of the naphtha fractions from the distillation of crude petroleum oils, the treatment of which and the quantity of the different fractions in various oils have been deal with already. A further small supply also is available from the naphthas of shale distillation. Certain qualities of natural gas also furnish a small amount of petrol by compression in order to cause liquefaction.

The amount of petrol which can be produced is being overtaken rapidly by the greatly increasing demand for it, and the motor industry is forced to consider the question of possible increase of supplies or the utilisation of other fuels which shall be equally serviceable. The question of supplies, etc., is discussed later (p. 179).

Composition of Petrol.—Petrol, consisting as it does of the more volatile portions of the naphthas obtained from petroleum, is a mixture of a large number of hydrocarbons of various series; since the spirits have been treated with sulphuric acid for purifying purposes it is improbable that unsaturated hydrocarbons of the olefine and acetylene series are present to any extent. Probably, therefore, it consists mainly of the lower liquid members of the paraffin series and of "naphthenes," together with small amounts of the benzene series of hydrocarbons.

Usually petrol distils completely between 60° to 150° C., and the normal hydrocarbons falling in this range may be—

Paraffin Hydrocarbons.

	Formula.	Boiling point ° C.	Specific gravity at 0° C.	Specific heat.	Latent heat of vaporization.
Pentane	C_5H_{12}	37	0·645	—	—
Hexane	C_6H_{14}	69	0·676	0·527	79·4
Heptane	C_7H_{16}	98	0·700	0·507	74·0
Octane	C_8H_{18}	125	0·719	0·505	71·0
Nonane	C_9H_{20}	150	0·733	0·503	—

"*Naphthene*" (*Methylene*) *Hydrocarbons.*

	Formula.	Boiling point ° C.	Specific gravity at 0° C.	Specific heat.	Latent heat of vaporization.
Methyl pentamethylene . .	C_6H_{12}	71·5	0·766	—	—
Hexamethylene	C_6H_{12}	79	0·790	0·506	87
Dimethyl pentamethylene . .	C_7H_{14}	90—92	0·778	—	81
Methyl hexamethylene . . .	C_7H_{14}	98	0·778	0·488	76
Dimethyl hexamethylene . .	C_8H_{16}	118	0·781	0·486	72
Trimethyl hexamethylene . .	C_9H_{18}	148	0·787	—	—

It will be noted that the hydrocarbons of the methylene series are of higher gravity than those of the paraffin series of about the same boiling point, and that the specific gravity in each case increases with rise of boiling point, whilst the specific heat and latent heat decrease.

The specific gravity alone of a petrol is therefore no true criterion as to its relative volatility, and a distillation test, by which the volume of the fractions obtained between certain fixed temperatures determined, forms at present the most satisfactory basis for a fair comparison. Since the boiling point is dependent upon the vapour pressure, the higher the proportion of distillates obtained at a low temperature, the greater the degree of volatility as a whole.

The variation in percentage composition of the paraffin hydrocarbons, which are the principal ones present in petrol, is small—ranging over only about 1 per cent.—so that the average figures of 84 per cent. carbon, 16 per cent. hydrogen may be taken for petrol.

When air is bubbled through petrol or passes at ordinary temperatures over a surface saturated with such a liquid of mixed composition, evaporation is selective, the less volatile portions remaining behind, *i.e.* the petrol becomes "stale." Air passed through petrol at atmospheric temperatures is stated to take up practically only the hydrocarbon hexane (C_6H_{14}). In the early days of the petrol engine carburation was accomplished usually by carburettors of the bubbling or surface-evaporation type, so that a much more restricted range of boiling for the petrol was essential, and its gravity was usually about 0·680. With the introduction of spray carburettors, in which the heavier less volatile portions of the spray get carried forward as a mist into the hot inlet pipe adjacent to the cylinder or to the cylinder itself and there become vaporized, a much greater range is permissible; the gravity of suitable spirit is now frequently 0·760. This improvement is of great economic importance in rendering a far greater proportion of the crude oil available, and further improvements in carburettors will doubtless permit of some extension of the range of boiling in the future.

It is important to note that the relative volumes of the fractions obtained from the same petrol vary considerably with the form of apparatus employed and the rate of distillation. The influence of the form of apparatus, etc., has been investigated by Garry and Watson (*J.S.C.I.* 1904, 704), in which paper numerous valuable tables will be found. The results in Table XXX. may be quoted to illustrate the importance of this point.

TABLE XXX.

INFLUENCE OF FORM OF APPARATUS IN DISTILLATION OF PETROL.

(*Garry* and *Watson*).

	Volume per cent. for fractions for each 10° C.								
	First drop condensed at	to 70.	70 to 80.	80 to 90.	90 to 100.	100 to 110.	110 to 120.	120 to 130.	130 to 140.
Plain flask, 3¾ inches from side tube to top of sphere	63° C.	0·5	3·5	40·0	32·0	16·0	5·0	1·0	1·0
Le Bel-Henninger's dephlegmator without obstruction (3 bulbs) . . .	58° C.	2·0	17·0	26·0	30·0	15·0	4·0	2·0	2·0
Ditto, with bead in each bulb	58° C.	2·5	9·5	37·0	27·0	15·0	3·0	3·0	2·0
Glinsky dephlegmator (5 bulbs)	64° C.	1·0	12·0	35·0	28·0	15·0	4·0	2·0	2·0

This is certainly the most important test to which petrol can be submitted, and taken in conjunction with the specific gravity of the fractions, it is usually all that is required for a comparison. In view of the results of Garry and Watson it is evident that the form of apparatus to be employed and the method require careful standardization. The writer's practice is outlined on p. 311.

In view also of the above results it is evident that published figures for commercial petrols are of little value unless the procedure adopted in making the tests is indicated, and this is most exceptional.

Physical Properties of Petrol.—Reference has been made already to the density or specific gravity, which may lie between 0·680 and 0·760, and the boiling range. According to Cabot, petrol of 0·698 sp. gr. at 22·8° C. did not show signs of solidification when immersed in liquid air until a temperature of −122° C. was reached.

The specific heat of the liquid and its latent heat of vaporization are of importance. The following figures (Table XXXI.) were obtained for the specific heat between 10° and 30° C. by the author :—

TABLE XXXI.

SPECIFIC HEAT OF PETROL.

	Specific gravity.	Specific heat.		Specific gravity.	Specific heat.
American	0·737	0·465	Sumatra	0·722	0·514
,, ...	0·724	0·483	Mexico	0·725	0·493
,, ...	0·712	0·477	Texas	0·744	0·472
Asiatic	0·767	0·450	Roumania . . .	0·740	0·473
,, ...	0·721	0·490	Burma	0·756	0·462
,, ...	0·713	0·512	Borneo	0·772	0·453

Although not strictly proportional to the density, for practical purposes the specific heat may be calculated from $\frac{K}{\text{sp. gr.}}$, K being approximately 0·350.

There are considerable practical difficulties in the determination of the latent heat of vaporization, and data are greatly wanting for petrols, etc. The figures given (p. 148) for the paraffin and methylene hydrocarbons are those of Maybery and Goldstein (*Amer. Chem. Jour.*, 1902, 28, 67). Graefe (*Petroleum*, 1910, 5, 569) gives latent heat of vaporization of crude light petroleum oil as 86 calories, and this value appears approximately correct for petrols on the basis of Maybery and Goldstein's figures.

According to Holde the flash points (° C.) for different petrol distillates are:—

Distilling between .	50–60° C	60–78°	70–88°	80–100°	80–115°	100–150°
Flash point below .	−58°	−39°	−45°	−22°	−22°	+10°

Calorific Value of Petrol.—The *gross* calorific values for a number of petrols have been determined by B. Blount (*Inst. Automobile Engs.*, March, 1909, pp. 1–6) by means of a bomb calorimeter. The majority of these results are given in Table XXXII.

TABLE XXXII.

GROSS CALORIFIC VALUE OF PETROLS.

(*B. Blount.*)

Trade description.	Specific gravity.	Calories per kilo.	B.Th.U. per lb.	B.Th.U. per gallon.
Anglo 0·760	0·739	11,162	20,092	148,480
Shell	0·717	11,252	20,254	145,220
Pratt's	0·717	11,229	20,212	144,920
Carless Capel "Standard"	0·700	11,302	20,344	142,400
,, ,, "Movril"	0·718	11,200	20,160	144,760
Carburine	0·717	11,187	20,137	144,380
Russian	0·705	11,232	20,218	142,530

The *net* calorific values have been determined by W. Watson (*J. Soc. Arts*, 1910, 58, 990) by carburetting air with the vapour and burning the mixture as a bunsen flame inside a Boys Gas Calorimeter. The method is equally applicable to the determination of the gross values, for as will be seen in the description of this type of calorimeter, both the gross and net values are obtained. Watson's results are shown in Table XXXIII.

TABLE XXXIII.

NET CALORIFIC VALUE OF PETROLS.

(*W. Watson.*)

Petrol.	Density.	Calories per gram.	B.Th.U. per lb.	B.Th.U. per gallon.
Bowley's special	0·684	10,660	19,190	131,500
Carless	0·704	10,420	18,760	132,300
Express	0·707	10,020	18,040	127,600
Ross	0·714	10,370	18,670	133,600
Pratt	0·719	10,340	18,610	134,100
Carburine	0·720	10,380	18,680	135,000
Shell (ordinary)	0·721	10,400	18,720	135,300
Dynol	0·725	10,290	18,520	134,600
Simcar benzol	0·762	9,490	17,080	130,400
0·760 Shell (Crown)	0·767	10,140	18,250	140,300

It will be noted that there is very little difference in the calorific value per pound of the different petrols, because the composition by weight is practically the same for any density, but when the gravity is taken into account it is an obvious advantage from the point of view of heat units available per gallon to employ the denser varieties.

The principal data in reference to petrol are given in Table XXXIV., p. 158, together with those of benzene and alcohol, so that a comparison may be instituted between these fuels.

The Petrol-Air Mixture.—The theoretical amount of air for the complete combustion of petrol, as deduced from the average composition by methods already described on p. 7, is—

		Cubic feet	
	lbs.	at 0° C.	at 60° F.
Per pound	15·24	187	197
Per gallon	109·60	1346	1420

One volume of the liquid requires, therefore, 8400 (at 0° C.) to 8900 (at 60° F.) times its own volume of air for complete combustion. Similarly, the percentage of carbon dioxide in the *dry* exhaust gases for petrol of this composition will be 14·3 per cent.

Owing to the complex nature of petrol, it is not possible to calculate accurately the actual volume in the state of vapour which a given volume of liquid petrol would occupy, as, for example, when it is taken up as vapour in an air current. 1 lb. of hexane would occupy 4·2 cub. ft. in a state of vapour at 0° C. (4·4 at 60° F.), whereas 1 lb. octane would occupy 3·15 cub. ft. at 0° C. (3·32 at 60° F.). Taking a round figure of 4 cub. ft. of vapour per pound of petrol, it will be found that the theoretical air required is about 48 times the volume of the petrol vapour, or the mixture contains practically 2 per cent. petrol vapour.

The calorific value of 1 cub. ft. of the theoretical petrol air mixture may now be calculated. The total volume of mixture per pound is $4 + 187 = 191$, and the calorific value of petrol per pound is approximately 20,000 B.Th.U., hence $\frac{20,000}{191} = 104{\cdot}5$ B.Th.U. per cub. ft. Similarly, at 60° F. the value per cub. ft. is approximately 99·5 B.Th.U.

Air is able to take up a far greater amount of petrol vapour than the above; according to Brewer (*Soc. of Engs.*, 1907), dry air will take up 17·5 per cent. by volume of 0·650 petrol at 50° F. (= 1 vol. petrol vapour to 5·7 vols. of air), whilst at 68° F. it will take up 27 per cent. (= 1 vol. vapour to 3·7 vols. of air). It is evident, therefore, that a large excess of air must be employed in practice to bring such a mixture down to theoretical strength.

Further, above a certain percentage of vapour the mixture, although highly inflammable, is not explosive. The range of composition between which mixtures of petrol vapour and air are truly explosive is very limited. The figures given in the "Motor Union Fuels Report" (1907) are: *minimum*, 1·1 per cent. by volume; *maximum*, 5·3; explosive range, 4·2. On the assumption that 1 lb. of petrol gives 4 cub. ft. of vapour, the explosive mixture figures are approximately—

	lbs.	Cubic feet	
	air.	at 0° C.	at 60° F.
At maximum for 1 lb. petrol.	5·76	71·5	74·5
At minimum „ „	29·0	360·0	375·0

The more generally accepted limits are: *minimum*, 2·0 per cent.; *maximum*, 4·5 per cent., and these figures are probably more in agreement with the true explosion conditions, as distinct from bare inflammation.

It must be remembered that although a mixture may be non-explosive at ordinary pressure, on increasing the pressure such a mixture may become explosive.

Rate of Flame Propagation in Petrol-air Mixtures.—This is obviously an important consideration, determining as it does whether combustion has ceased before the end of the working stroke of the piston, and how soon after ignition the maximum pressure is reached, which determines incidentally the point in the cycle where ignition should take place. Obviously, with an engine running at, say, 2000 revolutions per minute, a slow-burning mixture may even be alight when the inlet valve opens, with consequent firing back into the carburettor.

Neuman has made determinations of the rate for petrol-air, and his results are shown graphically in Fig. 29.

It will be seen that a maximum rate is obtained with about 12·5 parts by weight of air to 1 of petrol, which is considerably less than the theoretical air necessary.

With a slow-burning mixture (in practice one which should owe its comparatively slow rate to more air than the theoretical) the mixture would have to be ignited earlier for a given speed; again, if at a slow speed the ignition is correct for the mixture, increase of speed will mean a reduced interval between the top of the stroke and the ignition, so that the maximum effect will not be obtained when ignition takes place at the same point; in other words, the ignition must be made sooner in order not to lose efficiency.

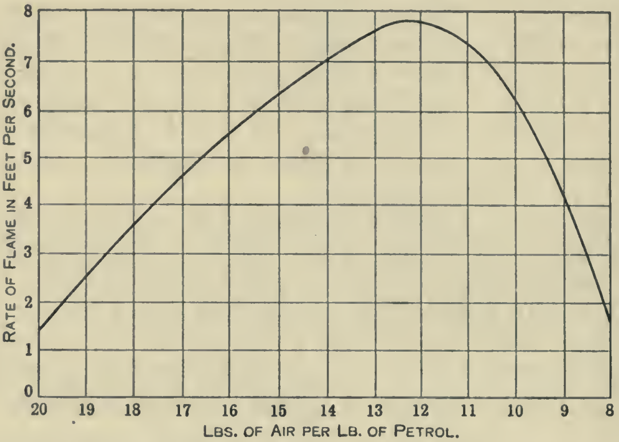


Fig. 29.—Rate of flame propagation in petrol-air mixtures (Neuman).

Combustion of Petrol.—When petrol (assuming the composition C_6H_{14}) is burnt completely with the theoretical amount of air (15·24 lbs. per lb.), the dry exhaust gases would consist of carbon dioxide 14·35 per cent., nitrogen 85·65 per cent. It has, however, been noted frequently that after undergoing combustion in an engine it is impossible to account for all the carbon and hydrogen consumed as carbon dioxide and monoxide, which points to the conclusion that products of incomplete combustion other than carbon monoxide are formed, and aldehyde seems to be produced under some conditions. The formation of carbon monoxide through insufficiency of oxygen is observed frequently when the exhaust gases are analyzed, and it has been observed by Mr. Dugald Clerk that an excess of oxygen may be present even when carbon monoxide is still being formed.

Professor W. Watson has carried out extensive investigations on the petrol engine (see *Engineering*, 1910, 88, 331, and *J. Soc. Arts*, 1910, 58, 988), and found that the highest thermal efficiency was not attained when the air for combustion was the theoretical amount, but was obtained actually with an air-petrol ratio of 17 lbs. to 1 lb. This is concluded to be due to two causes, a lower cylinder temperature, so that less heat is lost through the walls, and to the lower mean specific heat of the gases (the specific heat rising with the temperature), hence the rise of pressure is greater for a given quantity of heat supplied. In general, the best mechanical efficiency was found with about 12 lbs. of air to 1 lb. of petrol. With a weaker mixture than 17·5 to 1 there is risk of back-firing into the carburettor, the rate of burning being so reduced that combustion is not completed before the inlet port opens.

The Royal Automobile Club has adopted such a petrol-air mixture as will give about 1 per cent. of free oxygen in the exhaust gases.

It has also been shown above that 1 lb. of petrol vapour yields $4 + 197 = 201$ cub. ft. of theoretical mixture at 60° F. Since the average thermal efficiency of a good petrol engine is 22 per cent., corresponding to a consumption of 0·7 pint per B.H.P. hour,[1] or 0·63 lb. with a sp. gr. of 0·72, with the theoretical air ratio of 15·24 lbs. to 1, the number of cubic feet of mixture which must be supplied to give

$$1 \text{ B.H.P. } \textit{per minute} = \frac{201 \times 0{\cdot}63}{60} = 2{\cdot}1 \text{ cub. ft.}$$

Extinction of Petrol Fires.—Ordinary methods of extinction are useless in the case of burning petrol; the flame must be smothered by cutting off the air supply. By the addition of an equal volume of caustic soda to a solution of alum a mixture is obtained which gives a very bulky foam when pumped on the petrol. This mixture has proved very effective in smothering such fires, and is kept in readiness at many Continental stores and garages.

BENZENE (*Benzol*).

The hydrocarbon benzene (C_6H_6) is the first member of a series of hydrocarbons known as the *aromatic series*, which occur chiefly in tars obtained by the distillation of coal. The first three members of the series only demand consideration: they are :—

	Formula.	Boiling point ° C.	Specific gravity.
Benzene . .	C_6H_6	80·5	·886
Toluene . .	$C_6H_5.CH_3$	110·0	·865
Xylene . .	$C_6H_4(CH_3)_2$	137–140	about ·87

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[1] The consumption in aeroplane engines is considerably higher; 1 to 1·05 pints per B.H.P. hour.

Benzene was discovered by Faraday in 1825 in the liquid products obtained by condensing oil gas. Hofmann (1845) recognized it as a constituent of the light oils from coal tar. Benzene freezes at a temperature of + 6° C. Its *specific heat* is 0·416 between 19° and 30° C., and its *latent heat* of vaporization at 80·35° C., is, according to D. Tyrer, 94·35 cals. per gram, and at ordinary air temperatures about 100 cals.

Pure benzene is far too expensive to be used as a fuel. The material available for this purpose is a mixture consisting mainly of the three hydrocarbons described above, the proportion of each being dependent upon the process of distillation. The commercial mixture is commonly known as "benzol."

The light oils from coal tar distillation are redistilled, and the lowest boiling fractions collected separately. These are washed by agitating thoroughly with sulphuric acid (which removes some sulphur compounds, basic compounds, and certain unsaturated hydrocarbons), then with sodium hydroxide (caustic soda), which removes any tar acids, such as carbolic acid, which may be present, and finally with water. It is then submitted to a process of rectification in stills fitted with apparatus so that whilst the lower boiling and more volatile constituents pass forward to the water-cooled condensers, the higher boiling portions are flowing back continually to the still. According to the character of the commercial fraction desired, so the distillates are collected up to a certain temperature and specific gravity.

Large quantities of benzol also are extracted from the gases and vapour evolved in the production of coke in recovery ovens, generally by direct processes of absorption by heavy oils, from which the more volatile benzene is recovered by subsequent distillation. The whole question of output and possible supplies of benzol, which, being practically the only native fuel available in large quantities for use in internal combustion engines, is of immense importance, is discussed later in the section dealing with the economic aspects of liquid fuel (p. 181).

Commercial benzol is classified as 90 per cent., 50 per cent., 50/90 per cent., etc. This does not indicate the percentage of benzene present in the distillate, but the percentage distilling below a certain temperature, generally 100° C. Thus, a 90 per cent. distillate yields 90 volumes out of 100 below a temperature of 100° C.; 50/90 yields 50 volumes below 100° C., and 90 volumes, in all, before 120° C. is exceeded.

It follows that the commercial grades are mixtures of the hydrocarbons benzene, toluene, and xylene, the proportion of the last two increasing as the yield below 100° C. decreases. There is also present a varying amount of hydrocarbons of other series, which escape attack during the sulphuric acid washing; these are principally of the paraffin series, but some quantity of naphthene (polymethylene) hydrocarbons are also present. The quantity of hydrocarbons other than those of the aromatic series is of no moment from a fuel point of view, but in many of the applications in the Arts is a serious drawback.

The following proportion of the hydrocarbons present may be taken as approximately correct:—

	Benzene.	Toluene.	Xylene.	Other hydrocarbons.
90 per cent. benzol .	70–75	22–24	traces	4–6 per cent.
50 per cent. benzol .	50	35–40	10	

The commercial valuation of benzol is made in this country by a purely arbitrary and most unscientific method of distillation where the bulb of the thermometer is immersed in the liquid. As with petrol, the form of apparatus employed, the rate of distillation, etc., make a considerable variation in the volume of the fractions obtained for a given range of temperature.

Ninety per cent. benzol is the quality employed usually in this country as a petrol substitute in internal combustion engines. The full data on all the important chemical and physical properties for this class are given in Table XXXIV. (p. 158). The freezing point of pure benzene is 6° C., but, although definite results are wanting, the freezing point of the commercial benzol will be somewhat lower.

Benzol (90 per cent.) has proved a most successful fuel in internal combustion engines, where it may be employed without any alterations to existing arrangements for petrol. In tests made with a 12 H.P. stationary engine, the results obtained were about 12·5 per cent. better than with petrol in the same engine. Results in practice are referred to later in comparison with those for petrol and alcohol.

Possibilities of Crude Benzol.—The important consideration arises as to whether purification to the degree usually adopted for commercial benzol (which has to be used for many purposes where a fair degree of purity is essential) is necessary for its use in internal combustion engines. The exhaust from engines running on benzene has a characteristic odour. This may be due in part to sulphur compounds which are also present, but the smell certainly does not suggest that sulphur compounds are the principal offenders.

In evidence before the Motor Union Committee (p. 43 of M. U. Report), Mr. Edmond Ledoux stated that he had used unwashed 65 per cent. (below 120° C.) benzol in a car with every success, but that the smell was objectionable; whilst Mr. W. A. Bower considered that at present unwashed benzol could not be regarded as quite suitable, but expressed confidence that, by distilling out the lighter

TABLE XXXIV.

PROPERTIES OF PETROL, BENZENE (90 PER CENT.) AND ALCOHOL (METHYLATED).

		Petrol.	Benzene.	Alcohol.
Specific gravity		0·680–0·760	0·883	0·820
Composition		Paraffin hydrocarbons mainly of C_nH_{2n+2} series Carbon = 84 % Hydrogen = 16 %	Benzene (C_6H_6) and Toluene (C_7H_8) Carbon = 92·2 % Hydrogen = 7·8 %	Ethyl alcohol (C_2H_6O) Methyl alcohol (CH_4O) Carbon = 50·7 % Hydrogen = 13·0 % Oxygen = 36·3 %
Boiling range		60–150° C.	80–120° C.	80–110° C.
Freezing point		About −120° C.	Below 6° C.	About −110° C.
Coefficient of expansion	per ° C	0·0008	0·00140	0·00110
	,, ° F	0·00045	0·00077	0·00062
Specific heat		0·470	0·416 [2]	0·615 [2]
Latent heat of vaporization (calories)		86·0	94·35 [2]	203·0 [2]
Calorific value	B.Th.U. per lb. (gross	20,000	17,750	11,320
	,, ,, ,, (net)	18,450	17,100	10,350
	,, ,, gal. (gross)	144,000 [1]	156,700	92,820
	,, ,, ,, (net)	132,500 [1]	150,000	84,900
Theoretical air for combustion	lbs. per lb.	15·24	13·46	8·75
	cub. ft. per lb.	187 (at 0° C.), (197 at 60° F.)	165·5 (175)	108 (113·5)
	lbs. per gal.	109·6	118·5	71·80
	cub. ft. per gal.	1346 (0° C.), (1420 at 60° F.)	1456 (1540)	886 (930)
Calorific value of 1 cub. ft. of theoretical mixture		103	105	97·5
Explosive range (vapour per cent. by volume in mixture)		1·1–5·3 [3]	2·7–6·3	4·0–13·6
Compression limit in lbs.		About 70	Slightly above petrol.	About 200

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[1] Calculated on assumed gravity of 0·720.

[2] For pure benzene and ethyl alcohol respectively.

[3] Range given in M.U. Fuel Committee Report.

portions, whereby the bulk of the sulphur compounds could be eliminated, it could be made suitable.

According to A. Spilker (*J. S. C. I.*, 1910, 616), attempts to use crude benzol have failed owing to a separation of resinous bodies, their formation being attributed to cyclopentadiene (a "naphthene" hydrocarbon), which polymerizes. He mentions that on standing for some months crude benzol shows an increase in specific gravity, an increase in the non-volatile constituents, resulting in a fall of about 1 per cent. in the proportion distilling below 100° C. It may be noted here that the darkening in colour observed when unwashed benzene is kept for some time exposed to light supports this view of polymerization, and it is highly probable that the peculiar characteristics of the exhaust with benzol are due mainly to the incomplete combustion of such compounds, and that sulphur compounds play but a minor part.

ALCOHOL.

Although not a fuel in the commercial sense in Great Britain, alcohol offers so many advantages as a fuel that its extended use is rendered impossible at present only by reasons of cost of production and Excise restrictions. Its practical value has been demonstrated abundantly, for it has taken a place already as a commercial fuel in Germany, France and, to a less extent, in the United States. In each of these countries valuable Government aid has been given in investigating methods of production and application in suitable engines. Although the United States probably is provided more abundantly by Nature with fuels than any other country, its Government has not hesitated to expend considerable sums in investigating the value of alcohol, and the Report on the subject (*Bull.* No. 392, *U.S. Geol. Survey*, 1909) is worthy of careful study. No less than 2000 tests on gasoline and alcohol engines were carried out.

The necessity for careful consideration of alcohol as a fuel is crystallized in a simple statement that it is at present the only medium through which man is able to convert the heat energy of the sun into work in a sufficiently reasonable time and in sufficient quantities to justify the application of the term "fuel" to the product. For all other fuels mankind is dependent, sooner or later, on natural materials, the provision of which by Nature is not proceeding at anything approaching the rate of consumption; indeed, in some cases, the provision has probably ceased already. Alcohol, then, is the only fuel which can be manufactured in large quantities without recourse to existing fuel substances, and this possibility is of the utmost importance in countries devoid of any large quantity of natural oils suitable for internal combustion engines. It affords the only possible weapon of defence against increasing cost of imported fuel, and the almost certain increase in the cost of benzol when its use becomes more general. At some distantly future date, when our coal-measures are nearing exhaustion, it may become the fuel on which the nation will be primarily dependent.

Advantages of Alcohol.—Alcohol as a fuel offers the advantages of great safety, by reason of its low degree of volatility and higher flash point, about 17° C. (65° F.); its vapours are not quite half as heavy as those of petrol, so that it does not creep and accumulate in dangerous quantities on low levels, and a higher proportion is needed to form an explosive mixture; it mixes in all proportions with water, and burning alcohol can be extinguished with water. Although of much lower thermal value than petrol and benzene, it shows a relatively good thermal efficiency, and the actual consumption for a given power is not much higher than with these other fuels. Its uniformity of composition is another point in its favour.

On the other hand, there is the great problem of cost and exemption from many of the restrictions at present imposed on its production to be overcome. Further, as minor objections, come the question of possible corrosion; the fact that some 5·5 per cent. of the total heat of its combustion is required for vaporization, and that some addition, such as benzol, or the prior running of the engine on either petrol or benzol to warm up is necessary before alcohol can be used directly. The corrosion trouble is not serious, neither is that of vaporization, once the engine is hot, for there is always the sensible heat of the exhaust gases available; but that of difficulty in starting from the cold is almost inherent in a fuel of low vapour pressure.

The higher degree of safety renders the storage, handling and transport of alcohol more free from those necessary restrictions which have to be imposed on petrol and benzol, and would appreciably affect insurance rates. Further, in many hot countries the use of the more volatile spirits is almost impossible, whilst in the hottest climate alcohol is perfectly safe.

The exhaust gases from alcohol are, in addition, quite free from any objectionable odour.

Composition of Alcohols.—A large number of bodies having certain characteristics, which are typified in the ordinary ethyl alcohol of fermentation, are classed as alcohols, but only the first two members of the series, which may be regarded as hydroxyl (HO) substitution products of the paraffin hydrocarbons methane (CH_4) and ethane (C_2H_6), demand consideration as fuel. One very important point is that in all alcohols there is a fairly high proportion of oxygen which affects their calorific value adversely. The composition and physical properties of the fuel alcohols are as follows:—

Name.	Formula.	Percentage composition.			Specific gravity.	Boiling point.
		Carbon.	Hydrogen.	Oxygen.		
Methyl alcohol . .	$CH_3 \cdot OH$	37·5	12·5	50·0	0·810	66° C.
Ethyl alcohol . .	$C_2H_5 \cdot OH$	52·2	13·0	34·8	0·7946	78·5° C.

The *specific heat* of the ethyl alcohol is 0·615 at 30° C. Its *latent heat* of vaporization is from 200 to 205 cals. per gram. The latent heat of methyl alcohol is about 265 cals. per gram. Both mix perfectly with each other and with water in any proportion, a marked contraction in volume taking place in the latter case.

Methyl Alcohol is obtained mainly by the distillation of the pyroligneous liquids obtained in the destructive distillation of wood (see p. 21). These acid liquids are washed first with alkalies, and the remaining crude spirit contains about 80 per cent. of methyl alcohol or "wood spirit."

Ethyl Alcohol is the principal alcohol obtained in ordinary processes of alcoholic fermentation; small amounts of alcohols of higher molecular weight—the fusel oils—are produced simultaneously. With the realization of the possibilities of alcohol as a fuel much attention is being paid to cheap methods of production; these are referred to in detail later.

Pure absolute alcohol cannot be considered as a practical fuel; the elimination of the last few per cents. of water is far too expensive in relation to the gain in value. Further, because of necessary Excise restrictions, alcohol for commercial use must be rendered undrinkable by the addition of various other liquids, a process termed *denaturing*. The strength of alcohol is estimated in this country, France and the United States in percentages by volume; in Germany, in percentage by weight. Proof spirit derives its name from the old test of whether the alcohol-water mixture burnt with sufficient intensity to ignite gunpowder. Proof spirit contains 57·06 per cent. by volume, or 49·24 per cent. by weight of alcohol. Its specific gravity at 15° C. is 0·9198.

Denatured Alcohol (Methylated Spirit).—Various denaturing fluids are employed in different countries for rendering alcohol unpalatable. In England, 10 per cent. of methyl alcohol and a small quantity of a paraffin hydrocarbon, which causes turbidity when the methylated spirit is diluted with water, are employed. In France, the denatured alcohol is very similar in composition. In Germany, two classes of denatured spirit are available; for ordinary use, 2·5 vols of methyl alcohol in 100 of ethyl, together with a small quantity of the pyridine bases extracted from coal tar; for fuel purposes, half this quantity of methyl alcohol and not less than 2 per cent. of benzol, the mixture being given a distinctive colour by the addition of methyl violet—one of the coal tar colours.

Calorific Value.—The values determined by various observers differ somewhat, but the following mean values from all the reliable determinations available may be taken. The net values have been calculated from the gross values on the assumption that in the latter the water formed was condensed to a final temperature of 60° F.

	Specific gravity.	B.Th U. per lb.		B.Th.U. per gallon.	
		Gross.	Net.	Gross.	Net.
Methyl alcohol	0·810	9,570	8,320	77,500	67,450
Ethyl alcohol	0·7946	12,790	11,480	101,000	91,100
Methylated spirit	0·820	11,320	10,350	92,320	84,900

According to Schöttler, ethyl alcohol of various strengths has the following density and calorific value:—

Alcohol per cent. by vol.	Specific gravity.	Net heating value.
95	0·805	10,880
90	0·815	10,080
85	0·826	9,360
80	0·836	8,630

Air for Combustion.—By methods described earlier, the theoretical volume of air for the combustion of alcohol of various strengths may be calculated to be as given in Table XXXV.

TABLE XXXV.

THEORETICAL AIR FOR THE COMBUSTION OF ALCOHOL.

Strength.	By weight.		By volume.			
			Cub. ft. at 0° C.		Cub. ft. at 60° F.	
	Air per lb.	Air per gall.	Per lb.	Per gall.	Per lb.	Per gall.
Absolute	9·0	71·5	111·0	882·0	117·0	930·0
95 per cent.	8·48	68·2	104·5	841·0	110·0	890·0
90 ,,	7·75	63·2	96·0	783·0	101·5	827·0
85 ,,	7·21	59·5	89·4	738·5	94·5	780·5
Methylated spirit (0·820)	8·75	71·8	108·0	886·0	113·5	930·0

All necessary data relating to the composition, physical properties, air for combustion, etc., of methylated spirit will be found in Table XXXIV (p. 158). Attention need be directed only to the effect these various factors have on the practical application of spirit in internal combustion engines.

The *explosive range* is much greater than for benzene-air and petrol-air mixtures, which give greater "flexibility" to the engine. The *rate of flame propagation* in the mixture is much slower than in the case of other mixtures, so that more uniform pressure is exerted throughout the stroke; since combustion is more prolonged the sparking must be advanced as compared with that required for petrol or benzene, and the slow rate of propagation also indicates that a lower speed of running is required. The *calorific value of the mixture* with theoretical air will be seen on comparison to be only a few per cents. lower than that for petrol-air or benzene-air mixtures.

Thermal Efficiency of Alcohol.—It will be seen that the relative calorific value of petrol and alcohol per lb. is as 1·55 to 1. The thermal efficiency of an internal combustion engine is, however, largely proportional to the compression, and here the high compression which is possible with alcohol without fear of pre-ignition gives it a marked advantage; so great, indeed, that the discrepancy of their calorific values is largely eliminated. A good petrol engine will give about 20 per cent. mechanical efficiency; many Continental makers of alcohol engines will guarantee an efficiency of 30 per cent. It will be seen that the product of calorific value and mechanical efficiency in the case of these two fuels is approximately the same; indeed, the approximate relative efficiencies of engines of suitable design in each case, running respectively on benzene, petrol, and alcohol, conform to the ratios 1·1 : 1·0 : 0·9.

In the United States tests, with engines in each case working under the best conditions, very high efficiencies were obtained; with alcohol 39 per cent.; with petrol 26 per cent.; the approximate ratios therefore were 1·5 : 1.

Corrosion with Alcohol.—One of the troubles which have arisen with alcohol in engines has been that of corrosion of valves, etc., due to the production of acid bodies. The partial oxidation of an alcohol takes place at a low temperature, and leads first to the formation of a substance known as an *aldehyde*, and this in turn becomes an acid. Thus—

$$\begin{array}{ccccc} \text{Methyl alcohol} & & \text{Formaldehyde} & & \text{Formic acid} \\ CH_3.OH & \rightarrow & H.COH & \rightarrow & H.COOH \\ \text{Ethyl alcohol} & & \text{Acetaldehyde} & & \text{Acetic acid} \\ C_2H_5.OH & \rightarrow & CH_3.COH & \rightarrow & CH_3.COOH \end{array}$$

Sorel, in his exhaustive volume on "Carburetting and Combustion in Alcohol Engines," which should be consulted for detailed information on the whole subject, concludes that methyl alcohol begins to form aldehyde at 160° C. (320° F.), whilst strong ethyl alcohol does not show the formation of acetaldehyde until a temperature of 300° C. (572° F.). This confirms the general opinion that the high percentage of methyl alcohol in English and French methylated spirit is greatly against their use in internal combustion engines. Its reduction and the substitution of some other denaturant, although it is not easy to suggest one offering sufficient difficulties to prevent its too ready removal, would undoubtedly become necessary.

In the presence of oxygen at a moderate temperature some acetaldehyde and acetic acid are certain to be formed from the ethyl alcohol, and the exhaust gases are always liable to contain traces of acids. Running a few revolutions on petrol or benzene before stopping the engine is found to overcome the trouble of corrosion, and this offers no great difficulty, for in many cases such fuels are necessary for starting up. It must be remembered that while the engine is hot these acid products will not affect the metal; it is only on cooling, leading to their condensation on the surfaces, that action will be set up. For this reason the silencer generally is found to suffer most.

Sources of Industrial Alcohol.—The success of alcohol as a fuel will depend necessarily upon the facilities and cost of production. Until quite recent years alcohol has been obtained entirely by fermentation of materials derived from starch or from sugars, by the well-known action of the yeast cell. With either process the cost has been relatively high and dependent to a large extent upon the success of the potato and sugar-beet crops.

Much scientific skill has been expended in attempting to produce alcohol at a much cheaper rate from ordinary cellulose materials—waste wood, the sulphite lyes from the wood pulp mills, and other sources. It is not intended to discuss methods of production but to refer mainly to results which have been obtained, and their bearing on probable cost of actual production.

According to E. A. Mann (*J. S. C. I.* 1906, 1076) the following yield of alcohol is the average for the various materials commonly employed in ordinary fermentation processes:—

	Proof gallons per bushel of 60 lbs.	Equal to a yield in gallons per ton.	
		Absolute alcohol.	90 per cent. alcohol.
Pure starch	4·68	82·0	95·0
Wheat, barley, oats, etc. (average)	2·08	38·0	42·0
Potatoes (21 per cent. starch)	1·26	23·5	25·5
Sugar cane (12 per cent. sugar)	0·72	13·5	14·7
Beet (10 per cent. sugar)	0·60	11·25	12·25

Professor R. F. Ruttan (*J. S. C. I.* 1909, 1291) gives the cost of raw materials used in the fermentation processes per gallon of 94 per cent. alcohol as approximately—

Indian corn, the cheapest American grain source	24 cents
Raw molasses	21–22 ,,
Raw material in Germany	20–21 ,,

These prices he considers prohibitive, and looks to wood waste as the only available material for furnishing alcohol at a low price.

It is very difficult to arrive at the actual yield likely to be obtained from wood (sawdust and general waste) and from the sulphite liquors obtained in the production of cellulose for paper; the figures given by different writers vary very widely. From wood the yield stated ranges from 20 gallons of 90 per cent. alcohol to 52·8 gallons.

Professor Ruttan (*loc. cit.*) states that, although waste wood is being employed more and more for power purposes, there are still large quantities of which it is impossible to dispose, capable of yielding 20 gallons of 94 per cent. alcohol per ton (dry), and that the Standard Alcohol Company claim that their plant, which is already operating on 100 tons of (dry) sawdust in the 10-hour day with profitable results, could produce alcohol (90 per cent.) at a cost of 10·8 cents per gallon, if working 200 tons daily. On a still larger scale it is estimated that the cost could be reduced to 7 cents per gallon.

With waste sulphite liquors, fermentation yields, according to a United States Consular Report, 14 gallons of absolute alcohol for every ton of cellulose produced. Results given by W. Kiby (*J. S. C. I.* 1910, 1265) for Swedish wood pulp mills are nearly equal to this. It is estimated that the pulp mills of Sweden are capable of producing about 5½ million gallons per annum; the cost with present tax amounting to about 9·3 pence per gallon. Kiby further estimates that a plant producing 60 tons of cellulose per day would be equivalent to producing about 286,000 gallons of alcohol annually, and the cost, with 10 per cent. allowance for depreciation in capital, would amount to but little over 5½*d.* per gallon. In evidence before the Departmental Committee on Industrial Alcohol, Dr. Ormandy stated that, according to most recent information, alcohol could be produced from wood at an inclusive cost of just under 6*d.* per gallon.

According to T. Koener (*J. S. C. I.* 1908, 1216), these yields are likely to be increased materially by the addition of 2 per cent. of hydrogen peroxide to the dilute acid used in the treatment of the cellulose.

Many other sources of cheap alcohol have been proposed, but, in view of the absence of any quantities of waste wood in Great Britain, one for the production from peat by fermentation (see M.U. Report of Fuels Committee, p. 50) is of interest. It is claimed that this process would enable alcohol (90 per cent.) to be produced at 3*d*. a gallon in bulk at the works.

It appears evident that in large wood-producing countries alcohol certainly can be produced at a very much cheaper rate than it can possibly be produced in other countries dependent upon the fermentation of starches and sugars, and in such countries it would prove a cheap fuel when used in internal combustion engines.

For alcohol to become a practical fuel in the British Isles (outside the doubtful production from peat) fermentation processes dependent upon starch or beet sugar would have to be relied on. The actual cost of production from these sources varies from year to year with the crops. About 1*s*. a gallon appears to be the average cost of fuel alcohol in Germany, with the cost of denaturing and Government supervision. In Great Britain the cost of production alone appears to be about 11*d*. per gallon, and with the necessary restrictions on processes, supervision and duties, the price amounts to about 1*s*. 4*d*. to 1*s*. 6*d*. per bulk gallon; the retail price is about 1*s*. 11*d*. per gallon.

Mr. Tyrer stated before the M.U. Committee that motor alcohol was contracted for in Germany at just under 1*s*. per gallon in large quantities, but that this price was exceptionally low, and in 1906 the price was about 1*s*. 4*d*. and in 1907 about 1*s*. 3*d*. per gallon.

In the Report of the Departmental Committee referred to above the following occurs: "Any question of the use of spirit for motor vehicles will be one of price, and as the *present* price of petrol is about half the price of methylated spirit, we think that close investigation of the matter may be delayed until such time as there may be an approximation between the prices of petrol and spirit sufficient to create a practical alternative of choice between the two." In view of the big increment of price in petrol since this report was issued, this approximation is certainly very near to realization; the importance of a fresh consideration of the whole question of freeing alcohol to be used for fuel purposes from some of the onerous restrictions hitherto imposed is certainly desirable.

COMPARISON OF PETROL, BENZOL AND ALCOHOL IN PRACTICE

A large number of petrol engines have been run with every success with 90 per cent. benzol as the sole fuel, a point of very great importance in view of the latter being a home product. The only alteration in conditions of combustion has been the admission of a little more air than for petrol; no structural alterations have been required. The chief difficulty has been a little trouble in starting in cold weather; there is also the possibility of the benzene solidifying at low temperatures, but admixture with petrol obviates these difficulties.

The general experience with benzol is that a better efficiency is obtained with an ordinary petrol motor, and many who have tried benzol find a car takes a hill better on this fuel than on petrol. In an exhaustive trial made with a 12 H.P. stationary engine, benzol proved 12·5 per cent. more efficient than petrol. Brewer states that a 40 H.P. 6-cylinder Napier car gave a ratio of miles per gallon on benzol as compared with petrol of 1·25 : 1. In a record of trials given in the M. U. Fuels Reports the ratio for similar trials was 1·36 : 1.

Large numbers of tests are available showing the results obtained with alcohol, and in Germany alcohol engines have worked with success for many years; it is, however, to the large series of trials made in the United States that reference must be made for the most exhaustive results on alcohol as a fuel.

Amongst the earliest trials which demonstrated the success of alcohol were those at Vienna, where the consumption of alcohol per H.P. hour was 0·82 lb. and of petrol 0·75 lb. In the American trials, with engines built to give the best result with alcohol and petrol respectively, the compression for alcohol being 180 lbs. and for petrol 70 lbs. above atmospheric, the thermal efficiency on the I.H.P. and net heating value was for alcohol 39–40 per cent., for petrol 26–28 per cent. The actual fuel consumption was 0·7 lb. alcohol and 0·6 lb. petrol, so that for engines of the most suitable construction in each case, it was almost exactly equal by volume. Allowing for the difference in specific gravity the consumption of alcohol to petrol by weight is 1·14 : 1.

The general conclusions arrived at in these trials were—

(1) That any petrol engine of the ordinary type can be run on alcohol without any material alteration in the construction of the engine.

(2) The chief difficulties likely to be met with are in starting and supplying a sufficient quantity of the fuel.

(3) The maximum power is usually greater with alcohol, and the engines are more noiseless than with petrol.

(4) The fuel consumption per B.H.P. with a good small stationary engine may be expected to be 1 lb. (or a little over) with alcohol and 0·7 lb. with petrol.

The alcohol-air mixture burns at a slower rate than the petrol-air mixture, so that for the best results ignition must take place earlier with alcohol. In tests with a 15 H.P. petrol engine, load 85 per cent. of maximum, the best consumption of 0·66 lb. per B.H.P. hour was attained with ignition 13° before the dead centre; with alcohol, 79 per cent. load, the best consumption was 1·1 lbs., with the ignition at 25°.

The effect of more or less water in the alcohol is of importance, since the economic production of cheap alcohol for fuel will be dependent to a considerable extent on the degree of freedom from water in the alcohol. The conclusion arrived at in the United States trials was that for a given engine, load and compression, the consumption of pure alcohol per B.H.P. increases with the water, and the maximum available H.P. decreases, but not to a great extent. From 80 to 94 per cent. of alcohol the consumption of *pure* alcohol is about the same, *i.e.* the total consumption is almost directly proportional to the increase in the percentage of water. There seems little to be gained in the way of better performance of the engine with purer alcohol, so that the extra cost involved in obtaining very low percentage of water in the alcohol is by no means commensurate with the better result it gives in practice.

Alcohol mixed with other volatile inflammable liquids which are intended to obviate the trouble due to its lower volatility has met with considerable success, and during the war many such mixtures have been employed in Germany. The following are typical: Alcohol (95 per cent.), 70; benzol, 30 parts: alcohol (90 per cent.), 50; acetone, 20; benzol, 30 parts: alcohol, 90; ethyl ether, 10 parts. In many cases a considerable quantity of naphthalene is employed, but this is not advisable, as it tends to formation of carbon deposits. It is recommended to add about 1 per cent. of lubricating oil to prevent corrosion.

In this country a fuel consisting of alcohol, 60, ether, 40 parts, together with a trace of ammonia to neutralize corrosion, has proved successful. Slight reduction of the air supply is necessary with all mixed fuels of this type.

Chapter X

HEAVY FUELS FOR INTERNAL COMBUSTION ENGINES

Light Oils (Paraffin Oil, Kerosene)

The oils so largely employed in slow speed internal combustion engines are those sold mainly for general illuminating purposes, having a flash-point higher than 70° F., although some special oils intended for use solely in such engines are now put on the market. The usual temperature over which such oils are collected is from 150° to 300° C. (303–572° F.). The general distillation process by which these oils are obtained has been described already (p. 114).

The use of these oils for power purposes offers many advantages over petrol. They form a much higher percentage of the total distillate obtained from the crude oil; their flash-point is so high that no special precautions are required in their storage and distribution; they can be obtained more readily than petrol; all these factors making their average price about one-third that of petrol.

Having a calorific value per lb. equal to petrol, with their higher density they afford a much larger number of heat units to the gallon than does petrol, so that in suitable engines their use is very economical.

Owing to their relatively low vapour pressure it is impossible to form an explosive mixture with air in the same manner as with a petrol carburettor; heat has to be applied in order to vaporize the oil. Without special care this may lead to "cracking" of the oil, and this again to considerable modification of the air required, besides the almost certain appearance of carbon deposit. When a spray of paraffin oil is carried forward into the cylinder condensation of some portion is very likely to occur before complete combustion, and generally it is more difficult to attain that uniform composition of the mixture necessary in a high-speed engine. This uniformity is of far greater importance in a high-speed engine running on illuminating oils, because the range of explosion of the mixture is only about half that of the petrol-air mixture, which itself is a narrow one.

Engines on the lines of the petrol motor have been designed for use with illuminating oils and work successfully at nearly constant speeds, but the difficulty of maintaining the constancy of the mixture with variable speeds has practically confined the general use of these higher distillates to slow-speed engines running without those wide fluctuations which occur with the ordinary petrol motor.

Composition and Properties of Paraffin Oil.—The general character of these oils has been referred to under the composition of crude petroleum. Being higher members of homologous series of hydrocarbons their average percentage composition agrees with that of the petrols. The composition and calorific value, determined in a bomb calorimeter by W. Inchley (*The Eng.*, 1911, 111, 155) are given in Table XXXVI.

TABLE XXXVI.

Composition and Calorific Value of Paraffin Oils (*W. Inchley*).

Name.	Specific gravity.	Composition.			Calories per kilo.	Calorific value.	
		Carbon.	Hydrogen.	Oxygen, Nitrogen, etc.		B.Th.U. per lb.	B.Th.U. per gall.
Royal Daylight (American)	0·797	85·70	14·20	—	11,167	20,100	159,000
Kerosene (American)	0·780	85·05	14·40	0·55	11,163	20,095	156,500
Refined (Baku)	0·825	86·00	14·00	—	11,270	20,300	167,000
Russole, R.V.O.	0·890	85·95	13·50	0·45	10,901	19,620	174,500
Solar Oil	0·896	86·61	12·60	0·79	10,783	19,450	174,000

The following determinations (Table XXXVI.) of calorific value (bomb calorimeter) and specific heat were made by the writer:—

TABLE XXXVII.

Calorific Value and Specific Heat of Paraffin Oils (*Brame*).

Name.	Specific gravity.	Calorific value.			Specific heat.
		Calories per kilo.	B.Th.U. per lb.	B.Th.U. per gall.	
Royal Daylight (Tea Rose)	0·8055	11,100	19,980	160,500	0·450
Water White (White Rose)	0·800	11,140	20,050	160,400	0·457
Russian	0·8248	11,060	19,910	164,000	0·435
Roumanian	0·8127	10,900	19,620	159,500	0·444

The flash-point of these oils is seldom below 81° F.; that of the special engine fuels (Russolene, "R.V.O." etc.) is generally from 82–86° F.

The earlier oil engines were developed mainly with American oils of about sp. gr. 0·80 as the fuel. With the introduction of the heavier Russian oils, sp. gr. about 0·84, the results obtained were not so good. It was found, however, that by a slight increase of compression, by means of a plate fixed on the piston, and frequently increasing the proportion of air, the engine output was often considerably increased with the heavier Russian oils. This variation in conditions necessary to ensure the best results has led to a careful standardization of oils suitable for engines of this type.

Consumption of Oil.—Under test conditions at full load the consumption of oil of the above description has frequently not exceeded 0·6 lb. per B.H.P. hour. With a specific gravity of 0·80 the pint of oil would weigh one pound, so that the consumption in pints is practically synonymous with the consumption in pounds. Under everyday running conditions at anything closely approaching full load an average consumption of oil of good quality may be taken as 0·70 lb. (or pints).

The thermal efficiency of this type of engine is between 21–22 per cent.

HEAVY OILS

In this class are included those oils more particularly suitable for the Diesel or semi-Diesel type of engine. They include heavier petroleum oils (such as already described as suitable for fuel oils, providing they are reasonably free from solid carbon, etc.); the solar oils, gas and blue oils intermediate between the ordinary burning and lubricating oils; heavier shale distillates, especially the portion unsuitable for lubricating oil, and containing but little paraffin wax; heavy coal tar and coke-oven tar oils; and many crude tars, including the above and water gas tar.

In the preceding pages fairly complete information has been given on the composition and character of these various products. The important results in power production already achieved, and the very important place engines of this type are taking for both land and marine purposes, render it very necessary to consider the influence which the composition and properties of the different fuels exercise on their suitability for such use. The engines have hardly been established a sufficient length of time for the most desirable character of the fuel to be clearly established, but certain main conditions are recognized already.

In the Diesel type engine the initial compression raises the temperature of the air to 500–600° C. (1020–1110° F.), and the ignition of the oil should take place when forced into this highly heated atmosphere. Clearly much will depend upon the ignition point of the oil, and this is determined mainly by the percentage of hydrogen it contains. A high class heavy oil of the type which works perfectly in the Diesel engine contains approximately—

Carbon	84–15 per cent.
Hydrogen	12–13·5 ,,

It has a calorific value (gross) of approximately 19,500 B.Th.U. per lb. On the other hand are the fuel oils derived from coal tar and similar products, and crude tar itself. These have the approximate composition—

Carbon	78–80 per cent.
Hydrogen	6–6·5 ,,

and a calorific value of about 16,000 B.Th.U.

It is found that whilst petroleum oils ignite properly in the cylinder, tars and tar oils fail to ignite, and some small proportion of petroleum oil must be injected first to act as an igniter. Mr. P. Rieppel has suggested that those oils which ignite well owe this property to their "cracking" at the temperature of the compressed air; they thus set free hydrogen and form heavier hydrocarbons, the low ignition point of the hydrogen initiating the combustion by which the whole of the heavier residues ultimately become consumed. Dr. Allner considers that ethylene is a product of the cracking, and that ignition is brought about by this hydrocarbon, the ignition point of which is 542–547° C. With the other class of fuels this cracking is absent, and though the more volatile portions doubtless vaporize, the ignition is not satisfactory, and they are either not properly consumed or burn with explosive violence.

The conditions under which these two classes of fuel are produced strongly support these views, for although little is known of the higher members of the different hydrocarbon series present in heavy petroleum oils or tars, those in the former are unlikely to have undergone any notable change in the ordinary distillation process, whilst the hydrocarbons in tar are probably nearly wholly the result of destructive distillation at temperatures far higher than those attained in the engine cylinder, at which temperature they are almost certain to be quite stable.

The physical characters of the fuels must be considered briefly

Obviously, to avoid clogging of the fine injection orifices, etc., suspended matter must be absent, and water (such as may be present in considerable quantity in many tars, and which it is often very difficult to remove) must be practically absent.

It is found that the degree of fluidity of the oil is one of the most important factors—if too fluid the spray is too fine, and undue pressures are set up; on the other hand, if the viscosity is high the spray is too coarse, and results in incomplete combustion. Although no data are available on the point, it appears from these considerations that any sudden change in the character of the curve obtained by plotting viscosities against temperature should not be apparent in the region of the temperature at which the oil is sprayed.

Tar Oil and Crude Tar.—Although heavier petroleum distillates are undoubtedly the most suitable oils for these engines, the considerable success which has attended the use of tar oils and also crude tars, especially in Germany, is a factor of considerable economic importance since, whilst petroleum oils are of necessity imported, these coal products are obtained in very large quantities in this country.

The heavier oils derived from the creosote and anthracene oil fractions of coal tar distillation are available without further treatment. Crude tars, providing they are fluid, free from any quantity of water, free carbon and naphthalene, have been very successful. In many cases, however, it appears that such tars are improved greatly by submitting them to distillation. Reference to Table XXV. (p. 119) will show clearly that vertical retort tars and all tars derived from bulk distillation of coal, as distinct from small shallow charges distilled at a high temperature, are the only ones available in the crude state.

Carbon and other solid particles must be removed first by efficient straining through fine mesh gauze, and the water separated by heating, as for heavy fuel oil. To give sufficiently low viscosity the tar is used warm; provision is made for warming the supply tank, pump, and tar pipe. According to Dr. Allner, whilst the viscosity of ordinary vertical retort tars varies greatly at ordinary temperatures, between 50–70° C. (122–158° F.) the viscosity for all is practically the same. The same authority states that a Dessau vertical retort produces daily sufficient tar for running a 20 H.P. Diesel engine for 12 hours.

Consumption of Petroleum Oils and Tars.—The consumption of heavy petroleum oils in the Diesel engine is from 0·40–0·45 lb. per B.H.P. hour; with tar oils the consumption is from 0·48–0·50 lb., together with 0·01–0·02 lb. of petroleum ignition oil.

According to Prof. H. Ade Clarke, the air necessary for proper combustion in the Diesel engine is 3·3 times the theoretical. The theoretical volume at 60° F. would be approximately 190 cub. ft., so that, on Clarke's estimate, some 630 cub. ft. of air are actually required. It is evident that the heat losses in the exhaust gases with such a large mass of air will be very high.

The consumption in crude oil engines of the semi-Diesel type is about 0·55–0·6 pints per B.H.P. hour. With a sp. gr. of 0·9 this is equal to 0·62–0·67 lbs. A Blackstone engine at the Royal Agricultural Show, Gloucester, 1909, working on Texas crude oil at 50*s.* per ton (2½*d.* per gal.) consumed 0·49 pint (0·58 lb.) per B.H.P. hour.

Economic Aspects of Liquid Fuel

The practical advantages which liquid fuel possesses as compared with coal when consumed under boilers have already been dealt with fully in the preceding pages, but they will be summarized briefly here as greater evaporative power, ease of handling, cleanliness, absence of ash, clinker, etc., combustion with little attention once the proper conditions have been arrived at, all leading to great saving in the costs of operating a plant either for power or general industrial purposes. Further, the very great success which has attended the introduction of heavy oil engines of the Diesel type, and of other slow-speed oil engines for general power purposes, has added to the importance of the question, and renders it essential that careful consideration should be given to the economic aspects of the supply of liquid fuel. More especially is this the case in countries where petroleum oils, which furnish by far the largest proportion of liquid fuels of a suitable character, must always be imported fuels, and therefore dependent largly upon conditions outside our control.

Supplies.—The output of oil from the various oil fields of the world is given in Table III, Appendix. For a comparison of the coal output of Great Britain with the total oil production of the world, the relative value of oil in terms of coal must be taken. In the case of steam-raising, allowing for all the economies of oil, its superior evaporative duty and other advantages, it may be taken that 1 lb. of oil is equivalent to 1·5 lbs. of coal. In internal combustion engines using heavy oil, the type which gives the highest efficiency, it will be approximately correct to take the consumption per B.H.P. as 0·5 lb. with regular running conditions, as against an average coal consumption of 2 lbs. per B.H.P. Oil then may be converted into terms of coal in the two cases respectively by the factors 1·5 and 4.

The petroleum output in tons (2240 lbs.) for the periods below was as follows:—

1913.	1914.	1915.
50,000,000	52,550,000	56,200,000

Converting these values into terms of coal by the above factors, the corresponding quantities become—

	1913.	1914.	1915.
By steam-raising .	75,000,000	78,800,000	84,200,000 tons.
In oil engines . .	200,000,000	210,200,000	224,800,000 ,,

The coal production of the whole world is estimated to be 1000 million tons. If the whole petroleum output of the world were available for use under boilers, it would be equivalent only to some 8 per cent. of this, and if it all could be utilized in heavy oil engines it would be equivalent to under 22 per cent. Owing to the value of the many industrial lighter oils from crude petroleum, it may be estimated that not more than half of the crude oil raised would be available for general power purposes, and since about half the coal raised appears to be used for such, the above percentages remain unaltered.

The average coal output for the United Kingdom alone prior to the war was approximately 290,000,000 tons, so that the total petroleum production of the world in 1915 was equivalent approximately to 29 per cent. of the coal output of these islands in the one case, and over 65,000,000 tons short in the other.

It is impossible to obtain more than a wide approximation of the proportion of this coal used for power purposes, but the round figure of 45,000,000 tons is generally taken. Clearly, then, the natural petroleum supplies of *fuel oil* are about 5,000,000 tons (as equivalent to coal under boilers) short of the home consumption of coal for power purposes. Taking engines of the Diesel type, the world's present output of *fuel oil* is equivalent to two and a half times the consumption of coal for power alone in Great Britain.

In view of these important considerations it is clear that, great as are the advantages that liquid fuel undoubtedly possesses, and with the great advances in output of the last few years, it is still a fuel of very secondary importance in general, but in countries where it is bountifully supplied by nature, the enormous quantities there available render it the fuel demanding pride of place. The question of its general use resolves itself entirely into a question of locality, for an imported fuel is never likely to supersede a fuel native to the country or district, except for special applications where its practical advantages outweigh the disadvantage of its foreign source.

The point is well illustrated in the case of the Mexican Railways.

At one time from 120,000 to 140,000 tons of patent fuel were imported from South Wales for locomotive use. With the development of the Mexican oil fields, by 1908 half the engines had been converted to use liquid fuel, and with such success that the remainder have been adapted to use the native fuel.

There is the question of possible augmentation of supplies through the discovery of new fields and further development of existing ones. It will be seen that a considerable increase of output has taken place in the last few years, mainly through the oil fields of Mexico, California, and the Maikop field in Russia. It is impossible to prognosticate as to future developments; time alone will show whether supplies from such sources will more than counterbalance a certain decrease in output from older fields.

In a report on the industry at Batoum (1908), it was stated that the outlook was unsatisfactory and that the wells were showing signs of exhaustion, and "unless new territory is discovered, it is the general opinion that the wells of Baku will only be able to provide for home consumption." An official Report on the United States (1911) states that if the present rate of output is maintained it is probable that the older fields would become exhausted in 90 years, but if estimated on the average increase in rate of output being maintained in 35 years.

As far as the general use of oil as fuel is concerned, the position has been stated succinctly by Sir Boverton Redwood in his contribution to the Natural Sources of Energy Report to the British Science Guild, as follows—"It is evident that even if the available deposits were far larger than there is reason to believe them to be, the cost of doubling the present output would be great. In these circumstances it is not probable that there can be any general substitution of petroleum for coal as a source of power, although there is undoubtedly opportunity for making provision for a larger use of liquid fuel for certain selected purposes in which its advantages are conspicuous, especially in ships of war."

The question is one of considerable moment in the present position as regards power production, with the rapid development which has already taken place in the introduction of Diesel-type engines, and the undoubted still more rapid introduction of this form of power production in the next few years. This development is certainly not likely to be less rapid in the great oil-producing countries, notably America, so that the home demand for suitable oils may become so great that exportation to other countries will be checked, and a consequent rise in price result.

Great fluctuations in supplies and prices of liquid fuel have arisen in the past; the possibilities of interference with transport either through a series of accidental causes, as was the case recently when it was almost impossible to obtain fuel oil in this country outside existing contracts, or in the event of war, must always place an imported fuel at a serious disadvantage with a native fuel. Recognizing all the great advantages which it possesses, advantages which in spite of possible uncertainty of adequate supplies, are bound to lead to its far greater employment in the future, it becomes necessary to consider what sources of such fuel are open in this country.

Shale oil has been shown to be almost identical in character to the natural petroleum oils, and the heavier distillates are amongst the finest fuel oils. Some 3,000,000 tons of shale are retorted annually in this country, yielding approximately 250,000 tons of oil, of which a portion only is available for heavy fuel purposes. In 1910 the shale oil fraction suitable for fuel amounted to about 150,000 tons, so that supplies from this source are very small in comparison even with the present demand. Large quantities of shale oil will become available in New South Wales and New Zealand when the deposits there are worked on an extensive scale.

The tars obtained from coal gas and coke oven plants are certainly the most promising source of supply indigenous to Great Britain, and with the latest Diesel engines capable of utilizing heavy tar oils directly a very extended use of such products must follow in all countries where oil is not the native fuel.

It is difficult to compute the annual production of tar from these two sources: about 16,000,000 tons of coal are carbonized annually in the gasworks, and about the same quantity in coke oven plant, but in about half the latter no tar recovery is made. Assuming the tar is available from 25,000,000 tons of coal, and that the tar, free from water and light oils, which would be probably the only form in which it would be available generally as a fuel oil, amounted to 110 lbs. per ton, the available tar would amount annually to 1,250,000 tons. In a Diesel engine the consumption of tar per B.H.P. generally has been about 0·5 lb., so that, although proportionately to the total coal consumed for power purposes, the amount is small, yet it indicates sufficiently that coal tar must be considered seriously as a very important source of power in internal combustion engines in the future.

Crude tar also has been employed very successfully with atomisers for steam raising, and the following results have been supplied by Mr. S. Field.

TESTS ON FIELD-KIRBY CRUDE TAR AND OIL BURNER, WITH A LANCASHIRE BOILER 28′ × 7′ (for one hour).

	Test No. 1.	Test No. 2.
Total water evaporated	3280·0 lbs.	2798·0 lbs.
Total tar consumed	284·5 ,,	253·0 ,,
Actual evaporation of water per lb. of fuel	11·52 ,,	11·06 ,,
Evaporation per lb. of fuel from and at 212° F.	12·91 ,,	12·70 ,,
Average steam pressure per sq. inch	30·0 ,,	30·0 ,,
Corresponding temperature to the steam pressure	274° F.	274° F.
Average temperature of the feed-water	114° F.	87° F.

Crude tar (not containing any quantity of free carbon and fairly free from water) has proved a success for steam-raising, retort-heating, etc., but a very material change has taken place in the position of tar as a fuel since about the year 1909, when a marked advance in price set in. Several causes contributed to this, notably the increased use of tar for road spraying, the increased value of pitch, used for briquetting coal, and the good prices obtained for creosote oils. The following list indicates this advance in wholesale prices :—

	January, 1909	January, 1913.
Tar	10/9–14/9	28/6–33/-
Pitch	18/0–19/0	44/0–50/-
Benzol (benzene) 90%	-/6- -/8	1/0½

The natural effect of these rises has been shown by the practical discontinuance of the use of tar as fuel at gasworks and on the Great Eastern Railway, where at one time a large number of locomotives were running wholly or partly on this fuel.

There is a good demand for tar which has been dehydrated and from which the valuable light oils have been removed, for tar-spraying roads. This treated tar sells at 3½*d.* per gallon (London), and its specific gravity being about 1·2, this is equivalent to a price of 54*s.* a ton. The writer is informed by a large producer that it is improbable that contracts for tar for fuel purposes would be entered into for tar of any other character, which is indeed the safest and most suitable for such a purpose. Clearly it cannot pay to consume such tar for steam-raising or other heating purposes. If used in internal combustion engines tar at this price compares very favourably with coal under boilers, but it will be seen that it offers no advantage as compared with imported fuel oils, until a price of about £3 a ton is reached for the latter. Crude tar (if procurable) at its present market value is certainly a cheap and useful fuel in such engines. The installation of Diesel engines suited to tar oils and adaptable for these or natural oils, would certainly seem a wise proceeding, as it would place the user in a more independent position as regards supplies.

The important position which the petrol motor has attained both for commercial and pleasure purposes, a position which is increasing daily in importance, renders a consideration of the economic aspect of the supply of suitable fuel essential. The question already has received the attention of the Motor Union of Great Britain and Ireland, who in 1906, because of the "recent alarming rise in the price of petrol," appointed a Committee to consider possible supplies, and the Report of this Committee has been referred to already in several places. The matter also has been discussed widely in the technical press, in view of the still more alarming rise since that time.

The enormous increase in the quantity of petrol imported into Great Britain is shown in Table XXXVIII., which Mr. Alexander Duckham has kindly furnished in order to bring the information he laid before the Committee up to date. That this increase has exceeded far and away the rise in the production of crude oil throughout the world will be clear from the diagram (Fig. 30).

TABLE XXXVIII.

PETROLEUM SPIRIT IMPORTED INTO THE UNITED KINGDOM.

(*In Imperial Gallons.*)

Country.	1908.	1909.	1910.	1911.	1912.
United States . .	6,097,096	15,096,918	20,721,450	22,442,716	16,381,197
Dutch Possessions in Indian Seas .	23,130,989	28,088,321	25,537,818	18,687,674	32,325,185
Netherlands[1] . .	1,135,105	986,695	3,360,667	4,166,963	4,088,582
Roumania . . .	6,822,307	4,741,970	3,644,125	4,302,282	4,171,199
Other Foreign Countries . . .	4,622,498[2]	3,009,265	2,029,098[3]	8,961,080[4]	6,245,686
From British Possessions . . .	—	112	—	9,371,528[5]	16,378,206
Total . . .	41,807,995	51,923,281	55.293,158	67,932,243	79,590,155

[1] Derived from Dutch possessions and redistilled in the Netherlands.

[2] Russia increase from 321,690 to 4,018,790.

[3] Principally from Russia and Mexico.

[4] Practically all from Russia.

[5] Principally from India and Straits Settlements.

In 1913 importation had risen to 100,858,017 gallons; in 1914 to 119,222,828 gallons.

It is evident that although there has been a great increase in the petroleum production, the demand for petrol in this country has far outstripped this increase. When it is considered that the increase in the production of oil must cease; that no augmentation of supply is taking place through present natural production; that the development of the petrol engine in oil-producing countries leads to big demands for home-produced petrol, it is evident that alternative fuels must be considered, unless the use of such engines is to be hampered seriously, with a corresponding check to a big branch of engineering.

The alternatives appear to be—

1. The use of petrol boiling over a wider range, or mixtures of petrol with a certain proportion of illuminating oils.
2. The economic production of light oils by the "cracking" of heavier oils.
3. The entire use of other fuels, such as benzol and alcohol.
4. The use of mixtures of petrol and fuels from other sources.

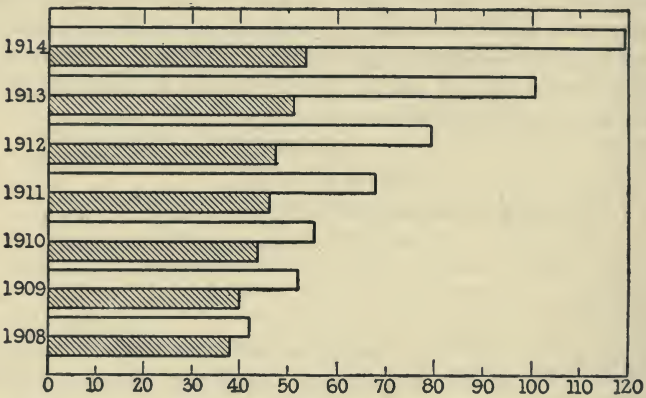


FIG. 30.—Diagram of production of crude oil and British import of petrol.

It is impossible to consider here the complicated problem of the financial considerations which must govern ultimately the price of petrol, which at the most does not average more than 10 per cent. of the crude oil, leaving a market to be found for the other 90 per cent., but the general introduction of heavier grades, thus greatly increasing the proportion of the crude oil available, and the increasing use, which is certain, of a considerable proportion of the higher boiling oils in internal combustion engines, are factors contributing to a better supply and against advances in price.

The use of benzol and alcohol as alternative fuels is of great importance. The former is a home product and, as shown previously, eminently suitable for use in petrol motors. The latter, although its production on a large scale in this country is unlikely to enter into serious competition with the production in many of our Colonies, may be regarded in any case as a possible fuel of entirely British production and available to almost any extent.

According to the evidence before the Fuel Committee, the production of benzol (about 1906) was from 4 to 5 million gallons; the production could possibly be increased to 8–10 million gallons in a reasonable period, but with a much larger proportion of coal coked in by-product recovery plant (say 20 million tons per annum), it would be possible to produce from 25 to 30 million gallons.

According to Mr. J. A. Butterfield (and the figures have been confirmed for London tar by Mr. S. Field) the yield of benzol from the tar alone is only equal to about 0·2 gal. per ton of coal carbonized. On a basis of 0·25 gal. throughout the country and with 15 million tons of coal carbonized annually in gas works, the total output from this source is under 4 million gallons. By suitable treatment of the gas the yield of spirit suitable for motors might be increased to some 2·5 to 3 gals. per ton; but the gas would be so impoverished in illuminating value as to fall below the legal requirements. This treatment is, however, carried out with coke oven plant, and assuming that 8·5 million tons of coal are coked in recovery plant the yield of spirit from this source is between 20–25 million gallons. According to results from German coke oven practice from 3 to 3·5 gallons of 65 per cent. benzol are recovered per ton of coal.

Even with due allowance for the higher efficiency of benzol in the engine, the total output of benzol is well below half the petrol imports. Benzol is, moreover, employed largely in many important industries, especially for the production of coal tar colours, for cleaning purposes, for certain kinds of varnish, etc., and large quantities are exported for these purposes. The competition for benzol, if its use extended greatly for power purposes, would become keen, and the price has markedly increased in recent years without any appreciable competition for engine use. Whilst benzol is, even at present prices, a valuable substitute for petrol, and has been used with so much success, it has been only by a very small proportion of motorists. Given a greatly extended demand for this purpose, it does not appear that, together with demands for other purposes, the output is sufficient to maintain a price greatly below that of petrol. It may, however, become an important factor in preventing a further great increment in the price of petrol.

Whilst benzol alone can be regarded only as a useful auxiliary supply of motor fuel, by reason of these economic considerations, its use in admixture with alcohol is likely to be of great importance. It has been shown already that alcohol is a fuel of proved value for internal combustion engines, but for the best results to be obtained these engines have to be built heavier to run at the high compressions necessary for the best efficiency, and generally are constructed to run at about one-fourth the speed of a petrol engine. A mixture of benzol and alcohol is more suited to the lighter engines and higher speeds.

For alcohol to become a practical fuel in this country the relaxation of many of the restrictions imposed at present will be necessary; but this is a fiscal question fairly bristling with difficulties. Further, some means of preventing the comparatively ready removal of alcohol from a benzol-alcohol mixture will have to be devised.

The advantages of a fuel derived from home-grown products, or possibly from raw materials produced at a lower rate in the Colonies, are apparent. Its adoption certainly would give encouragement to agriculture; it would provide a national weapon to fight artificial (or economic) shortage of other fuel for internal combustion engines; indirectly it would encourage the further development of a big and growing branch of engineering, the success of which is impossible without an assured supply of fuel at a reasonable cost. From every point of view it would appear that the claims of alcohol as a fuel are now so insistent that they can hardly be ignored.

Cracked Oils.—By subjecting the heavier hydrocarbon oils to moderately high temperatures, liquid products are obtained which consist of a complex mixture of hydrocarbons of the different series, having lower boiling points and densities than the original, so that a higher yield of spirit suitable for motors is obtained. In general the "cracking" process is carried out under pressure. A high proportion of unsaturated hydrocarbons is formed, and has to be removed by sulphuric acid washing. To reduce the quantity of unsaturated hydrocarbons, "hydrogenation" (the addition of hydrogen to convert them into saturated) is a feature of many processes, a catalyst, such as nickel or iron, being employed, the hydrogen being derived from water or steam forced through with the oil or oil vapours.

Crude cracked spirit is yellow and the colour darkens on standing; it has a characteristic odour. The di-olefines present cause the formation on storage of a viscous yellow liquid, but sparingly soluble in the spirit. Sulphuric acid treatment does not entirely prevent the further formation of this "gummy" product, or the development of colour and odour. Sunlight is an active agent in producing the change, and cracked spirit would appear to require early use after manufacture.

The reader is referred to the very comprehensive paper on the "Pyrogenesis of Hydrocarbons" by Lomax, Dunstan and Thole (*Jour. Inst. of Petroleum Technologists*, 1916, III. 36).

PART III

GASEOUS FUEL

CHAPTER XI

COAL GAS AND COKE-OVEN GAS

Introduction.—The important position which gaseous fuel has occupied for several years past is sufficient proof of its value from the commercial aspect as a heating agent, and as an economical method of obtaining power at a cheap rate; moreover, it is an important factor in the question of the abolition of smoke. It is highly probable that, with the development of the recent inventions involving the successful application of "surface combustion," its possibilities in both these respects will be considerably amplified. It is not only from a commercially economical point of view that gaseous fuel is of importance; it has played and will play an important part in conserving the natural fuel supplies of Great Britain.

This is not achieved solely by obtaining a better thermal efficiency from a given weight of fuel by suitable methods of gasification, but also by rendering available as fuels millions of tons of coal of such low grade that it is impossible to employ it economically by other methods. Further, by gasification large quantities of other materials—peat, waste wood, indeed, almost any carbonaceous material may be utilized—so leading to the prolongation of the period over which the more valuable coal will be available.

Enormous quantities of gaseous fuels of low thermal value are evolved daily during the reactions in the ordinary blast furnace used in the production of iron. For a long period the only use made of these was for heating the hot blast stoves and raising steam in boilers for the general operation of the plant. As will be shown later, these blast furnace gases are employed far more profitably in suitable gas engines, and since the amount obtained per ton of metal exceeds all direct and indirect demands for the actual production of the metal, systematic use is now made of this surplus for the generation of electric power for distribution. Here, again, gaseous fuel affords great possibilities for economizing in the use of other natural fuels.

To the simple methods of gasification may be traced directly the success of many metallurgical operations, such as the open-hearth steel process; the reduction in fuel consumption for other important processes, such as the distillation of coal; and its application as coal gas or pressure- and suction-gas for power purposes has led to big commercial developments. Its influence extends outside these limits, for the amount of ammonium sulphate produced with recovery plants is an important consideration in the question of the food production of these islands.

Classification.—Two main classes of gaseous fuels are recognized, leaving out of consideration "natural gas," which is of no importance in this country; first, those derived by the destructive distillation of coal and, to a small extent, oil; second, those obtained primarily by the action of steam, air or air and steam on carbonaceous substances. The former fuels are of much higher calorific value than the latter, and a method of classification on calorific value may be adopted. The following system of classification is a convenient one, and in the subsequent pages the different gaseous fuels will be considered. The numbers refer to the composition and other data given in Table XXXIX.

CLASSIFICATION OF GASEOUS FUELS.

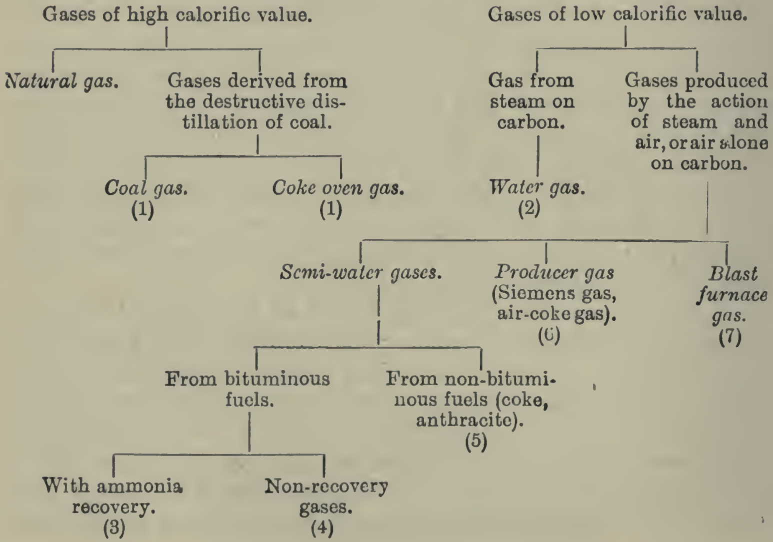
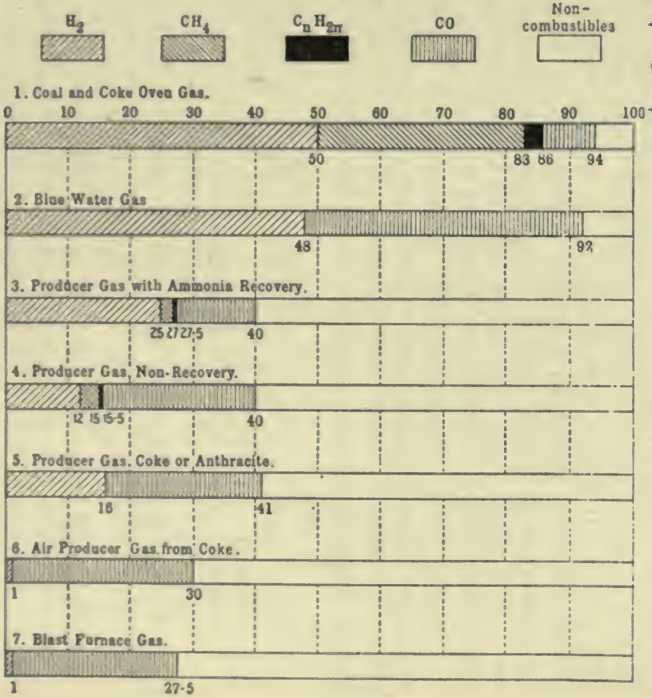


TABLE XXXIX.

Composition, Weight per Cub. Ft., Calorific Value, &c., of Gaseous Fuels.



B.Th.U. p r cub. ft.		Air for combustion.		B.Th.U. (gross) per cub. ft. of mixture.		Weight of 1 cub. ft. in pounds.		Approximate volume in cub. ft. per pound.	
Gross.	Net.	Theory.	Practice.	Theory.	Practice.	At 0° C. and 760 mm.	At 60° F. and 30 inches.	At 0° C. and 760 mm.	At 60° F. and 30 inches.
630	550	4·7	8·0	110	61	0·0345	0·0326	29·0	30·8
315	290	2·2	4·0 (?)	100	60	0·0460	0·0435	21·8	23·0
150	145	1·1	1·25	71	65	0·0665	0·0630	15·0	16·0
170	160	1·2	1·25	77·5	73	0·0720	0·0680	14·0	14·8
140	130	0·9	1·25	74·0	68·5	0·0700	0·0655	14·3	15·3
105	105	0·75	1·0	60·0	52·5	0·0780	0·0740	12·8	13·5
97	97	0·65	1·0	50·0	50·0	0·0835	0·0790	12·0	12·7

NATURAL GAS

The enormous quantities of gas obtained in oil-producing regions, notably those of America, are of considerable local importance. It is difficult to estimate the actual output, but in the West Virginia Oil Fields, 1300 million cub. ft. are stated to be evolved daily, one million cubic feet being actually utilized. The gas marketed in the United States in one year has been estimated at about 172,000 million cub. ft. Its heating value was approximately equal to 40 per cent. of the crude oil output, or to 8·5 million tons of coal.

Natural gas is found also in Canada, principally Ontario. The value of the Canadian output in 1908 was over £200,000.

Natural gas was obtained near Hamburg in 1910, and the boring was still yielding 20 million cub. ft. per day in 1911. Very great interest was aroused in England some few years ago by a boring at Heathfield, Sussex, which at a depth of 400 feet tapped gas from the Kimmeridge shale at 200 lbs. pressure. The output of the deepest boring was considerable and about 1000 cub. ft. per day was employed for heating purposes and for lighting the railway station. A barrel or two of oil also was obtained daily.

Composition and Calorific Value.—These vary over wide limits not only in different localities, but also from the same boring at different periods. The percentage of saturated hydrocarbons, principally methane (CH_4), is always high; in a large number of cases over 90 per cent. Hydrogen is present usually to the extent of 1 to 2 per cent., though in some few cases the amount has exceeded 20 per cent. The other combustible gases present in small amounts are ethane, unsaturated hydrocarbons and carbon monoxide.

Owing to the high calorific value of the saturated hydrocarbons and the small percentage of non-combustible gases present, natural gas has a correspondingly high thermal value. The following analyses may be taken as typical, the calorific values being calculated:—

	Pittsburg.	Ohio.	Heathfield.
Methane	72·2	92·8	93·16
Ethane			2·94
Hydrogen	20·0	1·9	
Ethylene	0·7	0·2	
Carbon monoxide	1·0	0·6	1·0
Nitrogen, etc.	6·1	4·5	2·9
B.Th.U. per cub. ft. at 0° C. and 760 mm.			
Gross	851	999	1050
Net	761	847	941

After gas has been evolved for some time its character is found to have changed, higher proportions of paraffin hydrocarbons of higher molecular weight being obtained. Such gas on compression yields a considerable quantity of liquid hydrocarbons; the lower boiling members are being distributed for industrial purposes in the usual steel gas cylinders; higher boiling members going to augment the output of petrol.

The gas in the West Virginia Oil Field is stated to have a calorific value of 1135 B.Th.U. per cubic foot. After compression, whereby some of the minor constituents are condensed, the value is about 900 B.Th.U.

COAL GAS

The use of coal gas was confined for the greater part of a century to purposes of illumination; the development of the gas engine and its great increase in thermal efficiency subsequently rendered coal gas an important power-producing fuel, and with its extended use for domestic heating purposes, and still more recently, with cheaper rates and highly efficient methods of combustion, it has become an important fuel in many manufacturing operations, such as metal melting, annealing, etc., all contributing to the further and extended use of this efficient and convenient form of gaseous fuel.

The main important features which contribute to the successful commercial application of coal gas are—the constancy of supply of fuel of very uniform composition, available at any moment, the avoidance of all stand-by costs, the high thermal value and high efficiency which can be obtained in engines or suitable furnaces, and in most cases in industrial centres the comparatively low cost per thousand cubic feet. Naturally costs vary over very wide limits, and the question as to whether coal gas is the most economical fuel must depend largely upon costs and quantity consumed, but this important question must be discussed later. It may be mentioned that in Sheffield and in one or two other towns coal gas for industrial purposes costs from 1/- to 1/3 per thousand, and in most large towns special rates enable it to be supplied at from 1/6 to 1/9. The extended use of coal gas, other than for illumination, has had an important influence on the "load factor" at many works; it is not unusual to have a day demand of nearly 50 per cent. of the night consumption.

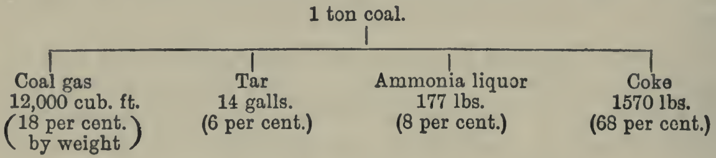
W. B. Davidson (*J. S. C. I.* 1909, 1283) gives the following figures illustrating the annual production of coal gas and its by-products in the United Kingdom:—

Coal carbonized	16,000,000 tons
Oil used for carburetted water gas	60,000,000 gallons[1]
Gas sold	190,000,000,000 cub. ft.
Coke, breeze, etc., sold	8,000,000 tons
Tar (coal and carburetted water gas)	900,000 ,,

Coal gas is considered here entirely as a commercial fuel for power purposes and industrial heating. Its use for illuminating purposes is clearly outside the scope of the work; neither is it proposed to deal with the question of its use for domestic heating, etc. The reader may be referred to the excellent reports of the Gas Heating Research Committee of the Institute of Gas Engineers (*J. Gas Ltg.* 1909, 106, 821; 1910, 110, 810; 1911, 114, 840).

Production of Coal Gas.—Space does not permit and neither is it necessary to enter into the question of the manufacture of coal gas, since such information is already fully dealt with in many excellent treatises devoted entirely to the subject. From the consumer's point of view coal gas may be taken as a "ready made" fuel, and only brief reference to some considerations of production as affecting the character of the products is required.

By the destructive distillation of gas coal at high temperatures the following yield of products may be taken as an average:—



Only within recent years have important changes been made in the manufacture of coal gas; under the older system, still most generally employed, the charge of coal of some 10 to 12 cwt. was always distilled in a comparatively shallow layer; the first improvement was the introduction of producer gases for heating the retorts, followed later by the employment of the regenerative system, whereby very great economies in the fuel required per ton of coal distilled are obtained, higher temperatures are possible, and the gas yield is considerably increased. This has a marked effect upon the quality of the gas and the products. The hydrocarbons in the gas suffer decomposition with deposition of carbon, yielding a correspondingly larger volume of hydrogen, which, being non-luminous, leads to a decrease in illuminating power. Naphthalene is formed in such quantities that the tar is semi-solid, containing much free carbon (see p. 118), and great

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[1] 11 per cent. of the gas made is carburetted water gas.

trouble is sometimes experienced through stoppage in the distribution pipes.

Within recent years a great advance has been made by the introduction of distillation in larger bulk, either in the old D-shaped retorts filled as full as possible, or in inclined or vertical retorts, which are nearly full and in some forms continuous in action, or in large chamber retorts akin to the coke-oven retorts. These improvements have led to great freedom from naphthalene, to the production of a thin tar containing less free carbon and suited for use in Diesel engines, to an improvement in the quality of the coke, to a greater yield of ammonia, and to reduction of carbonizing and operating costs. The make of gas has increased per ton of coal carbonized, but authorities differ as to the cause of this. According to Lewes, the earlier portions of the gas are rich in hydrocarbons; it is only the later portions which undergo great breaking-down of hydrocarbons through their passage over highly heated coke, this degradation leading to a higher gas yield.

As would be expected with the constant change in the temperature conditions existing in the retorts during distillation, leading to gradually increasing masses of coke at high temperature, contact with which tends to destroy the hydrocarbons, the gas issuing from the retorts at different stages of carbonization varies greatly; the earlier portions are rich in hydrocarbons and have high illuminating value, the latter portions are poor in hydrocarbons, rich in hydrogen, and of low illuminating value.

Since the retorts in a bench are always at different stages of carbonization, the mixture is fairly uniform even before reaching the holder, where of course by currents and diffusion it becomes quite uniform. In some modern forms of continuous plant, *e.g.*, the Glover-West retorts, the gas is fairly uniform throughout distillation.

As already mentioned, the make of coal gas frequently is augmented largely by the addition of carburetted water gas, the production of which will be referred to later (p. 221).

Composition of Coal Gas.—The following analyses of gas obtained by the older system of high temperature carbonization of small charges, still employed for by far the larger proportion of gas made, and of samples from the Glover-West continuous system of carbonization may be taken as representing fairly the composition of coal gas by either general system :—

COMPOSITION OF COAL GAS.

	Carbonization in small bulk. (Mean of 9.)	Continuous system. (Mean of 5.)
Hydrogen	44·8	53·2
Methane	34·5	31·2
Unsaturated hydrocarbons	4·5	2·8
Carbon monoxide	7·8	7·9
Carbon dioxide	0·2	1·4
Nitrogen, oxygen, etc.	8·2	3·5

Eliminating the nitrogen and oxygen, which vary widely in coal gas, due principally to the degree of suction on the system whereby more or less air is drawn in through cracks, joints, etc., it will be found that the hydrogen is about 7 per cent. higher, and the methane 5 per cent. lower in the modern gas as compared with the older type gas.

The constituent gases may be divided into (*a*) heating and illuminating; (*b*) diluting; and (*c*) impurities. The former includes the hydrogen, hydrocarbons and carbon monoxide. To unsaturated hydrocarbons—ethylene, propylene, etc., and to benzene vapour the illuminating power is ascribed principally. As the hydrocarbons have a much higher calorific value per cubic foot than hydrogen, and since the latter generally is credited with increasing the liability to pre-ignition in a gas engine cylinder, it would appear at first sight that coal gas with a relatively high content of hydrogen is not so suitable for power purposes as one with fairly high methane. In actual practice the difference in composition between the gas made by the old and modern systems of carbonization is not sufficiently great to be of importance, for in the actual charge of mixture drawn into the cylinder there will be from eight to nine volumes of air to one volume of gas, and the percentage composition of the *mixture* will not differ appreciably in the two cases.

The principal diluent gases are nitrogen, oxygen and carbon dioxide, though the latter may be regarded also as an impurity, since it is generally desirable to free the gas from it as far as possible. The impurities in crude gas are numerous, but as sent out after proper purification, carbon dioxide and organic sulphur compounds are the only ones of practical importance. The former will be present in very small amounts, insufficient to affect the quality; the latter however are of importance, and a legal limit is assigned to the amount of sulphur. Anything above traces of sulphur compounds may tend to induce corrosion through the acid products formed on combustion, especially when the exhaust gases cool so that acid water becomes condensed on the metal. In London gas the average content of sulphur is about 30 grains per 100 cub. ft.

Calorific Value of Coal Gas.—Although for over a century illuminating power was the main important factor by which gas could be judged, the introduction of the Welsbach mantle and the vastly extended use of gas for power and heating purposes have modified greatly the conditions, so that whilst illuminating power has still to be considered, the actual candle power required is recognized as lower, and reduction allowed in several recent Acts, whilst the importance of calorific power has become enhanced, and in many cases a standard has been legally defined. There is no direct relationship between illuminating power and calorific value, so that in time a legal calorific standard will become general.

By the Gas Light and Coke Company's Act of 1909, the candle power was reduced from 16 to 14, with a standard *net* calorific value of 125 calories (498 B.Th.U.) per cub. ft. The calorific value on any one day must not fall below 106·5 calories (425 B.Th.U.), or on an average over any three days in one week below 112·5 calories (449 B.Th.U.). From the regular tests made in the Metropolis, the gas supplied by the different companies has an average calorific value (net) lying between 122 to 130 calories (486–518 B.Th.U.). The gross value averages between 140–150 calories (557–597 B.Th.U.).

COKE-OVEN GAS

Since the method of production is practically identical with modern systems of coal-gas manufacture, coke-oven gas approximates closely to the former in composition and calorific value. In general, it contains more diluting gases than coal gas, because in most forms of coke-oven plant it is more difficult to prevent air leaking into the ovens, but when conditions are at the best, this undesirable result is avoided, and gas of practically the same composition and calorific power is obtained.

The economic utilization of coke-oven gas is a matter of national importance. As already shown in the section on coke, the use of by-product recovery ovens has been almost universal on the Continent, and is extending rapidly in this country. Mr. Ernest Bury, before the Cleveland Institute of Engineers, 1911 (see *J. Gas Ltg.*, 1911, 113, 917), stated that whilst in 1898 only 1·5 million tons of coal were carbonized in recovery ovens in this country, in 1911 the amount had risen to 8 million tons—about half the total amount carbonized in gasworks.

[1] See "Progress in By-product Recovery," O. Rau (*J. S. C. I.*, 1910, 868).

With modern systems of recovery of the valuable by-products, ammonium sulphate and benzene principally, and the utilization of the regenerative principle in firing the ovens, very considerable quantities of surplus gas are available from a modern coke-oven plant. With the possible production of cheaper producer gases made from cheap coals unsuitable for coking, in lieu of the coke-oven gas itself, as the source of heat, practically the whole of the gas could be rendered available for other purposes.

Whilst the aim of the coal-gas maker is to get the maximum percentage of the carbon in the coal into the gas, and of the coke maker as much as possible into the coke—in the one case the coke being the by-product, in the other the gas,—the nature of the processes in each case must necessarily overlap. In the older forms of coke ovens it was almost impossible to avoid big air intake through the walls, etc., and this, together with great degradation of the gas by overheating, led to a poor gas of low illuminating and calorific value. Only the first portions were sufficiently rich to be comparable with good coal gas. Owing to the generally accepted idea that high illuminating power is no longer demanded by the conditions of the modern gas industry, improvements in the construction of coke ovens and their working have led to the production of coke-oven gas almost identical in composition, illuminating and calorific value with coal gas produced by bulk distillation.

It is therefore easily understood that in Germany[1] and the United States coke-oven gas is employed largely in lieu of, or supplementary to, the coal gas directly made for town supply, and to a limited extent also in this country. That very great economical advantages lie with such an amalgamation of interests in the matter of conservation of our limited coal resources is evident, and although at present considerations of constant and unfailing supply of suitable gas from the coke ovens may not be assured, which is absolutely essential if gas producers are to meet their statutory obligations of supply, without expensive plant remaining idle to contend with such an emergency, wasteful overlapping of this nature is certainly unlikely to continue.

A diagrammatic illustration has been given already (Figs. 4 and 5) of the arrangement in by-product recovery plant, with and without the use of regenerators. In many instances, with modern systems the surplus gas has amounted to 60 per cent. of the total yield, but allowing a consumption of 20 cub. ft. per B.H.P. hour in a modern

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[1] For details of the progress in the use of coke-oven gas for town use in Germany, the reader is referred to an excellent summary from the "Frankfürter Zeitung," in the *J. Gas Ltg.*, 1911, 113, 921. One million cub. ft. of coke-oven gas per day are now supplied from a plant at Middleton to Leeds; regular hourly delivery is specified for and the quality is checked by recording gas calorimeters.

large gas engine, the following moderate estimate of the power available is obtained :—

1 ton of coal yields 10,500 cub. ft. gas of 500 B.Th.U. per cub. ft. (*net*).

Required for heating ovens.
5000 cub. ft. (47·5 per cent.).

Surplus gas available
5500 cub. ft. (52·5 per cent.
= 4800 B.H.P. per hour).

Even with only about one-half of the total coal carbonization for metallurgical coke being carried out in by-product recovery ovens, it is evident that a large amount of gas is available for distribution or conversion into electrical energy. In the North-East coast power scheme conversion into electric power for distribution in the district is already an important undertaking.

The yield of by-products per ton of coal in South Yorkshire, according to Prof. L. T. O'Shea (*J. S. C. I.*, 1911, 937) is :—Tar, 5 per cent. (say, 110 lbs. or 10 gallons), from which 2·25–2·5 gallons of 65 per cent. benzol is obtained ; ammonium sulphate, 22–35 lbs. ; gas 10,000–11,500 cub. ft. Payne (*Eng. & Min. J.*, 1910, 89, 927) gives the following yields at Gelsenkirchen, Germany :—Tar, 7·5 per cent. (say, 168 lbs. or 15 gallons), from which 3–3·5 gallons of 65 per cent. benzol is obtained ; ammonium sulphate, 25 lbs. H. G. Colman (*J. Gas Ltg.*, 1908, 102, 353) gives the following data for a Koppers plant in South Wales, working a high-class coking coal containing 21·6 per cent. volatile matter on the dry coal :—Coke, 81·75 per cent. ; breeze, 1·75 per cent. ; tar, 36·5 lbs. per ton (say, 3·33 gallons) ; sulphate, 19·5 lbs. ; gas, 10,000 cub. ft. at 460 B.Th.U. per cub. ft. (*gross*). A large installation of 280 Koppers ovens in America, working on coal containing 30 per cent. volatile matter, yields daily 3145 tons of coke, 35,000 gallons of tar, 44 tons of sulphate, and 22 million cub. ft. of gas of 500 B.Th.U. per cub. ft.

Great improvements have been made in the direct recovery of ammonia as sulphate,[1] and the recovery of benzol by washing the gas with heavy oils, both of which are important economic factors, the one from its influence on agriculture, the other as a source of benzol for internal combustion engines.

Composition of Coke-Oven Gas.—A number of analyses of the gas are given in Table XL. It will be seen that in some cases the evidence of air-intake is very apparent, leading to general dilution of the gas by nitrogen and the formation of carbon monoxide by the action of the air on the red-hot carbon. In many older forms of

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[1] The reader may be referred to *J. Gas Ltg.*, 1911, 113, 917 ; 116, 607, for description of these.

oven the hydrocarbon gases are broken down by overheating, leading to low percentage of unsaturated hydrocarbons and methane, hence poorer gas. With the most recent forms of ovens, both these causes of deterioration of the gas are avoided, and it will be seen that many samples compare well with coal gas from bulk distillation.

TABLE XL.

Composition of Coke-Oven Gas.

Authority.		C. E. Rhodes.	J. S. Lucking.	M. Cuvelette.[1]	E. Bury.[2]	A. Short.	E. Bury.[3]	E. Bury.	E. Bury.	E. Bury.
Hydrogen		39·85	47·7	52·0	50·3	51·5	49·3	44·4	43·8	49·1
Methane.		28·21	26·2	26·0	24·9	28·4	31·0	33·9	36·5	33·9
Unsaturated hydrocarbons		—	3·0	1·6	3·7	3·8	3·8	3·8	3·2	3 7
Carbon monoxide . . .		8·4	9·0	5·7	7·6	5·0	6·87	6·2	4·6	6·4
,, dioxide		—	0·5	2·1	2·8	1·8	2·15	3·3	2·3	2·9
Nitrogen		18·78	13·6	12·6	10·7	9·5	6·88	8·5	9·6	4·0
Calorific value in B.Th.U. per cub. ft. at 60° F.	gross .	467·5	542·5	511·0	549·0	585·5	612·5	626·5	633·5	640·6
	net . .	392·0	462·5	431·5	469·0	497·5	516·5	532·0	535·0	543·5

In the distillation of large masses of coal, the penetration of heat throughout the mass is slow, and the gases escaping through cool portions of the mass exhibit necessarily all the characters of coal gas distilled at very low temperatures. As the mass cokes through, the latter portions of the gas necessarily change their character and become very poor in hydrocarbons, rich in hydrogen, and consequently of lower illuminating and calorific value. O. Simmerbach (see abs. *J. S. C. I.*, 1913, 186), in a paper on the Decomposition of Coke-Oven Gas, shows that the hydrocarbons steadily decompose as the temperature increases; at 1000° C. half the methane has decomposed, the hydrogen, which formed 42·6 per cent. before heating, rising to 63·7 per cent. at 1000° C. This change is well illustrated by the results of P. Schlicht (*Trans. Inst. Gas Eng.*, 1907, 259) given in Table XLI.

[1] Mean of 8 Continental samples.

[2] Gas at Heinitz, quoted by Mr. Bury.

[3] Brackley gas supplied to Little Hulton.

TABLE XLI.

COMPOSITION OF COKE-OVEN GAS AT DIFFERENT PERIODS OF CARBONIZATION.
IN UNITED OTTO OVENS (P. Schlicht).

Hours after charging .	1	2	4	6	8	10	13	16	19	22	25
Hydrogen . . .	25·0	30·0	34·3	38·6	40·9	43·0	47·4	48·9	54·6	61·2	65·0
Methane	46·9	42·9	39·9	36·5	34·9	32·8	27·4	25·6	23·3	19·7	17·7
Unsaturated hydrocarbons . . .	7·8	6·9	5·8	5·4	5·0	4·4	4·0	3·5	2·4	1·8	0·9
Carbon monoxide .	6·4	6·3	5·9	5·9	5·7	6·4	7·0	7·1	7·0	6·5	6·3
B.Th.U. per cub. ft.	805·2	756·7	710·0	678·9	658·9	631·0	580·5	554·2	551·1	488·6	457·9

Other results of a similar character are given by A. Short (*J. S. C. I.*, 1907, 868) and J. D. Pennock (*J. S. C. I.*, 1905, 602). Both these papers are worthy of careful study.

Consideration of these figures will show why until quite recently, and even now with the older forms of ovens, or with modern ovens working on coals of moderate volatile matter content, it has been necessary to "fractionate" the gas for use as town gas, taking the portions evolved in the earlier distillation for this purpose, and utilizing the later portions of lower value for the oven heating.

The applications of coke-oven gas in practice evidently will be identical with those of coal gas, although the application in most cases clearly must be limited to certain special operations because of local conditions, so that the considerations relating to coal gas in the next section apply equally to coke-oven gas. It is, of course, essential that the latter shall be freed from tar and such sulphur compounds as may be removed by iron oxide treatment—chiefly sulphuretted hydrogen. In Germany the accepted standards are equivalent to 30 grains of tar and 13 grains of sulphur per 100 cub. ft.

One special application, approved by Mr. Bury and already adopted in some few cases, notably at Krupps' works, is the admixture with blast furnace gas for heating steel furnaces, etc. Where coke ovens, blast furnaces and steel making are carried out on one big system, as is often the case, the suggestion is obviously a practical one leading to great economy. Mr. Bury calculates the composition of such a mixture to be—

	3 vols. of Blast furnace gas. 1 vol. of coke-oven gas.	Average Producer gas.
Hydrogen	13·25	9–14
Methane	7·50	2–3·5
Unsaturated hydrocarbons	0·50	—
Carbon monoxide	22·75	22–28
Carbon dioxide	9·0	3–6
Nitrogen	47·0	about 60
B.Th.U. per cub. ft.	206	125–175

Besides the abolition or reduction in number of special producers such a gas is free from steam, which is certainly an advantage in the working of regenerators, but it would be liable to undergo alterations in the regenerators through breaking down of hydrocarbon gases, with deposition of carbon.

Bury estimates that an economy of from 2*s*. to 3*s*. per ton is possible in the production of the steel, and that coke ovens yielding 400 tons of coke daily would yield sufficient surplus gas, when mixed with three volumes of blast furnace gas, to be equal to a production of 1700 tons of steel weekly.

COAL GAS FOR POWER PURPOSES

As the whole question of fuel consumption must be deferred until all the various fuels have been considered, it is only necessary to point out here that coal gas offers many advantages in the absence of space for fuel storage, space for boilers or producers, no stand-by charges and constancy of supply, both in quantity and quality. The efficiency of the gas engine has increased from 16 to 37 per cent. in a little over a quarter of a century, and at or near full load gives frequently 27 to 28 per cent. effective output. Further, the efficiency from engines of moderate size to those of larger sizes is practically the same; it is only with smaller sizes that any marked difference is found.

Actual consumption in engines of moderate size frequently lies between 15 and 17 cub. ft. per B.H.P. hour, this being about 28 per cent. efficiency with gas of 570 B.Th.U. per cub. ft. net. Taking a round cost of 1*s*. 8*d*. per 1000, the B.H.P. cost is 0·32*d*.; 9000–9500 B.Th.U. per B.H.P. hour may be taken for approximate calculations of the gas required.

COAL GAS FOR INDUSTRIAL HEATING

Very great advances have been made in the application of coal gas for industrial purposes; advances in the construction of the burners and furnaces, and in the application of gas at high pressures. Further advances through the introduction of surface combustion have already been made, and great success may be expected from this system. The consideration of this important question is however deferred to a later section.

Where coal gas can be obtained at reasonably low rates it offers very great advantages for a large number of heating operations. These advantages may be summarized as—

1. Constant supply of gas in any quantity always available, the gas being of very uniform composition and calorific value.
2. Low fuel costs: in the case of melting furnaces the cost per pound of metal generally is less than with coke, and the first heat is much more rapid.
3. No space is occupied by fuel stores, producer plant, etc.
4. Reduction of labour for firing and cost of firing appliances.
5. Reduced cost of furnace linings, melting pots, etc., which have a longer life with gas than with solid fuel.
6. Spilt metal is far more easily recovered in the case of a broken pot than from a mass of coke and ashes.
7. Less loss of metal by oxidation, etc.
8. Great uniformity of temperature attainable for reheating furnaces, muffles, etc.

The success of coal gas for a large number of purposes has been amply demonstrated. In Woolwich Arsenal it has been employed for a considerable period for the thermal treatment of steel, especially projectiles, for heating long bars for springs, for axle hardening, etc. In Sheffield, where gas is supplied at very cheap rates, several hundred furnaces are employed, the consumption per furnace ranging from 20 to 5000 cub. ft. per hour. It finds application in practically all the metal trades, for melting, annealing, drying foundry cores, etc., and is of special service in the heat treatment of modern tool steels. Its recent introduction for bullion melting at the Royal Mint in place of coke, after all systems of firing for this purpose had been carefully investigated, has been a striking success.

At the Mint 16 gas-fired furnaces, each capable of taking a 400 lb. crucible, are installed, the burners being of the Brayshaw pattern (pressure air). The maximum capacity of these 16 furnaces is $2\frac{3}{4}$ tons of silver, or $2\frac{1}{2}$ tons of bronze per melt, and four melts of silver or three of bronze can be made in the working day. Four gas-fired furnaces were installed in May, 1910, for melting gold, and by the end of that year $283\frac{1}{4}$ tons of standard gold were melted. In one operation over 257,000 ozs. of gold were melted in the four furnaces; the time from lighting up was 27 hours 40 minutes, and the gas consumption 32,000 cub. ft. The cost of melting 1 cwt. of standard gold by gas is 4¼*d.*; with daily warming up 5*d.*; the former cost for coke was 7*d.* per cwt.

Aluminium and its alloys are being melted very successfully by gas in Birmingham. It is claimed that the cost of melting is halved (as compared with coke), labour costs about halved, oxidation is avoided by keeping a reducing atmosphere, the tensile strength of the metal thus being increased, the amount of metal melted per pot is greater, besides other minor advantages.

Systems of Combustion.—Three systems are available, all dependent upon obtaining the well-known non-luminous flame by admixture with a certain proportion of air.

1. Use of gas at main pressures, with air at ordinary pressures.
2. Use of gas at main pressures, with air blast under pressure.
3. Use of gas at high pressures, with air at ordinary pressures.

The former involves the use of burners of the ordinary bunsen or atmospheric type, which are so well known that description is unnecessary. The general principle of their action is that the gas at main pressure, issuing through a jet, draws in sufficient air through suitable orifices to render the flame non-luminous. This is the *primary* air; it is insufficient for complete combustion, and the flame requires further air from the free atmosphere around for completing the combustion. This is the *secondary* air. The greater the ratio of the primary air to that theoretically required (about 5·5 times the volume of the gas) the smaller the flame and the more intense the combustion; hence the increased intensity of the blow-pipe flame.

H. Schmidt, by the optical pyrometer, estimated the highest temperature of the atmospheric gas flame to be 1800° C. (3720° F.), this occurring at the outer edge. Mahler estimated the average temperature of the coal gas flame as 1950° G. (3543° F.). Experiments by the writer with thermo-junctions of various diameters, so that exterpolation may be made for a couple of infinitely small diameter (*i.e.* radiation effect eliminated) obtained the following maxima, always in the extreme outer envelope, a short distance above the top of the burner:—

	¼" Bunsen burner.		Kern burner.		
Gas per hour, cub. ft. . .	6·5	6·6	4·3	4·3	4·5
Ratio of primary air to gas.	3·8/1	4·3/1	3·4/1	4/1	5/1
Maximum temperature, °C.	1720	1770	1610	1730	1860

Many successful furnaces of smaller size, working with gas at main pressure in free air, give excellent results, but are not so satisfactory as the other systems when accurate control of temperature is required. Mr. A. W. Onslow, in a valuable paper on the use of high pressure gas at Woolwich Arsenal (*J. S. C. I.*, 1910, 395) says:

"Many years of experience in the employment of coal gas for heating purposes have led to the conclusion that taking gas from the mains and consuming with some form of bunsen burner is not only wasteful of gas, but quite incapable of giving anything like a constant temperature, or of heating any given kind of oven or other apparatus to the same temperature in the same time in consecutive operations."

The use of gas under high pressure generally has been more favoured than that of using air under pressure. It has been claimed that the variation in temperature is less with the former system and adjustment is more easy. There is no doubt but that very accurate adjustment is possible with pressure gas, but with high-class pressure air burners, where mixing is very perfect, excellent results also are obtained. Further, rotary compressors are quite capable of giving the requisite pressure to air, but for higher pressures are mechanically inefficient.

In Mr. Onslow's system at Woolwich, rotary compressors are employed for the gas, any excess gas beyond requirements on the pressure side being by-passed back to the supply through a weighted valve capable of adjustment. He takes as a standard pressure for maximum temperature (1425° C; 2600° F.) 100 ins. of water, and prefers reduction of the gas pressure as a means of controlling the temperature, thus—70 ins. for 1100° C. (2000° F.), and 35 ins. for 540° C. (1000° F.). This is effected by a reducing tap or governor with a pressure gauge to ensure correct conditions. Pressure gas has given highly satisfactory results at Woolwich for a number of very delicate thermal operations, such as the heat treatment of special armour-piercing projectiles.

A full description of the high-pressure gas laboratory instituted by the City of Birmingham Gas Department is given by Mr. E. W. Smith (*J. Gas Ltg.*, 1911, 114, 884). It was found that when the pressure jet played directly into a tube (expansion chamber) increase of the gas pressure did not cause a corresponding increase in the air injected, which is essential for maintaining a proper ratio. A very simple type of burner resulted, the tube carrying the jet injecting into a cone with an angle of 60°, and the position of the jet relative to the cone is adjusted easily by a small set-screw. Mr. Smith states that the efficiency depends largely on the cubic capacity and design of the combustion space; also on the nature of the refractory material used.

The supply to consumers is from compressors by the Worthington Pump Co., each delivering 60,000 cub. ft. per hour, at a maximum pressure of 15 lbs. It is governed down to suit individual consumers to between 7 and 12 lbs. Mr. Smith estimates that where gas has to be compressed at the factory and there is power available to drive the compressors, the outside cost of compression, including power, maintenance and interest on capital, is 2*d.* per 1000 cub. ft.

The Brayshaw burner, as installed at the Mint, after trials with both pressure gas and other pressure air burners, may be taken as one of the best types of this class of burner, or more correctly, "mixer." The gas comes from the main at about 3 ins. pressure, and the air is supplied by rotary blowers at about 2 lbs. pressure. Owing to the very efficient mixing and correct proportioning of the mixture, and the use of quadrant taps on the air and gas supply, the objections existing previously against the pressure air system no longer hold.

Mr. Brayshaw has kindly had a sectional drawing of the Royal Mint burner prepared, Fig. 31.

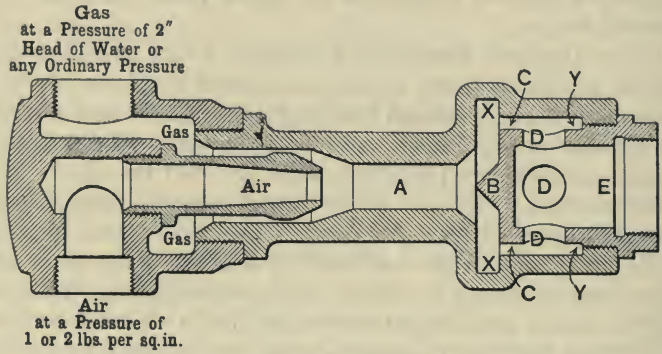

FIG. 31.—Brayshaw pressure gas burner.

The gas and air supply meet in the chamber A, and passing forward impinge on the cone B. The direction of flow is now completely changed; the mixture, already good, passes into the annular ring XX; its direction again changes, and it passes into another annular space CY, before finally issuing through the four circular holes D into the end chamber E, where the currents impinge on each other. Finally, the perfect mixture burns at the mouth without visible flame. The extensions of the channels into X and Y, beyond the points at which the mixture escapes from each, have been found very essential to obtaining the best results, and form an important feature of the patent.

In addition to gas of high calorific value, such as coal gas, burners of this pattern have been used successfully for producer gas of under 150 B.Th.U. per cub. ft. in the hardening of high-speed steels, brass melting, etc. A twin-chambered furnace for high-speed steels is shown in Figs. 32 and 33. The burner directs the flame on to the floor of the lower chamber, where it becomes spread out and combustion perfectly completed. A temperature of 1400° C. (2555° F.) is attained. The hot products of combustion escape into the upper chamber but no flame, so that its temperature is far below that of the lower chamber.

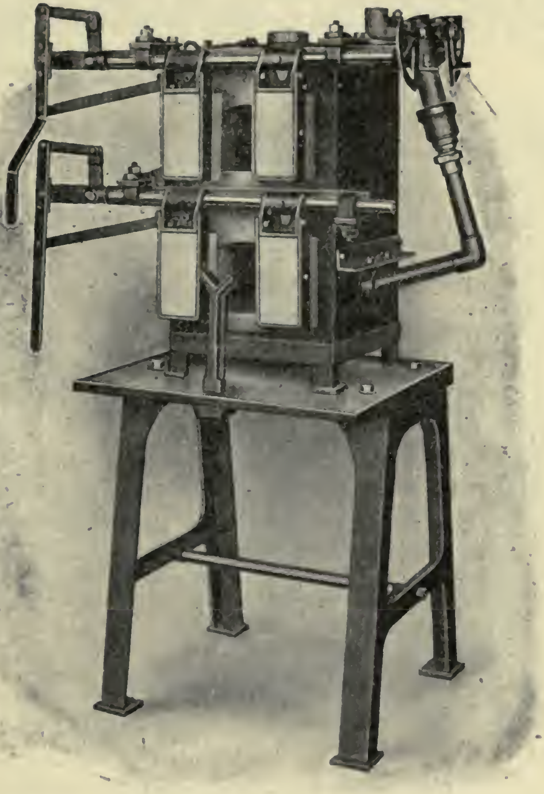

FIG. 32.—Brayshaw gas furnace—general view.

A valuable paper by L. F. Tooth (*J. Gas Ltg.*, 1910, 112, 844) gives very complete tables of consumption of gas, costs, etc., for melting most common metals. By adopting regeneration the rise to a given temperature above 1330° C. (2380° F.) is quickened, and when the desired temperature is attained, a much lower gas consumption serves to maintain it. The following abstract of details of brass melting well illustrate the advantages over coke:—

	Coke firing.	Pressure Gas firing.
Price of fuel	11*d.* per cwt.	1*s.* 11*d.* per 1000 cub. ft.
Metal melted per day	300 lbs.	540 lbs.
Fuel per day	$2\frac{1}{2}$ cwt.	1780 cub. ft.
Cost per cwt. of metal	14*s.* 6*d.*	8*s.* 4*d.*

With gas, more metal was melted per pot, a greater number of melts made in each pot per day, since the average time of melts was considerably less, labour costs for firing abolished, and repair charges were less.

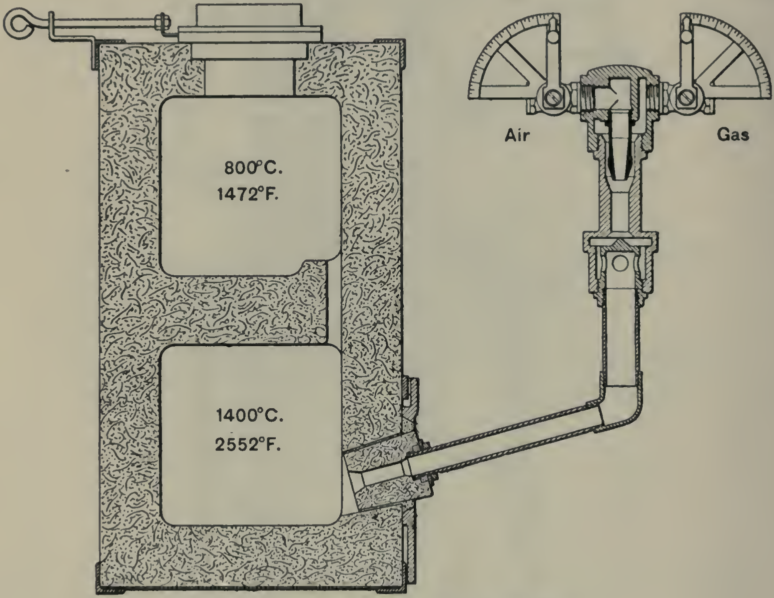

FIG. 33.—Brayshaw gas furnace—section.

SURFACE COMBUSTION

The remarkable developments which already have attended the introduction of methods of accelerating the combustion of gases and vapours, by causing their combustion to take place on the surface of refractory materials, are only the first steps in the realization of much higher efficiencies from the combustion of gases than were ever thought possible. The new system of surface combustion has its foundation mainly in the work of Prof. W. A. Bone, and numerous patents in the joint names of Bone, Wilson and McCourt have appeared already.

The effect of certain surfaces in enormously accelerating combustion has been recognized for nearly a century, since Davy conducted his memorable researches, but with one or two minor exceptions remained dormant until Dr. Bone took up the subject. It is now established that all solids have the power of inducing or accelerating combustion under suitable conditions. By accelerating the combination of combustible gases with oxygen very high calorific intensity is developed, and since the surface is in consequence raised to a very high temperature the great radiant energy which the hot surface possesses gives a large increment of heating effect.

The simplest form of apparatus in illustration of this principle is that where a flat diaphragm of porous but highly refractory material is provided with a shallow chamber at the back, to which a mixture of coal gas with slightly more than the theoretical amount of air is forced under pressure. Combustion takes place on the surface exposed to the air with such intensity that the refractory material is raised to a white heat. No flame whatever is visible, and that the air already mixed with the gas is sufficient for complete combustion is proved by immersing such a hot diaphragm in carbon dioxide, when no diminution of the action is noted.

The system is applied to crucible and muffle furnace heating by surrounding the crucible or muffle with granulated refractory material (generally carborundum), and forcing in the gas-air mixture at sufficient pressure to give velocity great enough to prevent back-firing in the explosive mixture. The difficulty has been to find materials sufficiently refractory to withstand the high temperatures. Platinum and alundum (which is nearly pure alumina) have been melted, and it is possible to maintain easily a constant temperature of 1500° C. (2732° F.).

From the industrial point of view the application of the system to steam-raising is probably most important. The efficiency of gas-firing in ordinary boilers always has been low. With coke-oven gas an efficiency of about 65 per cent. is the maximum to be expected; with blast furnace gas from 55–60 per cent. Gas-fired boilers are employed largely where there is plenty of surplus gas and efficiency has not to be considered. With the Bone-McCourt experimental boiler an over-all efficiency of 90 per cent. has been attained.

In its application for this purpose a cylindrical boiler was employed, having ten tubes running through below the water level; these tubes were 3 ft. in length, and 3 in. internal diameter, and they were packed with the broken refractory material. At the gas supply end a fireclay plug with a $\frac{3}{4}$-in. hole was inserted to give the necessary gas velocity to prevent back-firing. Combustion of the gaseous mixture was complete 4 ins. from the inner end of the fireclay plug.

The gas supply was at the rate of 100 cub. ft. of gas and 600 cub. ft. of air per tube per hour, supplied at a pressure of 17·3 ins. of water. At the exit the pressure was 2 ins.

The low temperature of the exit gases is a remarkable feature; at the end of the tubes they are only at 60–70° C. (140–158° F.) above the temperature of the boiling water, and by a small feed-water heater were reduced to 95° C. (203° F.). Evaporation was attained at the high rate of 21·6 lbs. per sq. ft. of heating surface, with a thermal efficiency on the net heating value of the gas of 94 per cent. Allowing 4 per cent. for obtaining the necessary pressure of the gas mixture, the over-all efficiency was 90 per cent.

A boiler 10 ft. in diameter, 4 ft. long, and with 110 horizontal tubes 3 ins. diameter, has been installed at the Skinningrove Iron Company's Works for use with coke-oven gas. The evaporative capacity is 5500 lbs. per hour at 120 lbs. pressure, and on test an evaporation of 20 lbs. per sq. ft. of heating surface was attained.

The supply of the gas and air at high pressures is one drawback to the system for general use, and Dr. C. E. Lucke has described (see *Gas World*, 1913, 59, 502) various forms of heaters for use with gas and air at supply pressure. The principle is to feed the mixture through heavy metal tubes with a central hole $\frac{1}{16}$ in. in diameter; through the high velocity obtained, and, by reason of the massive walls and each tube being isolated, the temperature is kept low and back-firing is prevented.

Chapter XII

GASEOUS FUELS OF LOW CALORIFIC VALUE

Introduction.—The underlying principle in the production of these gaseous fuels from solid fuels rich in carbon is the conversion of the carbon mainly into carbon monoxide, either by the action of air alone, steam alone, in which case approximately equal volumes of carbon monoxide and hydrogen are obtained, or by a mixture of air and steam. Obviously, the amount of heat available from a given weight of the solid fuel is unaffected whether the fuel is burnt directly on a grate, or is utilized indirectly by first gasifying and then burning the gases. The great advantages gaseous fuel undoubtedly offers in most cases can arise only from the better use, *i.e.* better efficiency, which can be made of the heat units of the fuel as a whole. Gaseous fuel can be more economical only when the higher efficiency attained in the combustion of the gas more than counterbalances the inevitable losses in the producer, gas-cleaning plant, etc.

In comparison with solid fuel for furnace and general heating purposes the better results with the gaseous fuel depend on several factors. Although the theoretical amount of air for combustion is the same whether solid fuel is burnt directly on a grate to carbon dioxide, or burnt partially in the producer to carbon monoxide, the combustion of this gas being completed finally in the furnace, practically a considerable excess of air over that demanded by theory is requisite for fuel burnt on a grate, whilst, all told, as gaseous fuel the amount need barely exceed the theoretical. Where high intensity is required the excess air with solid fuel is often so large that the efficiency is extremely poor. All excess air means great heat losses in the flue gases; losses mounting rapidly as higher temperatures of the flue gases are reached. The loss of sensible heat with gaseous fuel burning with a bare excess of air, even without any recovery, obviously will be much less.

Further, much of this heat may be recovered in the latter case by the regenerative system of firing commonly employed. It is not a very practicable proposition to work on the regenerative system with solid fuel. The combination of the use of gaseous fuel with the regenerative system of firing alone permits of sufficiently high and regular temperatures for many metallurgical operations, as, for example, the production of open hearth steel.

However carefully controlled the air supply may be with solid fuel, there is always some loss from incomplete combustion; with bituminous coal the loss of heat units through tarry vapours, etc., in the smoke is inevitable; with gaseous fuel used direct (without cooling, scrubbing, etc.), these heat units are rendered available; and absence of smoke is an important factor.

Again, better control of the temperature is possible, because of the ease of adjustment of the quantity consumed; more uniform heating effect over a large surface is attained, and at the conclusion of an operation the fuel supply can be shut off immediately. There is no fire to burn out.

Turning to power production, the saving in fuel by the direct use of these poorer gaseous fuels in engines is often enormous, certainly always great as compared with ordinary steam reciprocating engines, and still comparing very favourably with the best results obtained with boilers and large turbines. The efficiency of a whole steam plant, *i.e.* over-all efficiency of boiler and engine, in good practice seldom exceeds 9–10 per cent.; that of a good gas plant (producers and engines) easily attains 20 per cent. This is due largely to the great increase in efficiency of the gas engine. According to Mr. D. Clark, this increase has been from 16 to 37 per cent.

Besides direct economy in fuel consumption, gaseous fuel permits of the employment in large-sized plants of low grade and consequently cheap fuel, material quite unsuitable for boiler work. The introduction of ammonia recovery by Dr. Ludwig Mond further has rendered possible the recovery of a high proportion of the fuel costs by the sale of the valuable ammonium sulphate.

In small-sized units the fuel saving is proportionately more marked. Smaller steam engines are notoriously inefficient; the compactness, ease of working and fuel economy of the suction gas plant have been demonstrated amply by its success for several years past.

In many cases the advantage gas possesses in the matter of ease of distribution from a central generating plant to engines, furnaces, evaporators, etc., is sufficiently obvious.

Nature of Poor Gaseous Fuels.—The fuels used for heating and power purposes are principally Producer gas and "Mixed" gas. Water gas is used to some extent for special heating operations, but is employed mainly as an addition to ordinary coal gas after the addition of hydrocarbon gases, having their source in higher petroleum oil distillates.

The action of air alone on carbon under producer conditions will give rise principally to carbon monoxide, diluted with the nitrogen originally present with the oxygen in the air. This is true of a fuel such as coke, which is free from bituminous matter. With a bituminous coal, the ordinary products of destructive distillation of the coal, *i.e.* coal gas, tar vapours, etc., will be present also; one ton of coal, for example, will yield some 11,000 cubic feet of coal gas and about 112 lbs. of tar; the gas and tar vapour therefore will add appreciably to the calorific value of the gas produced, which now contains methane, hydrogen, traces of illuminating hydrocarbons, etc.

The action of steam alone, as in one phase of operating a water gas plant, will give rise to about equal volumes of carbon monoxide and hydrogen, non-bituminous fuel invariably being employed. The only diluting gases present should be those producer gases of the general composition given above left in portions of the plant.

In most cases of producer practice both air and steam are employed in the conversion of the solid into the gaseous fuel. The gases, therefore, partake of the component products of each reaction, the ratio of true producer gas to water gas depending primarily on the ratio of air to steam employed. This factor also exercises other important influences on the composition of the gas produced, but this must be discussed later. These gases are variously termed "producer" gas, which does not differentiate them sufficiently from a simple air-carbon gas; "Dowson" gas, after Mr. Dowson, who has done so much in perfecting their production and use; and "mixed" gas, which indicates more clearly that they are the result of the joint action of air and steam, and will be employed therefore throughout the subsequent pages. "Semi-water" gas is also employed frequently, and serves to indicate the joint reaction.

It will be clear that, except in the case of water gas itself, each of these producer gases must carry a large volume of inert non-combustible gas, the residual nitrogen from the air. The volume of true combustible gas present in relation to non-combustible is therefore low, and to this fact the low calorific value is due. The average composition, calorific value, and other data relating to gaseous fuels are shown in Table XXXIX., p. 185.

Where producer gases have to be employed in large heating furnaces the presence of suspended tar vapour derived from bituminous fuel is advantageous, because of the increased calorific value. Where such gases have to be supplied through cocks to burners or used in engines, the presence of suspended tar is inadmissible. The tar has to be sacrificed, and ample provision of cleaning plant provided for the gas. Sensible heat in the gases must at the same time be lost through the necessity of cooling and washing the gas. In some plants, however, attempts are made to convert the tar into permanent gases. Owing to the expense of erecting and operating devices for tar removal smaller sized plants more usually are designed to work with non-bituminous fuels such as coke.

THEORY OF PRODUCER GAS REACTIONS

The primary reactions which have to be considered are those resulting from the action of an air blast and steam blast respectively on highly heated carbon. Although bituminous fuels are employed largely, these are still the principal gas-forming reactions, the only difference being that instead of the resulting gas being produced wholly by the air-carbon and steam-carbon reactions, it is composed in part of the destructive distillation gases, accompanied by tarry vapours, etc., which have to be removed. The gas is in fact a mixture of producer gas and coal gas, where bituminous coal is used, and consequently of higher calorific value.

Air-carbon Reaction.—In ordinary processes of combustion of solid fuel, owing to the comparatively shallow layer of incandescent carbon and a relatively high air velocity, carbon dioxide is formed, and the greatest number of available heat units obtainable from the combustion of the fuel is arrived at. The reaction is

(*a*)

$$C + \overbrace{O_2 + (\text{nitrogen})}^{\text{Air}} = \overbrace{CO_2 + (\text{nitrogen})}^{\text{Flue Gases}}$$

1 lb. carbon yields 14,647 B.Th.U.

As is well known to engineers, too great a depth of fuel may give rise to the formation of carbon monoxide, with corresponding great loss of available heat units. With sufficient depth of highly heated carbon in relation to the air velocity, carbon monoxide alone may be formed, or at least only certain traces of carbon dioxide, the reaction being—

(*b*)

$$2C + \overbrace{O_2 + (\text{nitrogen})}^{\text{Air}} = \overbrace{2CO + (\text{nitrogen})}^{\text{Producer Gas}}$$

Here 1 lb. carbon gives 4400 B.Th.U.

Most recent researches show that the action of oxygen on carbon results in the simultaneous formation of carbon dioxide and carbon monoxide, but with a sufficient depth of fuel any carbon dioxide reacts with more carbon, producing carbon monoxide, so that for all practical purposes the above equation represents the net result in a producer.

The thermal efficiency as a gas-making machine will be given by $\frac{14,647 - 4400}{14,647} \times 100 = 70$ per cent. This is the efficiency with no sensible heat units in the gases produced, and is termed the *cold* gas efficiency. In practice the gases leave the producer at a very high temperature, often 800–900° C. (1470–1650° F.), so that the *hot* gas efficiency equals the cold gas efficiency plus the sensible heat of the gases. This may be equal to 85 or even 90 per cent.

The above reaction is *exothermic*, and the temperature in a producer blown with air will continue to rise for a given air blast until counterbalanced by losses of sensible heat in the gases, in the ashes and clinker, by radiation, etc. A limit is soon reached in practice beyond which it is undesirable to go, this being determined in general by the liability to form clinker from the ash of the fuel and trouble with the producer linings. The controlling medium employed almost universally to regulate the temperature is steam.

Steam-carbon Reaction.—Two reactions occur between steam and carbon. At low temperatures—about 500° C. (930° F.) the action is—

$$(c) \quad C + 2H_2O\ (\textit{steam}) = CO_2 + 2H_2$$

For this reaction 2840 B.Th.U. must be supplied for each 1 lb. carbon.

At temperatures above about 900° C. (1650° F.), the action is—

$$(d) \quad C + H_2O\ (\textit{steam}) = CO + H_2$$

For this reaction 4320 B.Th.U. must be supplied for each 1 lb. carbon.

Both reactions are markedly *endothermic*. It follows that if a producer be blown to a high temperature with air, either with the formation of carbon monoxide or a mixture of this gas and carbon dioxide, depending upon conditions referred to above, and then steam be substituted, the reaction (*d*) takes place at first, the temperature falls rapidly, and the reaction (*c*) asserts itself more and more. When the air and steam blasts are used independently, as is the case in water-gas practice, a point is soon reached when the production of carbon dioxide is so excessive (this gas being inadmissible in any quantity for the principal purpose for which water gas is employed) that steam must be cut off and the producer blown once more with air up to the proper temperature. The process is intermittent, consisting of alternate air "blows" and steam "runs."

Clearly, by the simultaneous action of air and steam it will be possible to make such a thermal balance between the air-carbon (exothermic) reaction and the steam-carbon (endothermic) reaction that a constant temperature, dependent on the relative proportion of air and steam may be maintained, and corresponding with this temperature a definite composition for the "mixed" gas obtained will be attained, depending on the relative parts played by the reactions (*b*), (*c*) and (*d*).

Steam then affords a practical means of controlling the producer temperature, of avoiding all those troubles associated with high temperatures, and, moreover, by producing a gas consisting almost wholly of two gases of high thermal value instead of simple producer gas with some 65 per cent. of inert gas (nitrogen), the resulting mixed gas is richer and of higher thermal value through its employment.

By making certain arbitrary assumptions, including that of thermal perfection, it is possible to calculate the composition, thermal value, etc., for the "mixed" gas theoretically obtained for any given air-steam ratio, but such results are inevitably far removed from those attained in practice, so that it is not proposed to introduce such calculations.

Reversible Reactions in Producer Practice.—Further important considerations govern the composition of the resulting gases. In the air-carbon reaction, allowing that all the oxygen already has entered into some form of combination with carbon, there exists simultaneously in the producer hot carbon, carbon dioxide and carbon monoxide. Carbon can react with any carbon dioxide with the formation of carbon monoxide; conversely, under some conditions the reaction may reverse, and carbon monoxide yield carbon and carbon dioxide. This is a *reversible reaction*, and is expressed as—

$$C + CO_2 \rightleftarrows 2CO$$

The reaction → is *endothermic*; the reaction ← is *exothermic*.

For a given temperature, in time an equilibrium between the two reactions in either direction will be set up. At high temperatures this equilibrium is attained far more rapidly than at low temperatures. Rhead and Wheeler (*Trans. C. S.*, 1910, 2178) showed that at 850° C. (1560° F.) equilibrium was attained in this mixture only in 240 hours, whilst at 1000° C. (1830° F.) or over it was attained in 48 hours. Further, they showed that at 850° C. the reaction $CO_2 + C = 2CO$ proceeded 166 times more rapidly than the reverse reaction.

In practice the formation of the maximum of carbon monoxide and minimum of carbon dioxide is what is aimed at. High temperatures clearly favour this; pressure (*i.e.* concentration) on the right-hand side, where the volume of carbon monoxide is double that of the dioxide tends in the reverse direction, but, as shown, this is a very slow reaction, and moreover in practice, the carbon monoxide is being withdrawn continually from the system; in other words, its removal accelerates the rate at which it is being produced.

In a valuable contribution on the "Essential Factors in the Formation of Producer Gas," Clements, Adams and Haskins (U.S. *Bureau of Mines*, *Bull.* No. 7, 1911) give results for equilibrium established when carbon dioxide is passed through tubes containing carbon in various forms. From the curves given the following data have been deduced, results being expressed in terms of $\frac{\text{velocity of gases}}{\text{length of fuel}}$.

Temperature.	To yield 90 per cent. CO.			To yield 95 per cent. CO.		
	Charcoal.	Coke.	Anthracite.	Charcoal.	Coke.	Anthracite.
1000° C.	22	*a*	*a*	6	*a*	*a*
1100	82	6	4	52	4	*a*
1200	—	18	10	—	12	7
1300	—	62	26	—	50	20

a In each case the required percentage was not attained.

The influence of porosity of the fuel and temperature clearly is very great. For a rapid rate of gasification in the producer it follows that as high a temperature of working as is practicable is required.

The actual attainment of the equilibrium in a producer blown with air is well shown from results obtained by Karl Wendt (*Stahl und Eisen*, 1906, 26, 1184); the fuel depth was 7 ft. 6 ins.

TABLE XLII.

COMPOSITION OF GASES FROM PRODUCERS (K. Wendt).

Height above twyer.	Temperature °C.	Composition of the gas.				
		Carbon dioxide.	Carbon monoxide.	Hydrogen.	Methane.	Nitrogen.
At outlet .	580	0·7	31·3	6·3	2·4	59·3
60 ins. .	—	1·0	28·9	9·8	2·0	58·3
50 ,, .	1030	0·6	30·0	11·7	0·6	57·1
40 ,, .	—	0·4	33·4	2·4	0·3	63·5
30 ,, .	1250	*nil*	34·5	0·4	*nil*	65·1
20 ,, .	—	0·2	34·3	*nil*	*nil*	65·5
10 ,, .	1400	0·2	34·1	*nil*	*nil*	65·7
At twyer. .	—	15·0	9·7	*nil*	*nil*	75·3

Equilibrium was established somewhere between 20 and 30 ins. above the twyer. The reversal of the action as the gases passed to a zone at lower temperature is shown by the slight increase of carbon dioxide at higher levels. Methane and hydrogen result from the use of bituminous coal; they make their appearance in the upper part of the producer, being eliminated completely by destructive distillation before the air-carbon reaction is set up.

More important reversible reactions occur when steam is employed. In this case varying proportions of carbon monoxide, carbon dioxide, hydrogen and steam will be coexistent, and by their interaction at various temperatures a constant composition for a given temperature will tend to be obtained. The reactions may be expressed—

$$CO + H_2O \rightleftarrows CO_2 + H_2$$

The reaction → is *exothermic;* the reaction ← is *endothermic.*

The composition of the ultimate "mixed" gas clearly will be dependent largely on the relative rate at which change is progressing in either direction. For any given temperature this depends on the relative mass (or concentration) of the gases on either side; that is, a constant K for the ratio $\frac{CO + H_2O}{CO_2 + H_2}$ will result. This constant has been determined by Oscar Hahn as follows:—

Temperatures °C.	K	Temperatures °C.	K
786	0·81	1086	1·95
886	1·19	1205	2·10
986	1·54	1405	2·49

In all ordinary practice, where a temperature of about 1000° C. (1830° F.) is usual, the constant is about 2. Should the gas be of other composition than that agreeing with this constant 2, and attain —either in the producer or regenerator—a temperature of about 1000° C., it will tend to undergo such of the reversible changes referred to as will bring its ultimate composition into agreement with this constant.

Lowering of temperature clearly will result in an increase of carbon dioxide at the expense of carbon monoxide. Again, rise of temperature will result in an increase in the amount of carbon monoxide present in the dry gas, with a corresponding decrease in the hydrogen and carbon dioxide. This is of great importance where the gas passes through regenerators, as is so frequently the case, and the issuing hot gases will be markedly different in composition from the original. A further point of note is that increased concentration of steam, apart from its effect in lowering the temperature and hence the value for K, by the increase of the concentration on the left-hand side of the equation will determine further a greater proportion of carbon dioxide and hydrogen in the gases.

Other experimental results by Karl Wendt in a producer blown with air saturated with steam at 60° C. (140° F.) illustrate this change.

TABLE XLIII.

Composition of Producer Gases with Air-steam Blast (K. Wendt).

Height above twyer.	Temperature °C.	Composition of the gas.					
		Carbon dioxide.	Carbon monoxide.	Hydrogen.	Methane.	Nitrogen.	Oxygen.
At outlet .	440	5·5	26·8	14·6	3·4	49·7	—
60 ins. .	—	5·3	28·0	19·0	4·1	43·6	—
50 ,, .	810	6·0	28·3	20·7	4·8	40·2	—
40 ,, .	—	5·0	28·7	21·8	5·0	39·5	—
30 ,, .	925	3·0	32·7	17·9	1·2	45·2	—
20 ,, .	—	5·5	28·0	13·7	0·9	51·9	—
10 ,, .	—	9·3	22·0	10·8	0·4	57·7	—
At twyer .	1110	11·4	*nil*	*nil*	*nil*	79·1	9·5

The increase of carbon dioxide and decrease of carbon monoxide above 30 ins. is shown clearly. Towards the top of the producer the diluting effect of the distillation products of the coal masks the results somewhat. The hydrogen and methane both result partly from the bituminous constituents of the coal and partly from the action of the steam on carbon. In the United States tests referred to above it was noted that at high temperatures and low velocity about 2 per cent. of methane was found in the gases from the steam-carbon reaction.

Advantages through Introduction of Steam.—The importance of steam in gas-producer practice is so great that it is desirable to summarize its advantages. These are chiefly—

1. Enables efficient control of the temperature to be maintained.

The higher the temperature the better the gas is, in general, an axiom, but the permissible maximum temperature varies with the class of fuel; principally with the liability of the ash to fuse and form clinker; to a less degree with the effect of high temperatures on the firebrick lining of the producer.

Where ammonia recovery is attempted, it is essential that a much lower temperature shall be maintained than with non-recovery; high temperatures lead to such decomposition of the ammonia that a very low yield is obtained. The use of an excess of steam is rendered necessary, and the quality of the gas sacrificed to some extent, through the production of considerable quantities of carbon dioxide, in order that the great gain possible in working costs through the recovery of ammonia may be attained.

2. By the gasification of a considerable proportion of the carbon by steam instead of wholly by air the gas contains less inert nitrogen (derived from the air), since that portion gasified by steam yields almost wholly combustible gases (carbon monoxide and hydrogen) of high calorific value.
3. The lower temperature of the producer means a lower temperature of the issuing gas; less sensible heat is therefore carried by the gases, and since the proportion of combustible gases is higher, they carry a greater potential heat which is rendered available on combustion.

Sensible heat units in the hot gas are not nearly as efficient as the corresponding number of heat units available on combustion. Since in the majority of cases the gases are cooled before use, with loss of a part and frequently nearly the whole of the sensible heat units, the use of steam proves an economical method of rendering heat units available which otherwise would be lost. In other words, steam transfers heat from where it is not wanted beyond a certain degree to the furnace or engine where these units can be utilized profitably.

The effect of steam in gas-producer practice has been investigated very fully by Bone and Wheeler, the results of their extensive trials being communicated to the Iron and Steel Institute in 1907–1908 (see *Eng.*, 1907, 83, 659, and 1908, 86, 837, 874). Trials were run over a whole week for each proportion of steam with two producers of the Mond type, with no attempt at ammonia recovery; the object in view was to ascertain the effect of steam, and not to test the Mond plant. In Series 1 the active fuel depth was the usual 7 ft., with a gasification of from 74 to 93 tons of dry fuel weekly. In the second series the usual deep cast iron bell of this type of producer had been cut off, the active fuel depth reduced to 3 ft. 6 ins., and the rate of gasification more than doubled. The principal data from the two series of trials are summarized in Table XLIV.

The make of gas showed considerable increase as more steam was employed; the gas showed the corresponding increase in carbon dioxide, at the expense of carbon monoxide, and of hydrogen, which would follow from theoretical considerations already given; the calorific value and thermal efficiency reached a maximum when the steam used per pound of coal gasified was about 0·45–0·50 lb. About 20 per cent. of the steam, on this rate of supply, escaped decomposition.

TABLE XLIV.

STEAM IN GAS PRODUCER PRACTICE (Bone and Wheeler).

		Series 2.				Series 1.				
Saturation temp. of blast. C.°		45°	50°	55°	60°	60°	65°	70°	75°	80°
Lbs. of steam in blast per lb. coal gasified		0·2	0·21	0·325	0·454	0·45	0·55	0·80	1·10	1·55
Percentage of steam decomposed		100	95	100	76	87·4	80·0	61·4	52·0	40·0
Cub. ft. of air (at 0° C. and 760 mm.) in blast per lb. of dry coal gasified		38·8	38·6	36·75	37·45	36·95	34·9	36·8	36·9	37·1
Ratio of $\frac{\text{oxygen from steam}}{\text{oxygen from air}}$		0·33	0·30	0·42	0·44	0·50	0·62	0·65	0·75	0·80
Yield of gas in cub. ft. at 0° C. and 760 mm. per ton of dry coal		133,700	132,500	132,700	135,000	138,250	134,400	141,450	145,800	147,500
Composition of the gas.	Carbon dioxide	2·35	2·50	4·40	5·10	5·25	6·95	9·15	11·65	13·25
	Carbon monoxide	31·60	30·60	28·10	27·30	27·30	25·40	21·70	18·35	16·05
	Hydrogen	11·60	12·35	15·45	15·50	16·60	18·30	19·65	21·80	22·65
	Methane	3·05	3·00	3·00	3·05	3·35	3·40	3·40	3·35	3·50
	Nitrogen	51·40	51·55	49·05	49·05	47·50	45·90	46·10	44·83	44·55
	Total combustibles	46·20	45·95	46·60	45·65	47·25	47·10	44·75	43·50	42·20
Calorific value of the gas.	B.Th.U. per cub. ft. gross	180·0	178·5	180·8	178·7	185·5	185·5	177·5	172·1	169·5
	,, ,, net	170·5	168·7	169·1	166·9	173·0	172·0	163·3	157·3	153·5
Efficiency ratio, including steam for blower		0·73	0·718	0·722	0·725	0·778	0·750	0·727	0·701	0·665

The effect of much undecomposed steam in gases will be to lower greatly the efficiency. A quantity of steam will carry a large amount of sensible heat at the temperature of the escaping gases, in addition to the quantity of latent heat also present. It is the necessity of recovering this sensible and latent heat in the excess steam, which must be used when ammonia recovery is attempted, which accounts largely for the extra plant and cost entailed when ammonia recovery is required, and determines whether recovery will pay.

In Series 2 further reduction of the saturation temperature below the 60° C. (which was the lowest in Series 1) had little effect on the thermal efficiency and no marked effect on the yield of gas or its calorific value. There appears to be no gain in reducing the saturation temperature below this, and its reduction would lead probably to clinkering troubles. At 45° saturation the temperature was so high that the ash fused and ran through the bars. It is of interest to note, in view of the reversible changes already referred to and the possibility of such reversal occurring in regenerators, that the gas obtained at 55° saturation was in equilibrium for a temperature of 1100° C., and passed through regenerators at this temperature unchanged.

One of the most important comparisons possible from Bone and Wheeler's results is that between the results when the fuel depth was halved and the rate of gasification almost doubled, for the same saturation temperature (60° C.). The composition of the gas was but little altered; there was rather more combustible present with the deep bed, and consequently the gas had a slightly higher thermal value. The efficiency with the deep fuel bed was some 5 per cent. higher than with the shallow bed and higher rate of gasification. It is clear that the shallow bed of 3 ft. 6 ins. was quite capable of giving satisfactory results, even with a rapid gas output, and since clinkering troubles are more likely to occur with greater fuel depth, clinker tending especially to grow on the firebrick sides of the producer, there is a distinct practical advantage in keeping the depth of the fuel as shallow as is consistent with the formation of good gas at a fairly rapid rate of working. A fuel with caking tendencies demands a greater depth than a non-caking fuel, owing to the liability of air channels forming.

The relative depth of the total fuel content to that of the highly incandescent portion may have an appreciable effect, in view of these reversible changes, on the composition of the gas issuing finally from the producer, providing the time necessary for appreciable change is allowed. Above the high temperature zone will be a layer of constantly decreasing temperature, in which reversal with the production of carbon dioxide and hydrogen will tend to occur.

The theoretical side of the use of steam has been considered by J. Voigt (see *J. Gas Ltg.*, 1910, 109, 168) from the results obtained by Wendt, and he has calculated the composition, calorific value of the gas, etc., for different proportions of steam. According to Voigt, the maximum efficiency would be attained with practically 0·3 lb. of steam per pound of carbon gasified. The gas would then have the maximum calorific value, but the yield would be at the lowest.

Chapter XIII

WATER GAS

Water gas, as already mentioned, is produced by the separate action of steam on carbon at a high temperature, to ensure the reaction taking, as completely as possible, the form—

$$C + H_2O = CO + H_2$$

Theoretically, then, water gas consists wholly of two combustible gases of practically the same calorific value per cubic foot. In actual practice a small quantity of carbon dioxide results from the reaction—

$$C + 2H_2O = CO_2 + 2H_2$$

According to the theory already given, the proportion of gases formed by this latter reaction increases with lower temperatures of operating. In addition to the non-combustible gas, carbon dioxide, small quantities of nitrogen, and occasionally a little oxygen accompany the gas, these being residual gases in certain portions of the apparatus from the air blast which precedes the steam blast. The following range of composition is deduced from a number of analyses:—

Hydrogen	45–51	per cent.
Carbon monoxide . . .	40–43·75	,,
Carbon dioxide	3–5·5	,,
Nitrogen	3·5–7·0	,,
Methane	0·1–0·5	,,

The calorific value of plain water gas is about 300–310 B.Th.U. gross, and 280–290 B.Th.U. net per cub. ft. The calorific intensity of the water-gas flame is high.

Since water gas contains only traces of methane and no unsaturated hydrocarbons, it burns with a non-luminous flame. For its principal application—as an addition to coal gas—water gas is "carburetted" to render it luminous; the uncarburetted gas is known as "blue" water gas.

Carburation of the gas may be attained by either a hot or cold process. In the former, suitable oils are "cracked" by subjection to a high temperature, the resulting oil-gas, of high illuminating power, mixing with the non-luminous water gas; in the latter, volatile tar spirits vaporize, and so confer the necessary illuminating power (benzol enrichment).

The manufacture of carburetted water gas is now a most important operation in the coal-gas industry, and the daily output of such gas is about 216 million cub. ft. Before the conditions of use of coal gas changed so that it is no longer a vital necessity that its illuminating power shall be high, the gas resulting from high temperature distillation of ordinary coal in small charges seldom reached the necessary standard of illuminating power. Prior to 1889, a proportion of cannel coal was generally retorted to raise the illuminating power, and the high price of cannel rendered this system of enrichment expensive. By the use of carburetted water gas enrichment is obtained at a much lower cost, and other economical advantages have contributed greatly to the extension of its use; among these may be mentioned that a water-gas plant enables the gasworks manager quickly to meet a rapid demand for gas owing to fogs, etc.; it provides a use for a considerable proportion of the coke produced in the gas retorts, so helping to maintain a fair price for the surplus available for outside disposal; it enables a smaller stock of coal to be maintained; and, lastly, leads to economy in labour, so that although its use specifically to give added illuminating power does not hold so generally as in the past, its other advantages determine the continuation and extension of its use in gasworks' practice.

The composition of carburetted water gas is—

Authority:	J. Körting.	V. B. Lewes.	G. W. Wallace.
Hydrogen	34–38	37·2	33·7
Carbon monoxide	23–28	28·26	30·0
Saturated hydrocarbons	17–21	18·88	17·5
Unsaturated hydrocarbons	13–16	12·82	10·2
Carbon dioxide	0·2–2·2	0·14	2·2
Nitrogen	2·5–5·0	2·64	6·2

The theoretical considerations governing the production of water gas have been given already. One point only demands further reference. It has been shown (Equation *d*, p. 209) that in the decomposition of 1·5 lbs. of steam by 1 lb. of carbon, in the ideal water-gas equation, 4320 B.Th.U. must be supplied. Many attempts were made to obtain this heat by the combustion of carbon in a furnace built around the generator in which the actual production of water gas was being carried on; the process would then be a continuous one, but all such attempts have resulted in failure in practice.

Recourse therefore must be made to an intermittent method, in which the fuel first is heated to high incandescence by an air blast, and then the steam passed through the same generator until the temperature has been reduced below the point at which good gas can be obtained. The process thus demands alternate "blows" with air, and gas-making periods, "runs," where steam is employed.

Any intermittent process necessarily suffers from certain disadvantages as compared with a continuous one. Either a gasholder must be provided in which to collect the water gas, or more than one producer must be installed, the number depending on the relative duration of the "blow" and "run" periods. Further, owing to the endothermic character of the steam-carbon reaction, the producer is working at a constantly falling temperature during the run; the gas consequently is not of constant composition, and, as shown by theoretical considerations already given, the carbon dioxide present will increase steadily in amount.

According to Equation *b* (p. 208), if the air blast results simply in the production of carbon monoxide, 4400 B.Th.U. are available per lb. of carbon gasified. It follows that per lb. of carbon converted into water gas $\frac{4320}{4470} = 0{\cdot}965$ lb. (practically an equal weight) of carbon must be used for the air-carbon reaction. On the other hand, if the working conditions could be made such that carbon dioxide alone resulted in the air blast, giving according to Equation *a* (p. 208) 14,647 B.Th.U., then the carbon for supplying the heat for 1 lb. of carbon converted to water gas would be only an additional $\frac{4320}{14{,}647} = 0{\cdot}30$ lb.

In actual practice the production of water gas per ton of coke may be taken as 35,000–40,000 cub. ft., when the air-carbon reaction results in the production of carbon monoxide, and approximately one-third of the coke is utilised in the water-gas reaction proper, the remaining two-thirds being concerned in the air-carbon reaction taking place during the blow. Since one ton of coke in the latter case yields about 185,000 cub. ft. of gas, the two-thirds of a ton will yield approximately 123,000–124,000 cub. ft. Then, for every 1000 cub. ft. of water gas made under these conditions, from 3000–3500 cub. ft. of producer gas will be obtained also. Lewes gives the volume as 4000 cub. ft.

Clearly, without efficient means of utilising the large number of available heat units in these gases (about 110 B.Th.U. per cub. ft.), the production of water gas under these conditions would be very inefficient and costly as compared with results obtained by the alternative method of blowing with air to produce the maximum practical amount of carbon dioxide.

Formerly these producer gases were employed for steam-raising partly to be used during the run. Now, since the introduction of carburetted water gas, they are employed profitably in heating the carburettors and superheaters. Where utilized to advantage, the total thermal efficiency of a water-gas plant may reach 80 per cent. Where water gas is required for general heating purposes, it is a great advantage obviously to blow the generators so that the maximum amount of carbon dioxide shall be produced, as in the Dellwik and Kramer and Aarts processes described later. Here, where the gases contain very little combustible, they still carry a large number of sensible heat units, which are recovered profitably by utilization for steam-raising, etc. With the latter procedure benzol enrichment will be most applicable.

Manufacture of Water Gas.—The process of Lowe and Tessie du Motay, originating in America in 1875, where the blow results in the formation of producer gas, formed the basis of most methods of production until quite recent years, and, since it so readily furnishes the necessary heat in the carburettors and superheaters for cracking the oils and fixing the hydrocarbon gases in the manufacture of carburetted water gas, adaptations and improvements in this process are still responsible for the bulk of the water gas produced.

Where water gas is required solely for heating purposes, for reasons already given, the more recent method of blowing to carbon dioxide is more suitable; here it is proposed to describe the general principle of operating on the Lowe system only for the production of the carburetted gas.

From the theoretical principles, for the blow to yield producer gases, the fuel depth in relation to the blast must be high. The generators in this type of plant are about 20 ft. high and 7 ft. in diameter. The general arrangement of the plant is shown diagrammatically in Fig. 34.

The generator A is lined with firebrick; it is provided with the necessary hopper for charging at the top, clinkering doors, ash-pit door, etc. During the blow valves 1 and 2 are open, valve 3 closed. The air blast from the blower B passes in at the bottom of the generator, the producer gas issuing through the large main at the top of the generator through the valve 2, and pass on to the carburettor C. At the top, where they enter, air from the blower is admitted for their combustion; the burning gases pass downwards through the firebrick chequer in the carburettor, heating it to a high temperature; they then pass into the bottom of the superheater D,

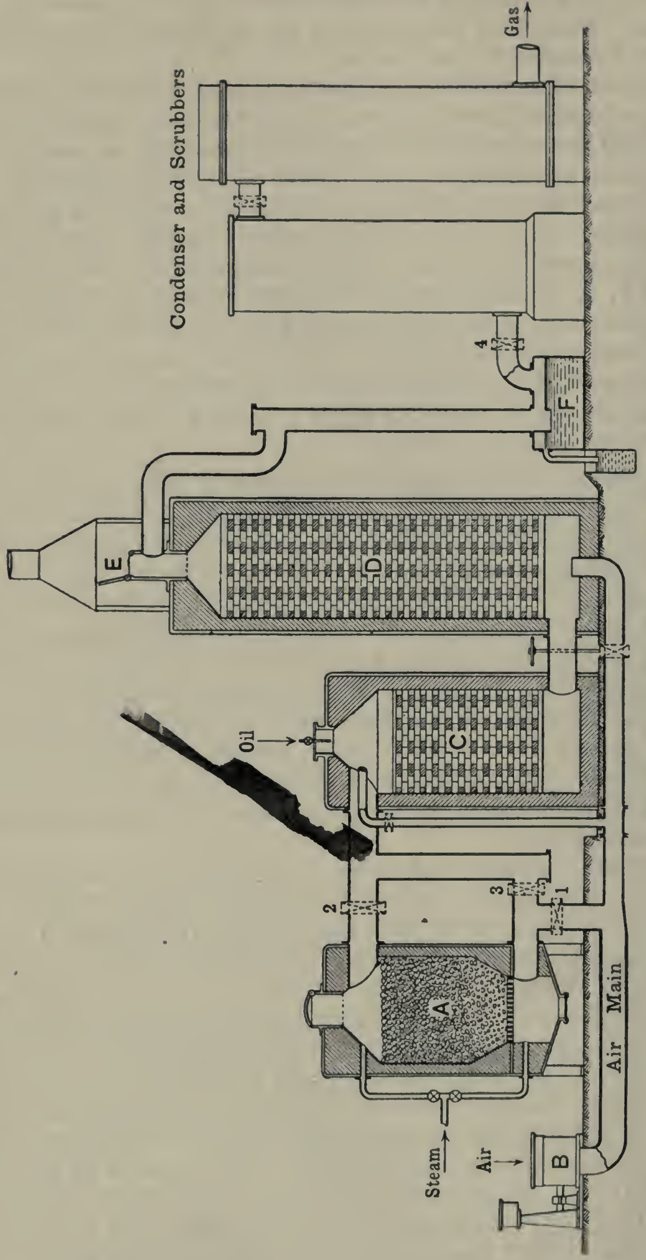

FIG. 34.—Carburetted water gas plant.

meeting a further supply of air from the blower to complete their combustion. Finally, the hot products of combustion escape through the stack valve E at the top.

During the gas-making period, the air supply valves having been closed together with the stack valve, and the valve 4, controlling the condensers and scrubbers, opened, steam is admitted, in one run at the bottom and in the succeeding run at the top of the producer. When admitted at the bottom, the water gas finds its exit through the valve 2; when at the top, through the valve 3, passes up the vertical main, in both cases passing ultimately into the top of the carburettor. The oil injector is now operated for a portion of the run, the water gas carries the oil vapours down through the hot firebrick, then into the superheater, where the hydrocarbon vapours become converted finally into stable gases. A considerable quantity of tar also is carried forward, some of which condenses in the vertical main, which terminates in the hydraulic seal F. The remaining condensation of tar and scrubbing of the gas take place in suitable condensers and extractors, and the gases pass forward through purifiers, where sulphuretted hydrogen and carbon dioxide are removed before the gas is admixed with the coal gas.

The alternation in the admission of steam to the top and bottom of the producer, which is common to most processes, is with a view to attaining more uniform temperatures. During the up run the extreme bottom layers of fuel are reduced greatly in temperature; when the succeeding blow takes place the blast air at high velocity prevents these layers again becoming highly heated, so that they remain chilled. On the other hand, when steaming from the top the bottom layers become extremely hot, hence the advantage of alternate steaming from above and below.

Two important points in relation to steam supply must be considered. Owing to the strongly endothermic character of the steam-carbon reaction, the driest steam will quickly cool the fuel down. Wet steam obviously will have a far more rapid effect in this direction, and quickly reduce the bed below the temperature at which good gas can be made. Superheating the steam clearly is very advantageous.

Again, excess of steam is to be avoided; it will pass through the fuel unchanged, leading to more rapid cooling; the loss of heat from the system by reason of the high specific heat of steam will be great; more fuel is required to raise this unnecessary steam, and more cooling water employed in the condensers.

G. W. McKee (*J. S. C. I.*, 1903, 1325) has shown that the make of gas falls off rapidly after the first three or four minutes of the run, and concluded that as the process goes on the steam supply should be reduced. By cutting down the nozzle pressure by one-half after the fourth minute a considerable saving of coke was effected, and the carbon dioxide in the gas reduced; it is suggested that by dividing the run into three periods and reducing the steam at the last two, further economy would result.

After the addition of coke to the producer the next blow should be of about one minute longer duration than the usual. This serves to heat up the added fuel properly. Further, immediately before coking the temperature of the fuel is at its maximum, and it is found in practice that another minute may be added to this run without the quality of the gas being impaired.

A valuable contribution on the Application of Chemical Control to the operation of Water Gas Plant, by G. W. Wallace (see *Gas World*, 1912, 57, 361; *J. Gas Ltg.*, 119, 503) should be consulted. The composition of the blow gases in different parts of the plant and the distribution of heat units in these sections is given as—

	Generator.	Carburettor.	Superheater.
Carbon monoxide . . .	15·0	6·3	0·5 per cent.
Carbon dioxide	10·2	15·5	19·1 ,,
Oxygen	0·8	0·2	0·3 ,,
Nitrogen	74·0	78·0	80·1 ,,
Distribution of the heat units of the fuel . .	59·2	20·8	18·7 ,,

From these and other data Wallace computes the distribution of the heat units of the fuel in the gas made, different parts of the plant, etc., although in the example given he does not consider the process working at its best, to be as follows:—

For gas making	31·2 per cent.
For blowing generator	40·8 ,,
For heating carburettor	14·2 ,,
For heating superheater	13·0 ,,
Consumed (?) outside	0·8 ,,

In good practice for "blue" water gas, the fuel consumption per 1000 cubic feet is given as 34·6 lbs. The estimated percentage of carbon of the fuel appearing in the gas is 33·75 per cent.

The following consumptions, etc., for 1000 cubic feet of carburetted water gas are given by T. W. Harper (Dundee) and S. Milne (Aberdeen):—

	Dundee.	Aberdeen.
Coke for generator, lbs. . . .	49·62	42·8
Coke and breeze for boiler, lbs. .	—	17·3
Oil, gallons	3·25	3·44
Water for steam, gallons . . .	9·77	10·50

According to A. Meade (*J. Gas Ltg.*, 1912, **117**, 211), with a large plant working under the best conditions with good coke, the weight per 1000 cub. ft. seldom exceeded 37·5 lbs.; under bad conditions it was 43 lbs. Coke is necessarily very variable in its carbon content, and, without the analysis being given, comparison between different results should not be instituted.

The steam required per square foot of cross-section of the producer is stated as 0·1 lb.; the consumption in an ordinary plant, including that for the blowers, as 62·4 lbs. per 1000 cub. ft. of gas. On theoretical grounds it may be calculated that with a gas yield of 1000 cub. ft. per 40 lbs. of coke containing 90 per cent of carbon, the steam used in the generator would be about 60 lbs. per 1000 cub. ft. make.

In the Loomis producer a considerable reduction in the ratio of depth to fuel area over the older types of generator has been made, together with other notable improvements. The height is usually 12 feet and the diameter 9 feet. The air supply during the blow is admitted around the charging hopper, so that the hottest zone is in the upper part of the producer. Beneath the grate a superheating arrangement is provided by means of fireclay slabs. When the steam for the run is admitted beneath the grate it becomes highly superheated by these hot surfaces, passes up through the fuel bed, leaving at the hottest part of the fuel, and the water gas produced passes through a number of ports communicating with an annular ring in the upper part of the lining, through which the gas passes to the main.

Dellwik-Fleischer Process.—The successful adaptation of the water gas plant so that during the blow the great advantage in output per ton of fuel arising from the production of carbon dioxide instead of carbon monoxide, was due to Mr. Dellwik. Theoretical considerations already given show that with the production of carbon monoxide an equal weight of fuel must be consumed during the air blast, whilst owing to losses by radiation, as sensible heat, etc., in practice only about one-third of the total fuel is actually gasified by the steam. On the other hand, where the blast results in carbon dioxide, the fuel demanded for the air-carbon reaction is only one-third that of the fuel gasified by the steam. It follows that a much higher gas yield per ton of fuel charged is possible in the latter case. In actual practice, the make of blue water gas by the Lowe process is about 35,000–40,000 cub. ft. per ton; on the Dellwik principle it reaches 75,000–78,000 cub. ft.

The actual thermal efficiencies of the two systems must not be compared by these data, for where good use is made of the heat units available in the combustible gases from the Lowe system, nearly as high a thermal efficiency is possible as on the Dellwik system. But the latter offers other advantages. By blowing to carbon dioxide the generation of heat is far more rapid, the required temperature for commencing the steam reaction being quickly reached, and gas-making proceeds over a far greater proportion of the time. In the early generators the "blow" period was frequently 10 minutes, and the run 4–5 minutes; in modern plants on the Lowe system the run period usually exceeds the blow period by one or two minutes. In the Dellwik process the blow may not exceed 2 minutes, with a run of 7–9 minutes.

The composition of the "blow" gases in both systems is given by Professor V. B. Lewes as—

	Old System.	Dellwik.
Carbon dioxide	4·5	15–18
Carbon monoxide	29·0	1·5–2·5
Nitrogen	66·0	80·0
Oxygen	0·5	1·0

In order that carbon dioxide may result in the blow the fuel layer must be shallow and the air blast powerful. The Dellwik-Fleischer producer is usually 14 ft. high, 12 ft. in diameter, and fuel bed about 3 ft. thick. It being necessary to maintain a sufficient thickness of fuel during the run, means are taken to control this carefully by the addition of fresh fuel at frequent intervals; usually coke is added at every second blow. The blow gases escape through a central stack valve at the top of the producer. Steam is admitted alternately at top and bottom in consecutive runs. The hot water gas passes through a superheater, through which the steam supply also passes, thus taking up the sensible heat units from the gas, then through suitable washers and scrubbers to the holders.

The average coke consumption in the Dellwik generator per 1000 cub. ft. of gas is given as 32–35 lbs., equivalent to a gas yield of 65,000–70,000 cub. ft. per ton. The steam requisite for the run and operating the blower is about 60–65 lbs. per 1000 cub. ft.

Kramer and Aarts Process.—This is one of the most successful forms of plant adapted to work on the Dellwik principle, and its ingenious arrangement for providing the necessarily shallow fuel bed for carbon dioxide to result from the blow with rapid attainment of the desired maximum temperature, and the manner in which complete decomposition of the steam is attained by causing the steam to travel through twice the depth of fuel that the air passes through in the blow, offer marked advantages. In the plant the water gas always leaves the producer at the hottest zone. This is a point of great importance, as affecting the regularity in composition of the gas made in successive runs. It has been shown that with gas formed at a hot zone passing on to cooler zones, reversal of the chemical changes takes place, and more carbon dioxide appears in the gas at the expense of the monoxide. When the gas is led off at the hottest zone its temperature is reduced so quickly below that at which reversal is appreciable that further change is negligible, and the carbon monoxide percentage will be the maximum attainable for the equilibrium corresponding to the existing temperature of the final layers of fuel.

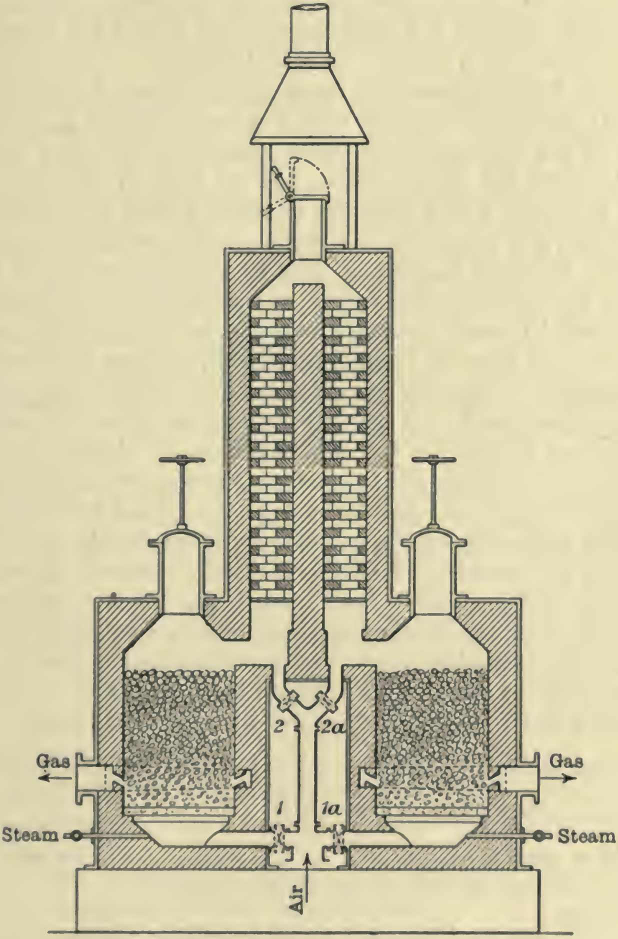

FIG. 35.—Kramer and Aart's water gas producer.

The general principle of operating on the Kramer and Aarts system will be followed from Fig. 35. The two small generators are blown *in parallel*, the air valves 1 and 1*a* being open. The gases escape at the upper part of each producer into the two chambers above filled with a chequer of firebrick, these chambers being built side by side and open to each other at the top. A secondary air supply is admitted through the valves 2 and 2*a*, serving to complete the combustion of any carbon monoxide produced. The hot blow gases escape through the stack valve at the top of the regenerator. The average duration of the blow is 45 seconds.

During the run steam is blown in at the bottom of one generator; the water gas formed, together with any excess steam, passes up the section of the regenerator in direct connection with this producer, down through the other section, and so through the fuel in the second generator, finally escaping at suitable ports in its lower part to the water gas main. In the run, then, the producers are worked *in series*. After the succeeding blow in parallel, the steam is sent first into the generator from which the gas was drawn in the previous run. It will be seen that by this arrangement the active fuel exposed to the action of steam is very large; further, that any steam escaping decomposition in the first generator becomes highly superheated in the regenerators, and so in the best possible condition for completing the water gas reaction in the second generator. Again, any carbon dioxide in the gas obtained in the first generator is certain of conversion into carbon monoxide in passing through the second generator.

Owing to the shallow bed of fuel operating during the blow the liability to the formation of clinker is greatly reduced, and with the large amount of superheating of the gases the fall of temperature in the second generator is less steep than with a single system plant, and good gas obtainable over a correspondingly longer period.

The following results were obtained by Professor W. A. Bone on a 500,000 cub. ft. per day Kramer and Aarts plant at Leeds:—

Average make per hour	21,833 cub. ft.
Calorific value, B.Th.U. per cub. ft.	308·9 gross 284·0 net
Yield of gas per lb. *carbon*	37·84 cub. ft.[1]
Percentage of carbon of coke appearing in the gas	60·65
Ratios of calorific values of the gas and coke	0·766 on gross 0·705 on net

Industrial Applications of Water Gas.—The principal application of water gas after carburation, as an adjunct to coal gas making, has

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[1] The coke as charged contained 84·7 per cent. of carbon; the yield per lb. of coke was therefore approximately 32·1 cub. ft., or coke per 1000 cub. ft. made = 31·3 lbs.

been dealt with. Blue water gas is, however, of special service in many heating operations. Its gross calorific value is about 310 B.Th.U., and net 280 B.Th.U. per cub. ft. The gas is capable of giving a very high flame temperature. According to Dr. Roessler, with pre-heated air a temperature well above the melting point of platinum (1780° C.; 3236° F.) is attained; under ordinary conditions of combustion the hottest part of the flame is from 1530–1645° C. (2800–3000° F.).

For furnace heating, where the work is intermittent and it is desired to get a quick heat, water gas has the advantage over ordinary producer (mixed) gas. It has been used to a limited extent in steel furnaces, but here producer gas—used hot and with its tar vapours—with its simpler production, continuous make, and less costly plant is more generally advantageous. For furnaces for heating drop forgings and stampings and such class of work, it is employed, and to a limited extent for metal melting. Plant is, however, unlikely to be installed specially for these uses.

Blue water gas is, however, very valuable for special welding processes, especially for steel mains and pipes. According to A. Meade, the burners for this purpose are supplied with gas at half a lb. pressure, the air at 2½ lbs., the consumption per burner being 9000 cub. ft. per hour. A steel main 18 ft. long and ½ in. thick can be welded along the joint in about one hour. The same writer states that water gas is used also for glass melting and for cement kilns.

The use of water gas for power production in gas engines is limited to works where the plant is installed for other purposes. For power production alone a water-gas plant would not be installed. An objection generally urged against it for use in engines is the liability to pre-ignition on compression, usually ascribed to a high percentage of hydrogen. Water gas, however, has given no trouble in many cases when too high a compression is not attempted. Meade states that for such use the gas must be subjected always to iron oxide purification.

The higher percentage of water gas to give an explosive mixture with air is 57; the lower limit, 12·5 per cent.

One of the most interesting developments in the use of water gas is in the production of pure hydrogen. By reducing to a low temperature the carbon monoxide may be liquefied and hydrogen of fair purity obtained. With the extending demands for hydrogen for balloons and dirigibles, and for use in the oxy-hydrogen blow-pipe for cutting metals, this process is likely to find extensive application.

Cost of Water Gas.—A. Meade gives the cost of blue water gas as 4½*d.* per 1000 cub. ft., which includes all charges together with depreciation. The cost of carburetted gas by the Kramer and Aarts process is stated by the makers to be 7*d.*–8*d.* per 1000 cub. ft., and the "blue" gas 3*d.*–4*d.*

In extensive tests at Cleethorpes with the Dellwik plant, the cost of "blue" water gas was 3½*d.* per 1000 cub. ft. At Ilford, with benzol carburation, the plant being rated for an output of 600,000 cub. ft. per 24 hours, 15 candle-power gas cost 7·27*d.* per 1000 cub. ft. At Cleethorpes, with oil carburation, capacity of plant 300,000 cub. ft. per 24 hours, 15·6 candle-power gas cost 8·64*d.*, the oil consumption being 1·27 gallons.

The possibility of obtaining better efficiency in water-gas plants by utilization of sensible heat units in both blow and run gases is generally overlooked. Taussig estimates the sensible heat units leaving the apparatus per 1000 cub. ft. as 110,630 B.Th.U., 62,400 from the blow, 48,230 from the run, and if carbon monoxide is present in the escaping blow gases, the loss is further increased.

Taussig advocates the use of these gases by passing through suitable boilers—those of the pattern used for exhaust gases from gas engines would prove suitable. In practice 70 lbs. of water have been evaporated per 1000 cub. ft. of gas made. Assuming the boiler evaporation per lb. of coal to be 8 lbs , the 70 lbs. evaporated are equivalent to 8·75 lbs. coal. He estimates that the coal consumption for steam-raising may be reduced from 10–20 lbs. at present required to from *nil* to 5 lbs.

Chapter XIV

PRODUCER GAS

Simple Producer Gas (Air-Coke Gas, Siemens Gas)

The gas resulting entirely from the action of air on highly heated carbon, and therefore consisting essentially of carbon monoxide with a large volume of inert nitrogen derived from the air, was the first form in which "gasified" carbon was applied in practice. Bischof (1839) introduced a simple form of producer, open to the air at the bottom, through which the air current was drawn by natural draught.

The development in the use of gasified fuel was associated closely with improvements in metallurgical furnaces with regenerative working, which the brothers Siemens introduced and developed. In the earlier forms of producer the fuel was gasified by an air current induced by natural draught; later, Siemens used a closed bottom producer, water being kept in the ash pit and air blown in; still later, a steam injection system for carrying in the air was introduced.

The composition of the gas obtained by the action of air alone should be approximately one volume of carbon monoxide and two volumes of nitrogen; its relation to the other fuel gases, average composition, etc., is given in Table XXXIX., p. 185. It has been shown that the "cold gas" efficiency of such a producer would be about 70 per cent.; by using the gas hot efficiencies of from 80 to 85 per cent. may be attained.

The composition of the gas obtained from a bituminous fuel partook naturally of the character of a mixture of producer gas proper and the gases distilled from the coal. The composition of a Siemens gas produced from bituminous fuel in a wet-bottom producer with some excess of air, as shown by the oxygen present was:—

Carbon monoxide	23·7	per cent.
Hydrogen	8·0	,,
Methane	2·2	,,
Carbon dioxide	4·1	,,
Oxygen	0·4	,,
Nitrogen	61·5	,,

The use of simple producer gas was confined entirely to metallurgical operations. With the knowledge of the advantages of the joint action of air and steam the production of this simple gas soon ceased, and "mixed" gas is now employed invariably.

"MIXED GAS" (SEMI-WATER GAS, DOWSON GAS)

It has been shown already that by the joint action of air and steam on carbon a mixed gas, consisting partly of the producer gas proper and water gas, may be made by a *continuous* process. This offers obvious advantages over any intermittent process.

The wonderful development in the use of these poorer gaseous fuels, the production of which led naturally to a simultaneous improvement in gas engine design and operation, formed a marked feature in industrial progress at the end of the twentieth century. Reference has been made already to some of the advantages gaseous fuels of this character offer. In the early years of its introduction for power and other purposes, the successful results obtained were due largely to the skilful handling of the problem by Mr. J. Emerson Dowson, who in 1881 demonstrated the value of poorer gases in a 3 H.P. Otto engine. The development of the large gas engines of the present day, working at high compressions on these poor gases, and the application of these engines to the efficient utilization of waste gases, or gases hitherto inefficiently utilized, as blast furnace gas, must be attributed in the main to the pioneer work of Mr. Dowson.

Pressure and Suction Plant.—The gasification of the fuel is carried out in cylindrical producers, in which an air-steam current acts upon the carbon of the fuel. The producers may be worked under pressure, the air being forced through either by a steam jet or by a fan blower. The natural development was to make the suction stroke of the engine itself pull through the necessary air-steam mixture, giving the well-known suction gas plant. The nature of the gas produced from a given type of fuel obviously will be almost identical for the same conditions of air and steam supply.

In general, the pressure plant is more particularly suited to the production of large quantities of gas, and is adopted almost universally where gas is required for both power and heating purposes. More recently special forms of such plant, in which air-steam is drawn through by a fan and the gas distributed much as with pressure systems, have been designed, but their advantages over the pressure system are not very obvious, beyond reduction of the risk of carbon monoxide poisoning should a leak occur. Working under suction, gas cannot escape outwards; any leakage will be of air inwards.

The suction plant is suited more particularly to power production on a small or moderate scale, and generally the gas producer, gas cleansing arrangements and engine form a complete unit. Where the engine alone is responsible for drawing the air-steam through the producer and the gas through the necessary cleansing plant, it follows that the resistance offered to its free passage must not be great, as would be the case where much tarry vapour is given off, requiring somewhat extensive cleansing plant. It follows that non-bituminous fuels, such as anthracite and coke, are most suitable for such plant.

Fuels for Gas Plant.—The design of the plant will be least complicated the purer the gas as it leaves the producer. Its simplest form then will be for plant utilizing anthracite or coke, whether for pressure or suction working. The very great advantage of being able to work with bituminous coals of much lower cost is obvious, but their use entails greater complication in design, higher first cost and working expenses, where the gas has to be used in engines. The tar vapours are advantageous in metallurgical operations, by reason of their adding to the calorific value of the gas. In this case the gas passes as directly as possible from the producer to the furnace, and its sensible heat also is utilized. In general, bituminous fuels are most suitable to pressure plant, although several forms of suction plant work successfully on certain types of bituminous fuel, and some on ordinary bituminous coals of low cost.

The variety of fuels which have met with successful application in gas-producer practice covers pretty well all carbonaceous materials, ranging from high-class anthracite to colliery refuse containing over 50 per cent. of ash, quite useless for fuel in any other way; it includes lignites, peat, wood waste, spent tan, coker-nut shells, etc. The limitation to use appears to be caking properties in the case of coals; this prevents the fuel passing through the producer in a proper manner, and leads to formation of channels through which the blast passes without proper action taking place.

Where bituminous coal is employed in large quantities the question of ammonia recovery has to be considered. The quantity of nitrogen in English coals averages about 1·3 per cent. (see Table XVII.), the greater proportion of which can be recovered in producer practice. This entails considerable addition to the usual plant, adding to its first cost, and its operation necessarily will be more expensive than with non-recovery. Further, the producer temperature must be much lower, otherwise large destruction of ammonia occurs. This necessitates more steam in proportion to the air; the lower producer temperature resulting leads to higher carbon dioxide and hydrogen in the gas, and much steam passes through without decomposition, carrying forward to the purifying plant a large number of heat units as latent and sensible heat. For economical working these heat units must be recovered, and this adds still more to the complication and cost of the plant. Against all this there is the great return from the ammonium sulphate made ; often 70–80 lbs. per ton of fuel, and worth from £12 to £13 per ton.

The selection of the most suitable form of plant for a particular factory is often a difficult matter. Improvements in the suction type and in simplifying and cheapening ammonia recovery plant have eliminated the old more or less recognized boundaries between the systems. Whether the plant shall be for non-bituminous or bituminous fuel ; whether, with the latter decided upon, for ammonia recovery or not, are questions bound up so intimately by local conditions, fuel prices, available water supply and other considerations that no general guidance is applicable.

General Considerations.—On theoretical grounds it has been shown that a temperature of about 1000° C. is requisite for the production of gas with low carbon dioxide content. The temperature attainable in practice is limited by excessive action on the lining of the producer, but more especially by the liability to form clinker from the ash of the fuel. The question of fusibility of coal ash has been referred to on p. 40. Unless the gas is used hot high temperatures in the producer lead to big losses of sensible heat in the gases, and low thermal efficiency results.

Clement and Grine (*U.S. Geol. Surv. Bull.*, 393, pp. 15–27) give the results shown in Fig 36, with a producer 6 ft. 6 ins. diameter at the top, 7 ft. at the bottom, and with a fuel depth of 8 ft. 6 ins. The maximum observed temperature was 1300° C. (2370° F.). It will be seen that the temperature towards the centre was much lower at a given height than at the sides, and this was ascribed to a badly designed twyer. Proper distribution of the blast through the fuel is an important question.

In a Taylor producer, J. S. Pennock (*J. S. C. I.*, 1905, 600) obtained the following temperatures above the fuel bed :—

At top of fuel	950–970° C. (1740–1780° F.).
2 ins. above surface	900–910° C. (1650–1670° F.).
1 ft. above surface	650–660° C. (1200–1220° F.).
2 ft. above surface (at outlet) . .	595–605° C. (1100–1120° F.).

The temperature conditions in a suction producer were investigated by Garland and Kratz ; the engine was cut out and suction obtained by a Körting steam injector. Temperatures were taken at the centre of the bed and 3 ins. from each wall at three different levels and at the gas exit and before entering and leaving the scrubber. The results obtained for the producer were—

Height above grate.	Temperature.					
	3 ins. from wall.				Centre.	
	Near side.		Far side.			
	°C.	°F.	°C.	°F.	°C.	°F.
24 inches	1150	2100	1105	2025	1115	2037
18 "	1290	2350	1245	2275	1220	2225
12 "	—	—	1315	2400	1205	2200

The mean temperature was 1200–1260° C. (2200–2300° F.), and that of the gases at the exit 590–600° C. (1095–1110° F.).

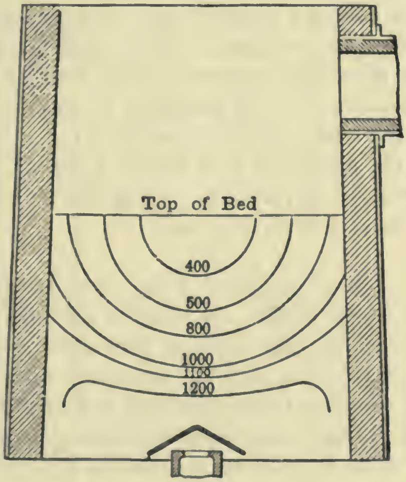

Fig. 36.—Diagram of temperature distribution in gas producers.

It has been shown also that steam is the temperature regulator, and it follows that the character of the fuel, both its moisture content and the character of the ash, plays an important part in determining the air-steam ratio demanded. A fuel holding much moisture will require less steam from exterior sources; with high moisture, as in many peats, it may not be necessary to supply any additional steam.

The quantity and character of the ash of the fuel is of very great importance. If the ash is fusible, in order to prevent formation of troublesome clinker, a high steam ratio has to be employed in order to keep a lower temperature and so avoid excessive clinker formation. This leads necessarily to impoverishment of the gas. Much clinker entails considerable labour in keeping the producer working under good conditions, and where a grate which actually supports the fuel bed is employed the ash and clinker interfere seriously with the free passage of the blast. In producers where the ash does not rest on a grate, little trouble is experienced with fuels having quite a high ash content, if the ash is not of a very fusible character. With suitable producers the gasification of colliery waste, etc., containing up to 50 per cent. of ash, material quite unfit for use as fuel in any other way, can be readily accomplished.

Producers for such fuels are constructed usually to work under a higher blast pressure than ordinarily; in many the water-sealed bottom is replaced by a closed-in bottom, and special mechanical arrangements provided for removal of the ash and clinker.

The rate of gasification is one of the most important points of a producer; for a given consumption it determines the number to be installed. There comes a natural limit to the rate by reason of the very high temperature attained at high blast pressure, with consequent formation of clinker, especially with fuels of high and fusible ash content. Marconnet has proposed a producer to operate on powdered fuel; the rate of working is kept so high that the ash fuses and is run from the producer, as a slag is from a furnace. The rate of gasification attained is very high; from 100 to 160 lbs. per sq. ft. of section per hour has been claimed.

Theoretically, 1 lb. of carbon at a high temperature can decompose completely 0·64 lb. of steam, in practice 0·75 lb. may be allowed without any appreciable loss through part being undecomposed. In ordinary producer practice, without ammonia recovery, about 1 lb. per lb. of fuel is common (corresponding to a saturation temperature of 70°). It is stated that the volume of steam is 10 per cent. of the air volume, or 6 per cent. by weight, in Dowson type pressure producers. It is commonly assumed that the additional fuel required under the boiler is one-sixth the weight of fuel gasified.

In pressure plant the air may be injected by means of a steam jet, or, usually in the larger plants, by a fan or blower, when it takes up the requisite steam from water maintained at a suitable temperature. Insufficient attention is paid in many injectors to providing easy control of the air-steam ratio. With a fixed steam jet and open air orifice variation is possible only by alteration of the steam pressure. A steam jet directed into a cone and capable of moving in and out will enable the ratio to be adjusted, or, in other cases, provision is made for excess air to be the normal condition, the actual admission being regulated by adjustable louvres. Annular steam jets are more efficient than "solid" jets.

In pressure plants operated by a blower, and in most suction gas plants the ratio is dependent on the saturation temperature of the air by steam. On theoretical grounds it may be taken that, with conditions of air and steam supply properly balanced for thermal equilibrium with the production of carbon monoxide and hydrogen only, each pound of carbon gasified requires 42 cub. ft. of air and 0·64 lb. steam. The curves given in Fig. 37 show the weight of 1 cub. ft. of air at different temperatures, and the weight of steam 1 lb. of air can carry at saturation at various temperatures.

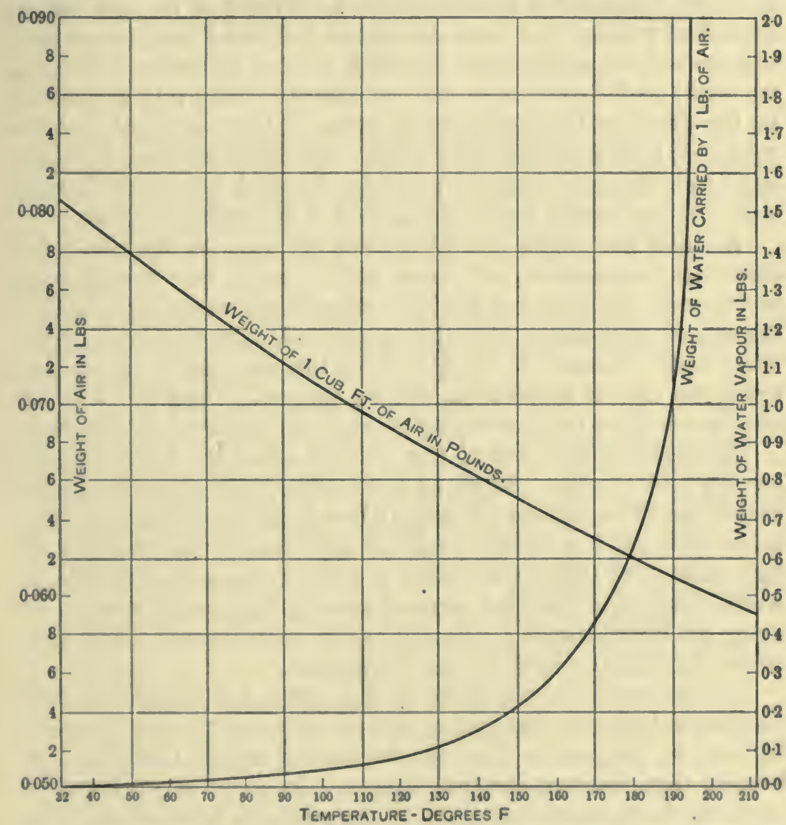

Fig. 37.—Diagram showing weight of 1 cubic foot of air at different temperatures and steam saturation of air.

The steam supplied should be dry; wet steam would clearly lead to greater cooling than a corresponding quantity of dry steam, hence when dry it is equivalent to the producer taking a greater proportion of steam, thus yielding a higher proportion of water gas in the "mixed" gas, with corresponding decrease in the volume of non-combustibles. Superheating is clearly an advantage, and since this can be arranged for by utilizing sensible heat in the gases produced, this heat is conserved. In many producers further superheating of the air-steam mixture is done by passing it through an annular space around the lower part of the producer. The cooling effect here is advantageous in checking the formation of clinker.

A producer must be capable of giving a high rate of gasification with simultaneous production of good gas. Allowing that the necessary temperature is maintained, the quality of the gas will be dependent primarily on intimate contact between the air-steam blast and carbon for equilibrium resulting in the formation of carbon monoxide and hydrogen to be maintained. This will depend on (*a*) the depth of the incandescent zone; (*b*) the cross-section of the producer; (*c*) the velocity of the blast. The first condition will depend greatly on the latter factor. The total depth of the fuel will govern largely the volume of the air-steam blast it is possible to admit.

A small fuel depth and high blast will lead to the whole fuel becoming incandescent, and some carbon dioxide may pass through unchanged. Reduction of the blast to avoid this would lower at once the rate of gasification. On the other hand, excessive depth of fuel offers much resistance to the passage of the blast and the gases, and, again, the rate of gasification will be reduced. Deep fuel beds are also conducive to the formation of clinker on the sides of the producer.

The size and character of the fuel will affect the depth required for the best results. Small or porous fuel, offering large contact surface for the reactions will require less depth than larger and more dense fuel, but the smaller fuel will offer greater resistance to the free passage of the gases. With a fuel having caking tendencies, whereby air channels may form, a greater fuel depth is requisite; again, producers working with bituminous fuel require a depth some 20 per cent. greater than for non-bituminous.

These considerations apply to the *active* fuel depth. A large amount of fuel over that taking part in the reactions may be advantageous in prolonging the time between charging fresh fuel, but beyond that appears disadvantageous. In such upper layers at moderate temperature reversals of the primary reaction are more liable to occur, leading to deterioration of the gas, and the mass offers greater resistance to the free passage of the blast, and hence rate of gasification. In certain producers for bituminous fuels a bell extends downwards from the charging hopper to well below the gas exit pipe. The gases do not pass through this portion, so that the actual fuel depth should be reckoned as from the bottom of the bell. The object of this bell is that the gases from the bituminous fuel may be distilled off slowly and pass through the upper layers of active fuel, where the tarry vapours are supposed to be converted into permanent gases.

In Bone and Wheeler's investigations on a Mond plant, the results of which have been given on p. 214, the bell extension was cut off for the second series of experiments, and the active fuel reduced to one-half of that in the first series, namely, from 7 ft. to 3 ft. 6 in., without appreciably affecting the working results. The advantage of the bell is not apparent, and makers appear to be discarding it. Bone and Wheeler's results further show that with proper distribution of the blast through the bed the excessive depth of fuel in many producers is unnecessary and disadvantageous, and that the depth seldom need exceed 3 ft. 6 in.; many producers give excellent results with well under 3 ft.

Arrangements for introduction of the Blast.—This is an important question, and the success of a producer is dependent largely upon a proper distribution throughout the fuel bed, otherwise zones at high temperatures and the reverse may result. Illustration of a cool "core" through faulty design for air admission has been given on p. 235.

In producers of larger size, chiefly employed for bituminous coals, the fuel is supported entirely by a thick bed of ashes, which serves to distribute the air supply from the twyers. No grate, in the ordinary sense, is usual for such fuels; the trouble likely to arise with the large amount of ash and clinker in a large producer is against the employment of a grate. The bottom of the producer extends into a circular pit containing water, which thus forms a seal, yet permits the removal of ash and clinker at any point without interference with the working. The Mason producer, shown in Fig. 38, is a good example of this type.

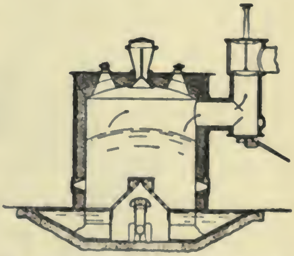

Fig. 38.—Mason gas producer.

In the Mond producer, the same arrangement of supporting the fuel bed on the ash already formed is adopted, but here, in place of the blast being introduced around the centre, an exterior sloping "grate" attached to the lower sections of the producer extends right round the upper portions of the ash heap. A similar arrangement is illustrated in the Alma producer, Fig. 39, designed by Bone and Wheeler.

This producer embodies the improvements suggested by Professor Bone's experience in the series of extensive tests carried out in conjunction with Mr. Wheeler. Distribution of the blast with such a pattern "grate" is very perfect, and large volumes of air can be introduced with very even distribution, giving high rate of gasification and preventing zones of excessively high temperature developing. The clearing of such a grate from clinker, etc., is a more simple matter than with one of the internal pattern, and bars may be renewed at any time, since they are easily accessible.

Smaller types of producers usually are fitted with grates which actually support the fuel bed and are of the closed bottom type, the blast being sent into the ash pit and so up through the grate. Suction producers are almost invariably of the closed bottom type, fitted with a grate. The layer of ash and clinker collecting on the grate serves to protect it from excessive heating, since the zone of intense combustion is thereby raised some inches. In many types the grate is operated mechanically at intervals to permit clearing. Simplicity in action is required in such a case, for at high temperatures something may go wrong, and there is always liability to jambing with a piece of clinker. The area of the grate should be equal to, or but little less than, the cross-section of the body of the producer. Too small an area produces high blast velocity immediately above the grate, developing excessive temperature, which may lead to trouble in operating.

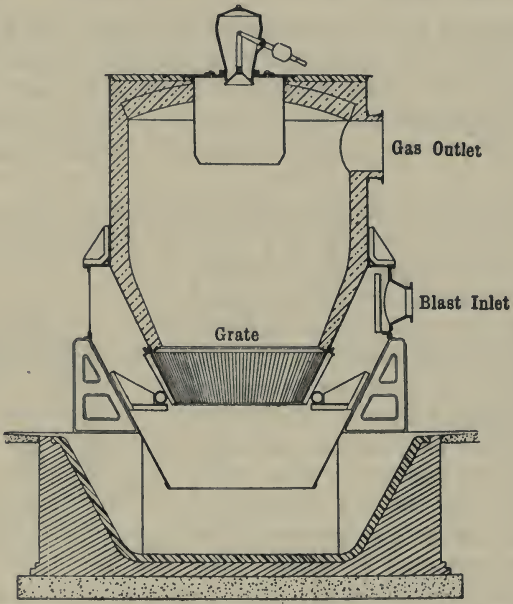

FIG. 39.—Alma gas producer.

W. L. Case (*J. S. C. I.*, 1905, 594) discusses the conditions which a producer should fulfil. Summarized these are: uniform feed to preserve uniform depth of fuel, a considerable fuel depth to ensure uniform gas and complete gasification, means to maintain a loose fuel bed and prevent packing, and ash bed of sufficient depth to prevent loss of good fuel and of internal heat, means for removal of ashes without disturbing detrimentally the fuel bed, lastly, uniform distribution of the air-steam blast throughout the whole fuel bed.

In considering these points briefly, it may be stated first that whilst mechanically-operated feeds offer theoretical advantages it is seldom that they are employed. The considerable fuel depth mentioned has been shown already to be unnecessary, providing a depth of some 3 ft. 6 in. is maintained, even with a rapid rate of gasification. The maintenance of a good ash layer above the blast inlet allows any unconsumed carbon to be utilized; the sensible heat in the ashes is taken through the producer by the blast, the ashes aiding in distribution. Condensation of steam is said to be possible with excessive ash, but the working conditions would have to be very exceptional, if the temperature of the ashes was reduced sufficiently for this to occur. Continuous and regular removal of the ash and clinker must conduce evidently to steady working conditions.

As an illustration of a modern producer in which special attention has been given to most of these points and additional ones of considerable importance, the Kerpely may be taken as a good example, the most recent pattern of which is shown diagrammatically in Fig. 40.

The fuel is fed from the usual closed type of hopper, and on top of the producer gearing is mounted for operating four bent stirrers of different lengths, which rotate on their own axes, these stirrers being continuously water-cooled. In addition the whole top central portion, including the hopper, rotates slowly, and the fuel is thus broken up continuously during the stages where caking occurs. The firebrick lining does not extend round the hottest zone of the producer; here a space is formed between the inner and outer plates which is cooled by water; this prevents clinker forming and adhering to the sides, as happens so frequently. The revolving "grate" through which the air-steam blast is supplied and the means for automatic removal of the ash may be regarded as salient features in the design.

The grate consists of a single oblong and spherically shaped cone fixed *eccentrically* upon the revolving water trough. The cone is built up of a number of plates, through suitable holes in which the air-steam passes. By the situation of the holes and the revolution of the grate even distribution of the blast takes place, but a very important further control is introduced. In ordinary types of producer, variation in the air-steam pressure is possible only as a whole. In the Kerpely producer the air-steam pressure to the centre portion of the grate can be varied as compared with the exterior portion. In the case of a large producer, should the outer zones reach a higher temperature, with a cooler middle zone, the outer pressure may be reduced and the inner raised until uniform temperature is attained.

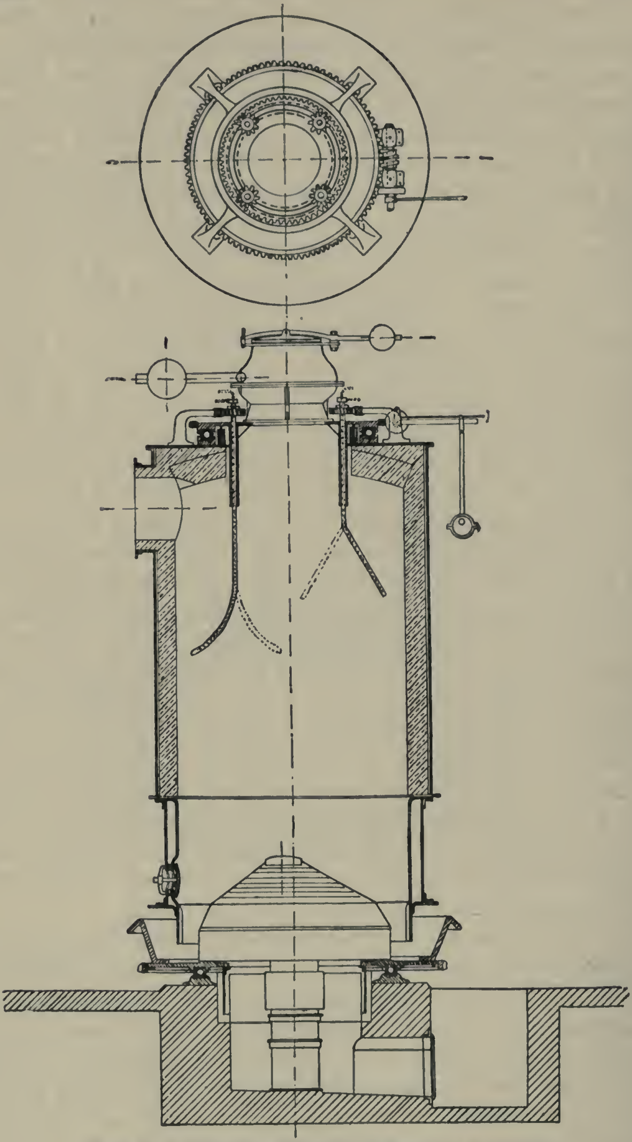

FIG. 40.—Sectional diagram of Kerpely producer.

The iron water trough carrying the grate is mounted on a ball race and is rotated slowly during working, one revolution in from 2½ to 4 hours. The eccentric position of the grate and its oblong shape act in crushing down against the lower fixed plates of the producer any lumps of clinker which have formed, so that it passes freely into the rotating trough, where by means of a scraper it is discharged automatically.

Removal and Destruction of Tar.—For engine work the gas has to be delivered cool and with only minute traces of suspended tar, otherwise trouble is experienced with valves, etc. Two methods of dealing with the tar are open: first, its removal from the gas, and, second, its destruction in the producer. For the first the necessary plant will depend on the character of the fuel used. For anthracite, a simple coke scrubber through which water is sprayed is sufficient, and because of the ease with which clean gas is obtained anthracite is employed almost universally for all smaller suction gas plants.

Ordinary coke contains less volatile matter than any fuel employed in producer practice; the amount will be dependent on the temperature of carbonization. A highly-carbonized coke may still contain 1·5–2 per cent. of tarry matter, and this of totally different character to that in anthracite. Although present only to the extent of one-fifth of that in anthracite its complete removal is more difficult, and should such tar get to the engine is much more troublesome than tar from raw fuel.

Sufficient attention has not been paid to the different character of the tar from different fuels. The writer has seen gas from wood, which was like moderately dense smoke, used successfully in engines, with valves properly shielded from direct tar deposition. In other cases the slightest visible trace of some tar vapours gives rise to trouble. The tar from coke is the ultimate result of heat up to the highest temperature reached in carbonization upon the volatile matter of the fuel. It must partake closely of the character of the hard pitch left when tar itself is distilled, and offers great resistance to destruction by further heat and removal by ordinary methods of water-scrubbing; should it deposit on a valve it quickly hardens and causes the valve to stick. In all plants where coke is employed a sawdust scrubber is introduced between the coke scrubber and the gas box.

Water forms the most convenient medium for cooling the gas, and cooling and tar removal in smaller plants usually take place simultaneously, by the use of coke scrubbers through which the water passes. The cleansing effect probably is due principally to constant change in direction of the flow of the gas by the irregular coke surface, and the tar already deposited in the coke plays an important part in removing further particles of tar. In the coke scrubber, at least, the action is not a filtering one, as is often supposed.

Water and tar do not mix, and have no appreciable solvent action on each other, and therefore, although generally used because of its great advantage of supply and cost, water is really a most unsuitable liquid for the purpose.

Particular attention may be directed to the patents of Chevalet, in which coal tar oils are employed. He has shown that heavy paraffin oils will collect the particles only mechanically, but that creosote and anthracene oils effect a solution of the tar, and the invention covers all oils from coal tar boiling above 150° C. (302° F.), preference being given to anthracene oil boiling between 250–400° C. (482–750° F.).

Tar itself then may certainly be regarded as a most important factor in removing further tar from the gas, and surfaces flooded with tar, against which the gases are forced continuously into contact, are very efficient. Water would appear to be actually derogatory to the cleansing effect beyond its action in mere condensation.

Many gas plants in which the ordinary coke scrubber is insufficient are provided with a tar extractor, in which constant change of direction of the gas current is caused by means of suitable baffles. In Fig. 41 the National tar extractor is illustrated; the gas impinges on plates carrying a series of flanges, and finally passes through a sawdust scrubber.

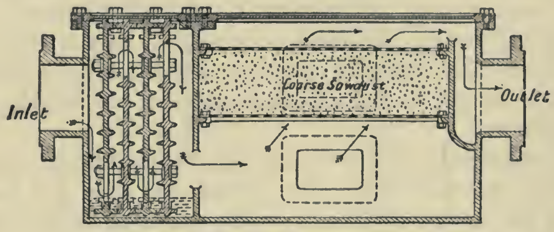

Fig. 41.—National tar extractor.

In large plants working on bituminous fuels, the gas is cooled either by sending it through horizontal chambers in which rotating paddles dash water continually up into the gas, as in the Mond and Crossley plants, Figs. 46 and 47, or by passing through cylindrical air-cooled towers, as in the Mason plant, Fig. 44, Wilson plant and others. In each case the bulk of the tar will be deposited, but the gas requires further treatment to remove the finer suspended tar particles.

Air-cooling would appear to have advantages over water-cooling. Bearing in mind the behaviour of hot liquids saturated with a crystallizable salt, rapid cooling precipitates the material in a finely divided state, slower cooling in a coarser crystalline condition. A gas rapidly chilled will deposit its tar as a fine fog; slowly cooled, as heavier globules, far more easily deposited or removed. Again, in the former the tar is very wet and more difficult to remove in later appliances than is dry tar, and the collection of the tar in a state fit for sale or burning under boilers is much simplified by the dry process. Where provision of the necessary water offers difficulties, the advantages of air-cooling are apparent, and although the first cost is usually higher, the water consumption for cleansing purposes is well below half that in the "wet" process, even where the water is employed over again. Air-cooled plants appear to be finding increased favour for these reasons.

The removal of the remaining tar fog, after the gas has passed the usual scrubbers, washers or cooling towers, is effected by either static or mechanically operated appliances. Static washers, of the Livesey type, which are employed in gasworks, cause the gas to pass in a large number of fine streams through water and the layer of tar collected on the surface. In Prof. Burstall's static washer capable of dealing with 50,000 cub. ft. of gas per hour, a large number of wires, fixed only at their upper ends, are suspended in a rectangular tank 3 ft. 4 ins. in depth at the inlet end, 3 ft. 7 ins. deep at the outer end, with a dished bottom. The wires are fixed in sections carrying 58 and 59 wires alternately, so that a wire in one section is in line with a gap between the two wires in the sections before and behind it. There are 117 sections, so that the total number of wires is approximately 6780. Water is forced against the top of the wires from transverse pipes through $\frac{1}{16}$-in. holes at $\frac{1}{4}$ in. pitch. Gas passing through the washer is thus bound to come into efficient contact with the wet wires.

Prof. Burstall's centrifugal extractor is constructed also with wires. The 30,000 cub. ft. per hour apparatus carries a 24-inch wire rotor running at 1800 revolutions per minute, requiring about 5 H.P. to operate it. The gas enters the casing near the centre and leaves at the outside, thus coming into intimate contact with the wires revolving at high speed, the wires being covered already with a thin tar film. The extractor can be worked dry, but it is stated to be desirable to inject a small quantity of water to assist in cleaning the wires. The extractor is very compact, and one has been in continual use at Birmingham University since 1907, passing 30,000 cub. ft. per hour, the extractor being 19 ins. in diameter. While the extractor is in use the gas does not pass through any final sawdust scrubbers, as is the usual practice.

The well-known Crossley fan extractor is shown in Fig. 42. The gas is directed to the centre of the fan on the inlet side and can pass to the exit only by travelling outwards on the inlet side of the casing and back to the centre exit to the outlet pipe. Water is sent through the extractor, and this with the separated tar is thrown against the casing, to drain finally to the tar sumph.

A form of static tar extractor, which has extensive use in coal gas practice especially on the Continent, is the Pelouze and Audouin's extractor. The principle is that of sudden change of direction of flow of small streams of gas issuing from round holes in one series of plates, and which impinge on plates correspondingly slotted, where tar from gas previously passed through takes up the fine globules from the fresh gas.

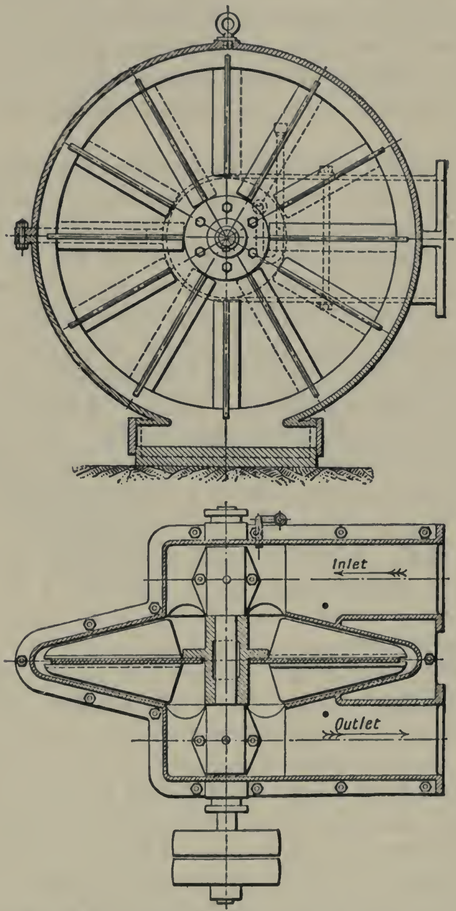

FIG. 42.—Crossley centrifugal tar extractor.

Clayton and Skirrow (see *J. Gas Ltg.*, 1907, 98, 660) investigated the efficiency of extractors of different types on coal gas. After condensation, and before any special treatment for removal of tar fog, coal gas showed from 3–25 grams of tar per 100 cub. ft. The Livesey washer removed from 85–88 per cent.; the Pelouze-Audouin apparatus, when the differential pressure between the inlet and outlet was 2 ins., 97–99 per cent., but the efficiency fell rapidly with lower differential pressure, *i.e.* when the speed of the gas through the orifices was reduced. With producer gas the cage became clogged too rapidly. Experiments were also made on producer gas with a Crossley fan extractor, capable of dealing with about 200,000 cub. ft. per hour, but operating much below this capacity. Here, with a gas temperature of 84° F., passing 50,000 cub. ft. per hour, the purification was 97·4 per cent. at the same temperature, and with 100,000 cub. ft. of gas per hour, it was 93·9 per cent.

Gasification of the Tar.—Much attention has been paid to this question, the obvious advantages of converting the tar into permanent gas, thereby adding its calorific value to the gas, and theoretically, but by no means practically, rendering further scrubbing and cleaning unnecessary, are apparent. It may be stated approximately that 1 ton of bituminous coal will yield at least from 11–12 gallons of tar; about 6 per cent. by weight of the coal, and with a calorific value of 15,800 B.Th.U., the tar carries about 8 per cent. of the calorific value of the coal, but it must be remembered that this tar, when separated, has a commercial value of 14*s*. to 18*s*. per ton, and is frequently burned with every success by a suitable atomiser under boilers.

For large power plants gasification of tar is seldom attempted, but for smaller pressure plants and especially for suction plants for bituminous fuels, innumerable patent specifications have been filed.

Destruction of the tar may be of one of the two methods :—

(*a*)Simple distillation through hot zones in the producer.

(*b*) Distillation with partial admission of air so that the tar vapours may be burnt to carbon monoxide (or dioxide) and water, these products passing through high temperature zones again.

In the first system the gas and vapours distilling from the raw fuel are either caused to pass down through the upper layers of the hot fuel bed by suitable internal construction of the producer, or they are drawn off through suitably located pipes by means of steam injectors, and returned to the producer at the zone of most intense heat. Interesting diagrams may be drawn in specifications showing the path the gases should travel, but it is doubtful whether they behave as intended by the inventor. The proper adjustment of the pressure conditions for this must always be a matter of difficulty.

The value of the system of direct destruction by heat is very problematical, and in this connection the work of Karl Bunte should be considered carefully.

As early as 1845 Bunsen and Playfair showed that, with a bituminous coal, there was very little difference in the amount of tar collected (*a*) when the distillation products passed through a length of cold fuel; or (*b*) when they were forced to travel through a considerable length of red-hot fuel; *i.e.*, there appeared to be very little destructive action on the *tar*.

The economy which would result in ordinary coal-gas making if tar could be converted easily into illuminating gas, did not escape the attention of gas engineers, but such attempts were not successful. Karl Bunte (*J. Gas Ltg.*, 1910, **110**, 957) points out that tar is composed mainly of pyrogenous products formed at the high temperature of the retorts, containing only a small proportion of the coal constituents in an unaltered (or slightly changed) condition, and that possibly these are the only bodies capable of destruction at a high temperature, those portions which have resulted already from high temperature reactions being capable of decomposition only at much higher temperatures than those existing at the time of their formation.

Bunte distilled two tons of coke breeze saturated with one ton of dry tar at a temperature of 1050° C., and found the ton of tar yielded 11,580 cub. ft. of gas of 470 B.Th.U. per cub. ft., equal to 15 per cent. *only* of the calorific value of the tar; the tar coke accounted for 57 per cent. of the calorific value (which would be recoverable in producer gas working), but of particular importance is the fact that the hydraulic main became blocked with a substance having the appearance of axle grease, and equal to 24 per cent. of the tar.

In the second method the distinctive difference is in the combustion of tarry vapours by air; if this is complete it should yield nothing but carbon dioxide and steam. On these products again passing through the incandescent fuel bed, the carbon dioxide will be converted into the monoxide and the steam will give the usual water-gas reaction.

This method has worked well in a number of producers of different design. In many there is an underfeed of raw fuel to the producer, but many factors militate against the working of such appliances. In some cases a worm feed has been tried; Farnha has proposed a producer the grate of which can be raised 18 ins.; when a good coke fire is established, a plate is pushed in to hold the fuel bed up, the grate then lowered, and the intervening space filled up with bituminous coal. Such a method would appear to lead to interruption of the regular working of the plant.

In other plants steam injectors draw off the gases and vapours, returning them below the grate so that they are carried up through the incandescent fuel by the blast. Double producers have, on the whole, met with most success; the first producer in which the fresh fuel has been charged, undergoes the usual bottom to top blow, the gases produced by the blast together with the tarry vapours being carried off at the top. Here a second supply of air is admitted, and the mixture passes downwards through the second producer which is at a high temperature from the preceding bottom to top blow.

The natural development was to combine the reactions in the one producer, drawing the final gases off at a point well below the top of the fuel bed, where the temperature is fairly high, and admitting air at the upper part of the producer so that it carries down with it the tarry vapours through the upper hot fuel zones. As the coked fuel reaches the lower sections, it is gasified by the usual air-steam blast admitted at the bottom. It is clear that success will be dependent largely on the proper proportioning of the two air supplies to fulfil the conditions simultaneously of maintaining the zone above the gas outlet at a suitable temperature, of giving good gas, and properly gasifying the tar. The Dowson Suction gas plant for bituminous fuels (Fig. 53) is a good illustration of this type.

Electrical Separation of Tar.—In view of the work of Sir Oliver Lodge and others on the dispersal of fog by high-tension electrical discharges, which act on a small scale in a wonderful manner, the experiments of White, Hacker and Steere (*J. Gas Ltg.*, 1912, **119**, 825) on the application of such discharges to tar fog are most important. These experimenters treated gas at temperatures from 24–68·5° C. (75–150° F.), and found the elimination of the tar so complete that the gas appeared perfectly colourless and left only a faint brown stain on a piece of filter paper through which a cubic foot of the gas had been drawn. In one case the small separator operated continuously for 5 hours, dealing with the gas from 400 lbs. of coal (say, 2000 cub. ft.); the ordinary condensers separated 12·8 lbs. of tar and 12·2 lbs. of water, the electric separator afterwards throwing down 17·7 lbs. of tar and 2·8 lbs. of water.

W. McD. Mackey (*J. S. C. I.*, 1913, 523) proposes testing the liability of fuels to give tarry deposits on valves in the following manner. Three grammes of the powdered fuel are placed in a platinum crucible, 1½ in. high, 1⅝ in. diameter at top and 1 in. at bottom. The top is closed by a 4-in. clock glass, containing 20 c.c. of water. The crucible is supported by asbestos board, the bottom projecting through a suitable hole, and is heated by the bunsen flame for seven minutes, the crucible bottom being just above the top of the inner cone. With a good fuel no tarry deposit is found, only a whitish powder or stain on the glass; a bad fuel gives a distinct tarry deposit.

Determination of the Yield of Gas and Efficiency.—The practical determination of the yield of gas by direct measurement offers considerable difficulty. The subject has been discussed very fully, and a description given of various methods tested, by Mr. R. Thelfall (*J. S. C. I.*, 1907, 355). The most generally convenient way is from a determination of the total carbon in the gases, deduced from their analyses. The following example will make the method clear.

Coal (brown) employed—contained 57·7 per cent. carbon.

Composition of the gases—

Carbon dioxide	2·8
Carbon monoxide	30·5
Methane	2·0

Hydrogen, nitrogen, etc., need not be considered, but only those constituents containing carbon.

The volumes first are converted into weight by multiplying by the weight of 1 cub. ft. of each gas in lbs. (see Table I., Appendix)—

	Volume in cub. ft.		Weight of 1 cub. ft. in lbs.		Weight in cub. ft. (lbs.)
Carbon dioxide	2·8	×	0·1234	=	0·3455
Carbon monoxide	30·5	×	0·0781	=	2·3820
Methane	2·0	×	0·0447	=	0·0894

From the composition of these gases, 44 lbs. carbon dioxide contain 12 lbs. carbon; 28 lbs. carbon monoxide contain 12 lbs. carbon; and 16 lbs. methane contain 12 lbs. carbon; then—

	Lbs. of carbon in gas.
Carbon dioxide	$0·3455 \times \frac{12}{44} = 0·0942$
Carbon monoxide	$2·3820 \times \frac{12}{28} = 1·0210$
Methane	$0·0894 \times \frac{12}{16} = 0·0670$
Total weight of carbon in 100 cub. ft. gases	1·1822 lbs.

As 1 lb. of fuel charged contains 0·577 lb. of carbon.

Yield of gas per lb. of fuel $= \frac{0·577 \times 100}{1·1822} = 48·8$ cub. ft., and per ton 48·8 × 2240 = 109,000 cub. ft.

The *efficiency* of a gas producer plant will be found from the ratio of the heat units in the gas to those in the fuel charged.

The *cold gas* efficiency would be obtained from the calorific value and volume at 0° C. and 760 mm. In the *hot gas* efficiency it would be necessary to add to this value the sensible heat of the gases as delivered to the furnace, reheaters, etc., deducing this from their weight and mean specific heat. In the case considered above the cold gas efficiency would be—

Calorific value of gas (net) per lb. of fuel = 48·8 × 159 = 7760 B.Th.U.
„ „ 1 lb. of fuel = 9720 B.Th.U.

$$\text{Efficiency} = \frac{7760}{9720} \times 100 = 80 \text{ per cent.}$$

Professor Bone claims that the *net* calorific value of the gas should be taken, and that the coal required for raising any steam for the blast and for operating the blower, together with fuel required equivalent to the mechanical work of washing the gas, should be included, that is, an over-all efficiency.

The approximate rating in B.H.P. of a producer plant is given by—

$$\text{B.H.P.} = \text{tons gasified in 24 hours} \times 100.$$

Volume of Air for Combustion of Gases.—It is important to know the theoretical volume of air required for the combustion of the different gaseous fuels, both the theoretical and the amount general in practice. In conjunction with the thermal value of the gas it is possible to compute the calorific value per cub. ft. of the mixture entering the gas engine cylinder. These data are given for different fuels in Table XXXIX., p. 185.

An important point is at once established, namely, that in spite of the big difference in calorific value between the rich and poor gaseous fuels, the mixture with the amount of air required in practice will give a higher calorific value with the producer gases than with richer coal and coke-oven gas.

Pre-ignition of the Charge.—The cause of this trouble in gas-engine practice, due to the charge firing prematurely on compression, is to be sought in the composition of the charge to the cylinder and the ignition point of the gases, providing that the construction of the cylinder is good, being free from projections which may become overheated and cause ignition.

It is well known that high initial compression in the cylinder means both higher thermal and cyclic efficiency, and the safe limit of compression is that below which pre-ignition is unlikely to occur.

Pre-ignition is accounted for generally by a high percentage of hydrogen in the gas, the hydrogen having an ignition point some 60–70° below that of carbon monoxide, for it is well known that with gases containing mainly carbon monoxide and but little hydrogen, as with blast furnace gas, compression may be carried safely to a much higher point than with coal gas.

The following average figures for the safe limit of compression, as given by Lucke, illustrate this point:—

	Coal gas.	Producer gas.	Blast furnace gas.	Petrol.
Compression pressure lbs. by gauge	80	135	155	65
% clearance in terms of piston displacement .	26	20	17	35

It is by no means established that hydrogen is *per se* the cause of pre-ignition, for although it is certainly one of the principal constituents of gaseous fuels which will not stand high compression, the actual percentage in the undiluted gas can influence only the quantity present in the final air-gas mixture, and it is the *composition of the mixture* which should receive attention. Taking the data given in Table XXXIX., the percentage of hydrogen in the charge with different gases, etc., will be—

	Coal and coke-oven gas.	Producer gas.		Blast furnace gas.
		Ammonia recovery.	Non-recovery.	
Air in practice to 1 vol. of gas	8·0	1·25	1·25	1·0
H_2 in original gas . .	50·0	25·0	12·0	1·0
H_2 in charge	5·3	11·0	5·5	0·5

The coal gas and non-recovery producer gas mixtures with air carry about the same percentage of hydrogen; it is nearly twice as great in gas where ammonia recovery is practised. The obvious inference is that hydrogen plays only a minor part, if any, in causing pre-ignition, and that some other constituents occurring in gases which happen to be rich in hydrogen are primarily responsible. Seeking for an obvious difference in composition, the writer believes that the presence of unsaturated hydrocarbons, especially acetylene, may be the factor chiefly concerned. From the table of ignition points by Dixon and Coward (p. 5) it will be seen that ethylene ignites 40° C. lower than hydrogen, whilst acetylene *may* ignite 175° C. below, and the least difference between their ignition points is 140° C.

CHAPTER XV

PRODUCER GAS PLANTS

TYPICAL PRESSURE PRODUCER GAS PLANTS

Non-bituminous Fuel.—The *National* Plant is illustrated in Fig. 43. The producer is of the closed bottom type with grate and is arranged in a pit, so that charging is a simple operation. The steam injector is of the annular pattern, with both air and steam adjustable. The gas passes first through the inverted U tube, where some cooling and tar deposition take place, then through a pair of coke scrubbers with water sprinklers at the top. The gas, leaving these and containing only a small amount of tar fog, passes through a tar separator of the pattern illustrated in Fig. 41, p. 244, and finally into the gasholder. When the plant is running on fair loads automatic control of the steam injection, and consequently of the air supply and gas make, is made by a cut-off actuated by the rising of the holder, as indicated by the broken line running from the framework of the holder to a valve on the steam supply pipe.

Bituminous Fuel Plant (non-recovery).—The *Mason* plant,[1] illustrated in Fig. 44. is a good example of this type of plant, in which atmospheric coolers are employed. The producers B are of the type shown in Fig. 38. Each producer is carried on four brick pillars and has the usual water-sealed bottom. A supply hopper P is arranged over each, to these hoppers fuel is carried by an elevator and conveyor O. The air blast is supplied by a Roots blower A.

The gas passes first into a dust catcher C, then through the atmospheric coolers D in series to the coke scrubber E, through which water is sprayed. The remaining tar fog has now to be removed by the washing fans F, and after traversing a dash-box passes through sawdust scrubbers H to the holder K.

Ammonia Recovery Plant.—Reference has been made already to the general principle on which ammonia recovery is based and the

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[1] This particular type of plant is no longer manufactured by the Dowson & Mason Gas Plant Co. In the most recent plant air-cooling by means of numerous vertical iron condenser tubes is employed, in conjunction with the Moore Water-Jacket Producer.

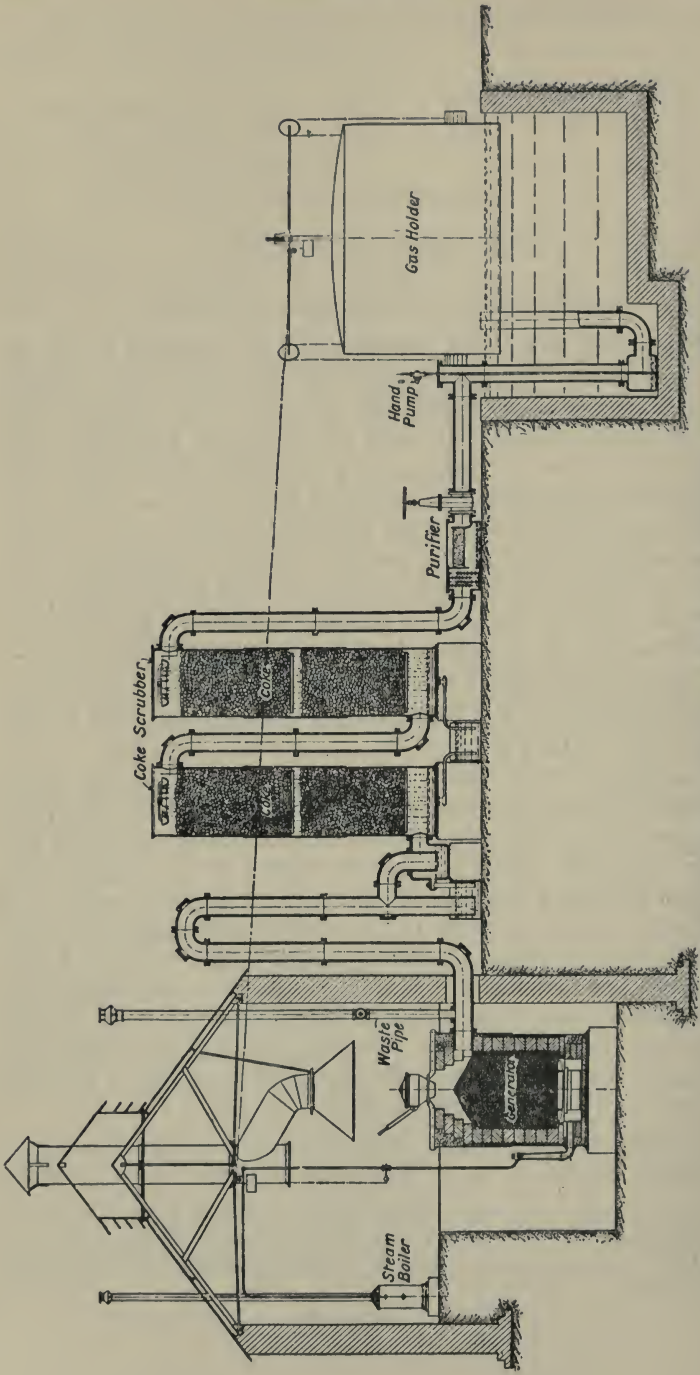

FIG. 43.—National pressure gas plant for non-bituminous fuels.

necessity for keeping down the temperature in the producer by means of excess steam, in order to ensure a good percentage of the nitrogen of the fuel appearing as ammonium sulphate. It has been pointed out also that, for economic working, the latent and sensible heat in the undecomposed steam must be returned in some way to the system, which necessitates additions to the plant beyond those required in non-recovery plant.

The successful introduction of ammonia recovery into producer gas practice was due to the scientific skill and enterprise of Dr. Ludwig Mond, F.R.S. In 1879 Dr. Mond put up his first experimental plant for converting cheap bituminous fuels into fuel gases and the recovery of the valuable by-products. After many years' experimenting the well-known Mond recovery plant was established on a firm basis, and has been employed on a very large scale. An extensive plant for the generation and distribution of the gas over a large area in the Midlands has been in operation for some years, and it was anticipated that other large districts would be supplied ultimately with cheap fuel for heating and power purposes, but the cost of distribution of a gas containing so large a percentage of

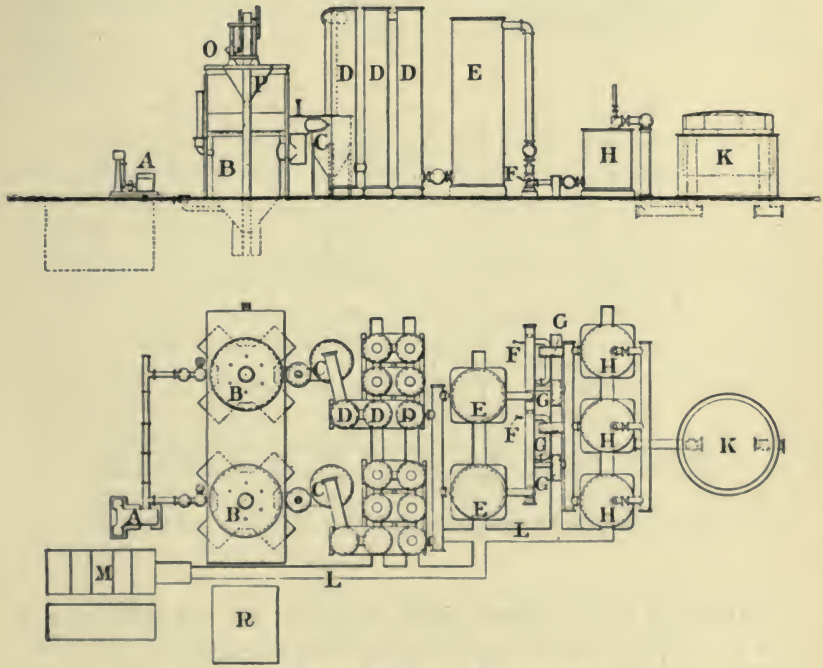

Fig. 44.—Mason bituminous fuel gas plant.

inert gas must militate always against economical transmission over long distances.

The production of ammonium sulphate from coal is a most important consideration, both from the point of view of the considerable monetary value, which may be set off against the first cost of the fuel, and from the national point in relation to the supply of sulphate for agricultural purposes. The great increase in the production of ammonium sulphate in recent years is illustrated in Fig. 45. It will be seen that the greatest increase has been due to coke-oven plants, and this in a measure indicates the progress in substituting recovery plant for the old wasteful types of plant.

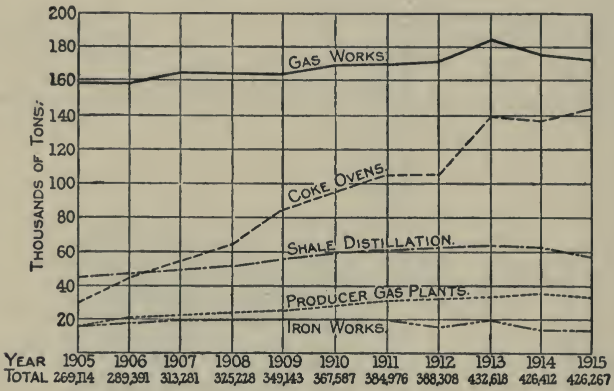

FIG. 45.—Diagram of progress in production of ammonium sulphate.

Although in some cases yields of 90–100 lbs. are obtained per ton of coal, this would be over-estimating the production for the bulk of English coals. The cost of production must vary with the type of plant, but, according to Andrews and Porter, one ton of sulphuric acid at 30*s.* is required per ton of sulphate, bags are estimated to cost 5*s.* per ton, and extra cost of handling 1*s.* 6*d.* The net value per lb., allowing for cost of acid and all manufacturing expenses, will be from 0·8 to 1*d.*, so that a yield of 90 lbs. per ton of fuel gasified would effect a net saving of 6*s.* per ton on the fuel. With slacks suitable for such producers frequently costing but little more than this in favoured districts, the statement that fuel will cost nothing is not so incredible as at first sight it appears, when capital charges and the extra cost of operating the whole gas plant are not considered.

The general experience with the earlier type of recovery plant of the Mond pattern was that recovery did not pay for a rating of less than 2000 H.P. and at a good load factor. Mr. A. Rollaston, in a paper on Mond gas in the early days of its introduction, said, "If the quantity of fuel to be gasified does not amount to 30 tons per day, and the necessary exhaust steam or vapour beyond that recovered from the gas-cooling tower is not available, the sulphate recovery and evaporating plant are better dispensed with." Two hundred tons gasified per week was another way of expressing the lower limit for the older type plant, but with the more modern and less costly plant of the type introduced by Messrs. Crossley and Mr. Rigby, it is claimed that recovery pays with little over 100 tons gasified weekly.

Recovery Plant of Mond Type (Fig. 46).—The gas generated in the producer A passes first into the superheater B, thence into the washer C, where, by division into suitable chambers in which rotating paddles are operating, the gas is cooled and much tar removed. Ammonia absorption is accomplished in the acid tower D, the liquor collecting at the bottom of which passes into the tank E, and is pumped back to the tank at the top of the tower by a small pump. Additions of fresh acid are made from time to time, as from 3 to 4 per cent. of free acid must be present for proper absorption of the ammonia.

In the washing tank the sensible heat of the gas has been converted largely into latent heat, carried by the water-saturated gas. After the ammonia separator comes a gas-cooling tower F, where the heat is abstracted by water supplied from the tank at the top, to be returned to the system later.

From the tower F the gas passes to the works; if for heating purposes it requires no further treatment; for power purposes the remaining tar fog and moisture must be removed by suitable rotary or static tar extractors, etc.

A most important point is to trace the system by which the heat units in the gas are recovered. As shown, the water in the cooling tower F abstracts the heat, and the hot water flows through the tank G and is sent up by a pump to the top of third tower—the air-saturating tower K. Through this tower the air blast is forced by the blower M shown on the extreme right, and is met by the descending current of hot water, which, after giving to the in-going air the bulk of its heat in the steam, is sent once again through F. The air blast, more or less saturated with water vapour, is sent through a main (shown at the top of the diagram, to avoid confusion)

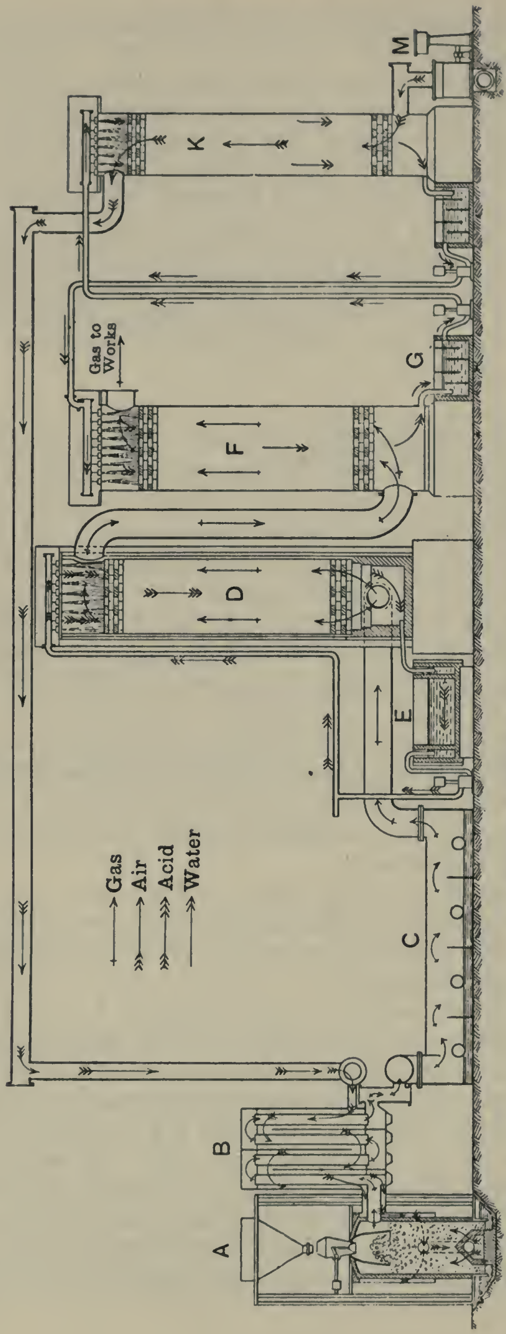

FIG. 46.—Mond-type ammonia recovery plant.

to the superheater B, additional steam being added if the saturation is not sufficient. In the superheater the blast takes up much heat from the issuing gases, and before entering the producer usually passes through an annular space round the producer itself.

The Crossley Recovery Plant.—The outstanding difference between the older ammonia recovery plant and that constructed under Messrs. Crossley and Rigby's patents is the reduction in the number, or total abolition of, cooling towers. This has led to a very considerable reduction in the first cost of the plant. The first type of recovery plant had one tower only, the air saturation tower. In the latest plant no tower at all is employed.

The general arrangement will be followed from Fig. 47. The gas passes from the producer A through suitable dust catchers to the superheater B, and from here into the washer-condenser, in the first sections of which C water is kept circulating and sprayed up into the gas by paddles revolving at high speed, so that the gas is cooled, remaining dust removed and the heavier proportions of the tar.

The ammonia absorption takes place in the subsequent sections DD. Instead of containing water, however, these contain a weak solution of sulphuric acid. The gas in passing through this washer comes into intimate contact with a spray of acid, and by this means the ammonia gas is absorbed. Fresh acid is added as the absorption of ammonia goes on, care being taken that the excess of free acid does not exceed 0·5 per cent. By this means the specific gravity of the sulphate liquor gradually increases until it reaches about 1·15, which is equivalent to 26 per cent. sulphate of ammonia.

While the absorption is going on the sensible heat still carried by the gases maintains the temperature of the sulphate liquor at about 80° C.

The hot sulphate liquor is sent into another and similar washer, the air-saturating chamber E, shown above the washer-condenser, for clearness, through which the cold air from the blower M is being passed. The hot liquor is sprayed by means of paddles into the cold air, when an interchange of heat takes place, the air being heated and saturated with steam to a temperature of about 60° C, and the hot liquor is cooled down to about 40° C. The liquor is then pumped back again into the ammonia absorber, the whole operation forming a continuous cycle of interchange of heat. The volume of the sulphate liquor is increased gradually by condensation of steam in the gas and the addition of acid, etc., and periodically a corresponding volume of liquor is run off into settling tanks, the light tar oils skimmed off, and then pumped by injector into the tank G supplying the evaporator F.

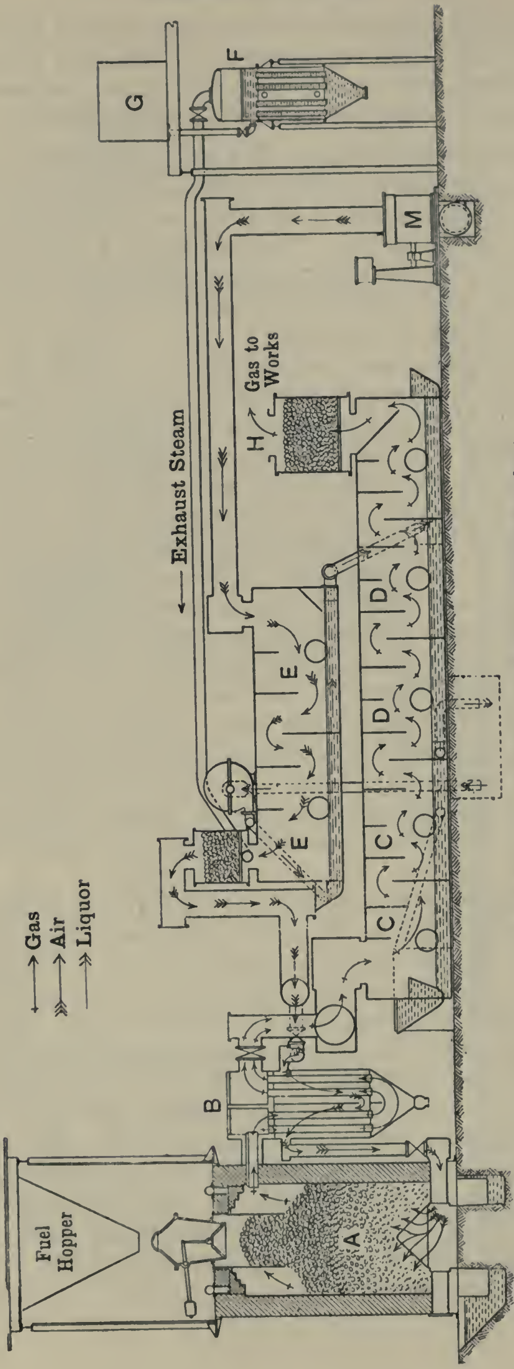

FIG. 47.—Crossley improved ammonia recovery plant.

Evaporators.—The evaporator is fitted with copper tubes and end plates. Steam is admitted, and the liquor evaporated until its boiling point reaches 110° C. under a pressure of 1·05 Kg. per sq. m. Fresh liquor is pumped in to make up for the loss due to evaporation. The exhaust steam from the evaporator and the steam from the boiling liquor are carried away by a special main into the air-saturator or blown to waste, as desired.

When the liquor is concentrated sufficiently as above, it is run out into lead-lined crystallizing tanks and allowed to cool.

The gas issuing at H requires further treatment for the removal of remaining traces of tar, if it is to be used in gas engines.

It will be seen that the recovery of the latent heat from the steam in the gas after passing through the water washer, much of which latent heat is derived from the sensible heat of the gas passing in, by the evaporation of the water, is returned to the system through the medium of the sulphate liquor, which itself becomes concentrated by evaporation.

The yield of gas per ton of bituminous fuel gasified for ammonia recovery is usually from 140,000–150,000 cub. ft.; and its calorific value 135–140 B.Th.U. On a basis of 145,000 cub. ft. at the lowest thermal value, the heat units per ton gasified would be 19,600,000; then as 1 B.H.P. hour can be obtained readily from 9,800 B.Th.U., a 2000 H.P. plant will require to gasify the fuel at the rate of 1 ton per hour.

No difficulty is experienced in the even distribution of fuel of fairly uniform size, such as washed nuts, in a producer, but with cheaper low-grade fuels, in which there is generally a considerable proportion of dust and fine coal and variable size in the larger pieces, distribution through an ordinary hopper is by no means good, especially in large producers. For such fuels a double-cone arrangement of the hopper is preferable. An illustration of such a feed-hopper (Kerpely patent) is given in Fig. 48.

The outer cone A is worked by the lever B; the inner cone C by the lever D. These cones can be operated together, when the coal falls through the two simultaneously. By operating either cone independently the fuel may be dropped to the outer or inner sections of the producer, as desired.

SUCTION GAS

Once the principles of the production of power gas by the action of air, or air and steam, on carbon had been elucidated, the natural development was to employ the suction stroke of the engine for producing the necessary current of air through the producer. No more important invention from the point of view of the production of power in small and moderate sized plant has been made, and the simplicity of working, the compactness of the plant and the wonderful economy of this system, as compared with the extreme waste of fuel entailed in nearly all the small type steam engines, which suction gas plants are qualified more particularly to replace, account for the rapid advances made in the use of such plants in recent years.

Although the use of such plants was confined to non-bituminous fuels for some years, and although such fuels are still those most generally suitable, the suction plant now has reached such a high state of perfection that almost any bituminous material sufficiently rich in carbon to give good gas can be employed. Certain classes of bituminous coals, peat, wood-waste, spent tan, etc., may be cited. Indeed, in any industry where carbonaceous material is a waste product, or at present is burnt inefficiently under boilers, the possibility of its better utilization in a suction gas plant should receive consideration.

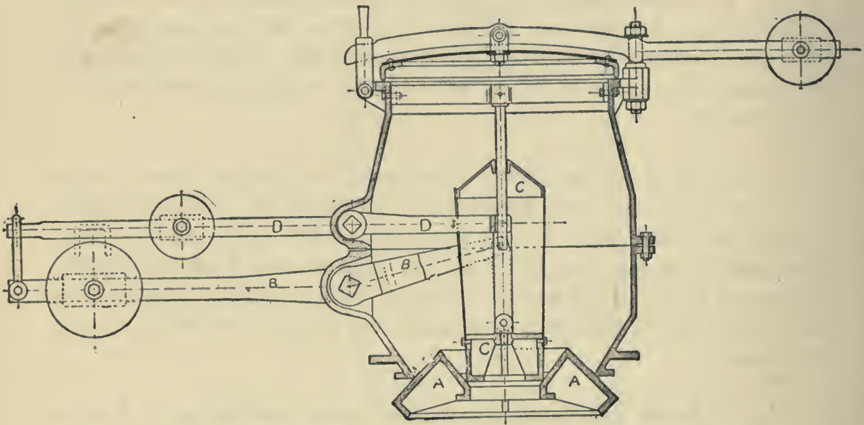

Fig. 48.—Kerpely double-cone hopper.

In the ordinary type of suction gas plant the air and steam mixture is drawn through the producer by the suction stroke of the engine. In some special plants, especially those of later date intended to deal with certain forms of bituminous fuel, a fan is employed; up to the fan the pressure is below atmospheric, and on the engine side above. In the former the actual quantity of gas to the charge is less than when gas is supplied at pressure; the volume is of course the same, and an engine supplied with gas of identically the same composition, but in the one case made in a suction plant and in the other in a pressure plant, will not develop quite the same power with the suction-made gas.

It follows that the more resistance there is to the flow of gas, either through faulty design or undue length in the gas mains, or too much resistance to flow in the scrubbers, the more difficult will it be to get maximum results with the engine.

It is not proposed to enter into detailed consideration of the construction and operation of plants of various types; for such information the reader may be referred to Mr. P. W. Robson's exceedingly practical book;[1] but to deal with the question generally, attention being directed more particularly to the principles involved.

In the suction gas plant the essential point is the maintenance of a negative pressure right through the system, from the point at which the air enters the producer up to the point where the gas passes into the engine cylinder or the fan, where employed. This entails particular attention to the tightness of all parts, especially joints, and, with one or two exceptions, the use of a closed-bottom type of producer. Leakage of air to the producer itself through cracks in the lining clearly will give rise to trouble; if in the zone of active combustion, the dry air drawn in will develop very high local temperatures and cause further trouble with the lining, and tend to produce clinker at this point; if above the fuel bed, portions of the gas will be burnt, the quality of the gas being impaired, and the gases will leave at an excessively high temperature.

For a given producer it follows that the blast velocity through the fuel bed, and consequently the active depth of fuel, will be dependent largely on the number of suction strokes the gas engine makes in a given interval of time; in other words, the make of gas is proportional to the requirements of the engine, the apparatus being thus perfectly automatic. Some qualification of this statement is necessary where there are wide and sudden variations in the the demands of the engine, that is, with very variable loads, for it is clear that the producer will be much slower in adjusting itself to altered conditions than will the engine, but this question is discussed in more detail later.

Two independent supplies of air must be provided, the one from a blower of some description, to be used in starting up the plant; the second for the supply once the plant is running, this air being aspirated through the producer by the suction stroke of the engine. The necessity for steam has been emphasized already, and the supply is arranged for by utilizing the sensible heat of the outgoing gas to vaporize water, the steam from which is picked up and carried into

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[1] "Power Gas Producers," P. W. Robson. Edward Arnold.

the producer by the air current. This arrangement is doubly economical; it reduces the temperature of the gases and obviates the necessity for an independent boiler.

The general arrangement of a typical plant with closed hearth is shown in Fig. 49. The producer B is fed with fuel from the hopper A, which must be provided with some feeding device so that the fuel may be dropped into the "container" below without the admission of air. A rotary type of feed-hopper, Fig. 50, is employed in the Crossley plants. The container must have a sufficient fuel capacity to enable it to supply the producer for about two hours, in order to avoid the necessity for frequent charging.

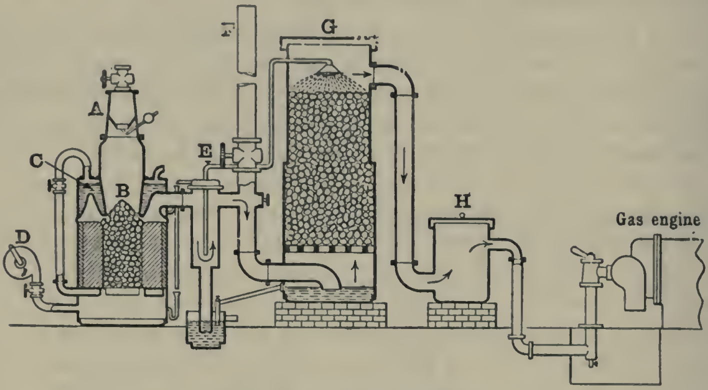


Fig. 49.—Suction gas plant.

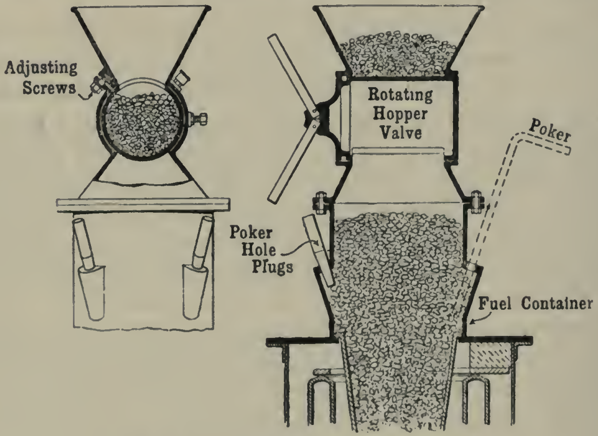


Fig. 50.—Crossley rotary feed-hopper.

Around the top of the producer the vaporizer C is situated, in this case it is of the boiler type. The air inlet is shown at the top right hand, and the steam-saturated air passes down through a pipe, with a valve, to the closed bottom of the producer. The fan for starting is shown at D. The hot gas leaving the producer passes through a vertical separator E; in some plants this is jacketed and the in-going air thus pre-heated. Here dust is deposited, and some tar condensed, which passes down into the water seal at the bottom.

The gas leaving the separator enters a vertical pipe, which extends upwards to the open air through F. When starting up the valve E is opened, so that all poorer gas may be sent to waste until a sufficiently good quality is obtained, as found by its burning at a suitably situated test cock. When running E is of course closed, the gas then passing through a water seal into the coke scrubber G. This provides all the scrubbing required when anthracite is the fuel, but when coke is employed an additional scrubber must be provided. In the Crossley plant this is fixed to the top of the coke scrubber (Fig. 51).

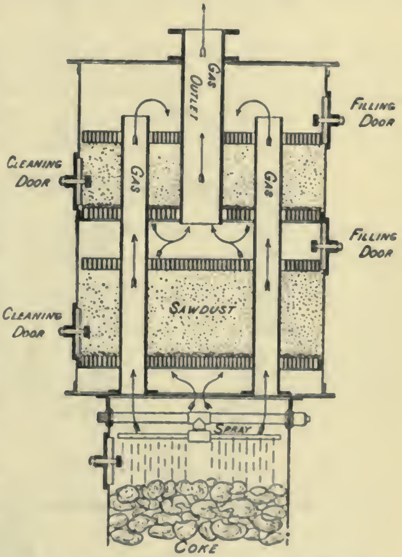


Fig. 51.—Crossley sawdust scrubber.

From the coke or sawdust scrubber the gas passes into the expansion box H, from which the piston draws the supply for the next charge into the cylinder. Generally it is regarded as desirable for the volume of the expansion box to be at least three-quarters that of the cylinder charge. The expansion box provides a supply of good gas ready to fill the cylinder in the short space of time occupied by the suction stroke, which would not be the case had it to draw directly on the pipes, coke scrubber, etc. It tends to minimize the fluctuations in flow of the gas through the whole system which must occur between successive charging strokes.

In order to determine when good gas is coming through, a test cock is placed as near the engine as is convenient, generally on the expansion box, and a further waste pipe is installed here in order that the poorer gas from the scrubbers and various connections may be swept out.

The *open hearth type* of suction plant is designed to work with small fuel of non-caking character, such as coke breeze, anthracite refuse, etc., fuels inadmissible with the ordinary grate pattern.

The Campbell open hearth plant is illustrated in Fig. 52. The points of radical difference from the preceding type are the absence of a grate, the open circular air space around the dead plate A, the vaporizer B, which forms the bottom section of the producer, the top part of which only is lined with firebrick, and the circular steam ring C, running round the extreme bottom of the producer. Ash and clinker are thus removed readily, and with the lower sections of water-cooled iron plates clinker cannot adhere. The dead plate is supported on a column which is mounted on wheels, so that it may be run out when the producer has to be emptied (D). Accessibility is a great feature of this design.

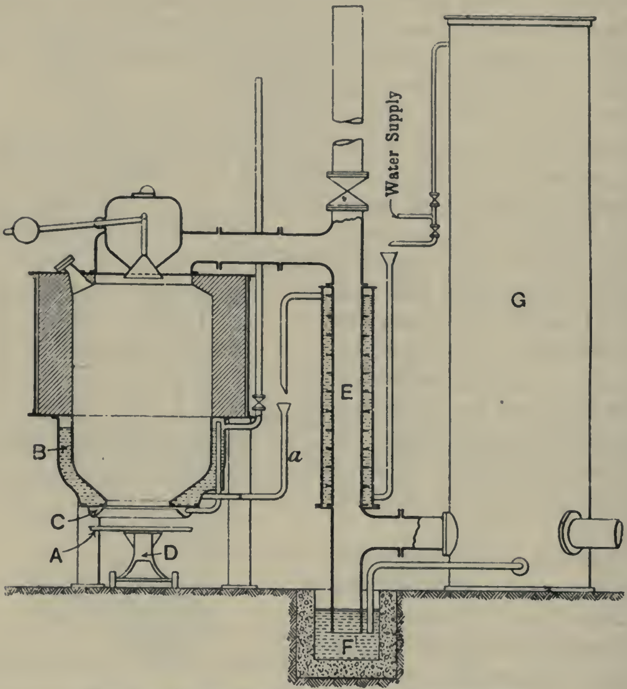


FIG. 52.—Campbell open-hearth suction plant.

A, Dead plate; B, Vaporizer; C, Steam distributing ring; D, Trolley carrying dead plate; E, Gas cooler; F, Water seal; G, Scrubber; *a*, Water supply to vaporizer.

It will be seen that the gas passes first into the separator, which is water-jacketed, the gas pipe having several flanges upon it to assist in cooling the gas. Here the water for the vaporizer becomes heated, at the same time cooling the gas, so that heat is returned to the producer. From the upper part of the vaporizer a pipe leads down to supply the steam ring situated immediately on the bottom of the vaporizer. Ample provision is made of cleaning doors to the vaporizer, so that scale, etc., from the water may be removed, as necessary.

Starting is accomplished by a fan attached to the expansion box, thus drawing the air and gas right through the system to this point, where it is sent to waste through a suitable pipe. During stand-by periods a second waste gas-pipe is provided at the top part of the separator.

For ordinary fuels cleansing of the gas is done by the usual coke scrubber. For dusty fuels a special dry scrubber may be necessary. With bituminous fuels, the tar is removed by a centrifugal extractor.

SUCTION GAS FROM BITUMINOUS FUELS

Two types of plant are in use for the production of suction gas from bituminous fuels, which may be taken to include non-caking coals, peat, wood-waste, etc. In the one, chiefly for operating with coals, tar destruction is aimed at; in the other type, which is more generally favoured, tar removal is accomplished first by the usual condensation and in scrubbers, the remaining "tar fog" being dealt with by a fan extractor situated between the scrubber and the expansion box.

Many suction producers for tar destruction have been designed; all depend on causing the distillation products from the fuel to pass through a section of the fuel bed at a much higher temperature. This portion is the one in which the coke produced by the distillation is undergoing the ordinary producer gas reactions with a steam-saturated air current. The Dowson plant is chosen for illustration of this principle because, as will be seen later, it has proved efficient in many cases over an extended period.

The plant is illustrated diagrammatically in Fig. 53.

The producer is so constructed that the gases are withdrawn about halfway up the fuel bed. The air-steam supply passes into the water-sealed bottom of the producer, this water-seal permitting the withdrawal of clinker and ash during working, and a secondary air supply is admitted at the top of the producer, which is open. The heat resulting from the actions in the lower sections of the fuel slowly distils out the volatile constituents of the raw fuel lying in the upper sections, and these are drawn down with air for their combustion through a zone at high temperature on a level with and a little above the gas exit. The coked fuel thus gradually works downwards to the section where the producer gas reactions proper take place.

The hot gases pass through a vaporizer where they are cooled, at the same time raising the necessary steam for the plant. Afterwards they pass through suitable scrubbers and finally a saw-dust scrubber. Where there are several engines, or gas has to be supplied for heating purposes also, a gasholder is provided. This is unnecessary with only one engine, the gas production being regulated by a suitable governor. It is claimed that with ordinary bituminous coal, lignite and some other fuels, the tar is removed completely in the producer, and no mechanical or other tar extractor is required.

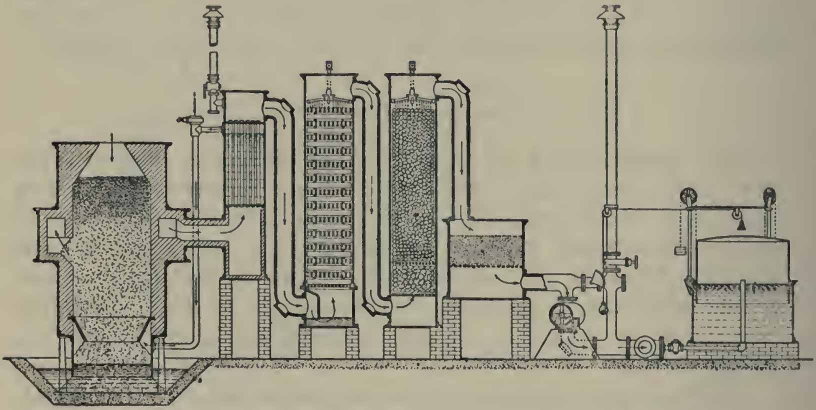


FIG. 53.—Dowson bituminous fuel suction plant.

Mr. Dowson (*Inst. Mech. Eng.*, 1911) stated that one of these plants (500 H.P.) has been working regularly at West Bromwich since 1908 on fuel of the following composition :—

Fixed carbon	55 per cent.
Volatile hydrocarbons	30 ,,
Moisture	8 ,,
Ash	7 ,,

The cost per ton is 8*s*. The consumption has been about 1 lb. per I.H.P. hour, which includes all stand-by, cleaning and starting losses. Another plant of 700 H.P. was installed in 1909, and the two supply thirteen gas engines, previously worked on anthracite pressure gas. The composition of the gas from the larger plant is given as—

Carbon monoxide	23·9 per cent.
Carbon dioxide	7·2 ,,
Hydrogen	16·0 ,,
Methane	1·0 ,,
Nitrogen	51·9 ,,

Other sets of smaller capacity are in use, working on coal ranging from 6*s*. to 8*s*. per ton, and the plant has been adapted for use for sizes from 25 H.P. upwards.

Dimensions in Suction Plants.—Although it is clear that there must be a general relationship between the size of the engine cylinder and the number of strokes made and the sectional area and fuel depth of the producer, in order to give good gas with the given velocity of the air and gases in the producer, the actual dimensions vary within very wide limits in different plants.

The *cross-section* of small size English producers varies from about 6–9 sq. ins. per H.P.; there is a proportionate reduction as the power increases to about 4 sq. ins. for 200 H.P. A fair average appears to be 7–8 sq. ins. for plants of 20 H.P. and less. When coke is used the dimensions are increased with advantage.

The *grate area* with small size producers is the same as the fuel section. With larger sizes there is generally a reduction, in some cases as much as 50 per cent., though this is excessive.

It is claimed for the reduced grate area that, since the velocity of the blast is thereby increased, at light loads the fuel is kept at a better temperature and the fire responds more quickly with increase of load. The blast being directed more to the centre of the producer high temperatures around the lining are not so likely to develop, with consequent formation of clinker; into the dead space around the grate large pieces of clinker can be pushed while working, to be removed later.

The *fuel depth* (*i.e.* from the lower edge of the container) is not less than 1 ft. 9 ins. in the small producers, increasing to about 3 ft. for 200 H.P.

Mr. Burt gives the *cubic capacity* of producers as: 20 B.H.P., 0·12 cub. ft.; 40 B.H.P., 0·14 cub. ft.; 100 B.H.P., 0·18 cub. ft.

Since during a week's run it is possible to remove only portions of the clinker, some must always be accumulating and can be removed only by emptying the producer; the area and capacity must be sufficient to allow for this.

The *scrubbers* have a capacity of from 0·75 to 1 cub. ft. per B.H.P. for anthracite. They are packed at the lower part with coke, of a size equal to about 3–4-in. cubes, and at the upper part with 2-inch cubes. The coke requires removal about every six months.

A fair water consumption in the scrubbers is about 1·25 gallons per hour per B.H.P., but often this is exceeded greatly.

Mr. W. A. Tookey says that under the best conditions 36 lbs. of anthracite can be gasified per square foot per hour, this being equivalent to 1 lb. (1 B.H.P.) for 4 sq. ins., and regards this as the probable practical limit, as above this the air velocity would be so high that cores, blowholes and clinker would form, with much dust and small carried forward.

The general average gasification per square foot is given as 24 lbs., equal to 1 lb. to 6 sq. ins. area. With coke 18 lbs., equal to 1 lb. to 8 sq. ins. area. With poor fuels, the rate per square foot per hour may be as low as 12 lbs.

Variation in Gas under Changing Load.—Although the suction gas plant is capable of a great deal of self-adjustment when in operation, it is certain that the quality of the gas is not the same at all rates of production. In general, the gas has the best composition, and hence the maximum calorific value, at or near maximum load. The draught through the producer is now most uniform and of sufficient velocity to give a good depth of incandescent fuel, so necessary for the production of good gas.

Reduction of the load, on whichever system the engine is governed, decreases the blast velocity, the depth of incandescent fuel is lessened and its temperature follows. Consequently, the proportion of carbon dioxide in the gas increases at the expense of carbon monoxide. Mr. Dowson (*Inst. Mech. Eng.*, 1911, 335) gave the following results for a 40 B.H.P. engine, working on gas coke, the no-load test being of three-quarters of an hour duration :—

		Per cent. by volume.	
		Full load.	No load.
Carbon monoxide		27·65	22·4
Hydrogen		9·85	7·0
Carbon dioxide		3·80	4·9
Oxygen		0·3	0·5
Nitrogen, etc.		58·4	65·2
B.Th.U. per cub. ft.	*gross*	128·9	101·0
	net	123·0	97·0

In further tests at the Royal Agricultural Show (Derby, 1906) quoted by Mr. Dowson (*loc. cit.*), a still greater difference in composition is shown and one other important comparison rendered possible, namely, between no-load conditions maintained after a cold start and no-load conditions after the plant had run an hour on full load, time having been allowed for normal equilibrium to be attained.

		Second hour, cold start.	After full load.
Carbon monoxide		12·45	18·30
Hydrogen		12·15	13·60
Methane		2·0	1·2
Carbon dioxide		10·1	9·05
Oxygen		—	0·3
Nitrogen		63·3	58·55
B.Th.U. per cub. ft.	*gross*	105·8	122·8
	net	97·0	113·5

The better gas obtained after the producer has heated up thoroughly is due to generally higher temperature, and once a good depth of incandescent fuel has been produced it takes a long time for it to be reduced to such an extent that poor gas is obtained when the engine is running light. These results have a bearing also on the conditions maintained during stand-by periods. It is false economy to try to cut down the fuel consumption to the minimum possible. For one thing, over a long period, such as over-night, some alterations of external conditions may take place and the fire may die out. Again, the producer temperature may be so far reduced that an unnecessary long interval may ensue before it is producing good gas when the load is applied. A cool producer hence will necessitate the load being put on more slowly than if a reasonably high temperature has been maintained during stand-by time.

Probably the most frequent adverse criticism of suction gas plants is based upon their reputation for not responding quickly to variation in the load. Experience now has enabled makers to adjust the various sections of the plant, especially of the producer, so that reliability for all reasonable fluctuations is assured. Sudden and wide changes of working conditions will cause trouble unless special steps are taken to overcome them, and the conditions leading to failure in this respect must be considered in detail.

It has been mentioned already that, within limits, the make of gas is proportional to the requirements of the engine. If the engine has been running at a fairly good load, the producer will be making good gas for these conditions, the depth of incandescent fuel will have adjusted itself to the velocity of the induced air current, given a proper system of obtaining the right air-steam ratio, the temperature will be satisfactory and good gas obtained.

With a steadily falling load, the inspiration of air will be less frequent, the incandescent zone will be reduced, the steam supply will diminish automatically, either by reason of the lower temperature of exit gases in producers with boiler vaporizers, or through hand or automatic adjustment with flash vaporizers. The excess steam, if saturation has not been attained with normal working, will lead to a quicker cooling of the fire and assist matters. The gas made will be quite satisfactory for use, although analysis will show it to be of reduced quality. So the conditions will adjust themselves throughout right down to those of no-load.

Similarly, with gradual rise of load, the producer will work itself up to the best conditions, the steam supply, with "boiler" vaporizers, being last to respond; but this is an advantage, for in working up diminished steam will cause a more rapid rise in temperature of the fuel bed.

It is when the plant has been running for some time on light load or no load and suddenly has to supply the demand for a heavy load that trouble is experienced. The engine demands a greatly increased volume of *good* gas, and the fire is under the least favourable conditions for its supply at a rapid rate. The average temperature of the greatly reduced active zone is low. At every charging stroke of the engine the air-steam mixture is drawn through a bed of fuel too cool and too shallow for the formation of good gas, the theoretical conditions for which have been considered fully in Chapter XII. The gas is so poor that the charges fail to ignite, and unless the load is removed the engine probably will pull up.

No trouble is experienced on the other hand where the load is removed suddenly, for the fire can be relied on to give much better gas than actually demanded for running the light engine.

Where exceptionally wide variations of load are experienced, makers of plant provide for such contingencies, usually by making a direct connection between the gas main and the cylinder, so that at every suction stroke some gas is drawn through the producer independently of any governor employed, the quantity so taken being insufficient to cause explosion with the air drawn in. A small proportion of the gas has to be sacrificed.

Steam Supply to the Producer.—The action of steam in producer practice already has been discussed fully. Here it need only be restated that the temperature of the fuel bed and consequently the quality of the gas are dependent upon a proper air-steam ratio, and that for the best results this ratio be maintained. Now this is one of the difficulties in the operation of a suction gas plant with variation of the load.

Taking first producers in which the steam is supplied from water in bulk in the vaporizer. The amount of steam carried by the in-going air will depend primarily on the air temperature, but with the water more highly heated steam in excess of the saturation amount may be carried forward in suspension. Theoretically, in a system properly balanced to give nothing but carbon monoxide from the air-carbon reaction and carbon monoxide and hydrogen from the simultaneous steam-carbon reaction, each pound of carbon will require 3·36 lbs. of air and 0·64 lb. of steam. The steam per pound of air will be $\frac{0·64}{3·36} = 0·19$ lb. From the curves given in Fig. 37, p. 237, the temperature of the air corresponding to this degree of saturation is 147° F. (64° C).

Two factors combine in enabling an actually greater quantity to be employed. The above figures are deduced from consideration of ideal conditions, no heat being supplied outside that arising from the air-carbon reaction, and none lost in the whole system. In practice, the blast is always at a moderately high temperature, in many cases is superheated. It follows that a larger proportion of steam to air may be employed without reducing the temperature unduly. Secondly, the gases escape at a high temperature: according to Garland and Kratz (see p. 234), 590–600° C. (1100° F). A 25 per cent. increase in the steam in practice over that theoretically demanded gives about 0·8 lb. per lb. of carbon; per lb. of air this is $\frac{0·8}{33·6} = 0·238$; the corresponding saturation temperature is 154° F. (68° C).

According to experiments made by E. A. Allcut (*Inst. Mech. Eng.*, 1911) with a small suction producer, the maximum amount of steam which can be decomposed by anthracite at 1000° C. (1832° F.) is about 0·535 lb. This, on the theoretical air basis given above, would correspond to a saturation temperature of 143° F. (62° C.). High steam ratio should mean high hydrogen content in the gas, providing the steam is decomposed. Allcut found there was no further appreciable rise in hydrogen after the water feed reached 0·75 lb. per lb. of coal; this corresponding to a decomposition of 72 per cent. of the steam.

It is necessary, therefore, to have some control over the steam-air ratio to get the best results with the normal load. With vaporizers situated at the top of the producer and containing water in bulk this is not easy to arrange, and for this reason many makers provide a "flash" type of vaporizer, the cold feed to which can be adjusted by hand or automatically. With boiler type vaporizers, providing the arrangement is such that the maximum permissible saturation temperature is not exceeded at or near maximum load, no excess of steam should go forward. Some vaporizers get much hotter and the air becomes super-saturated, the mechanically held particles being vaporized completely later at higher temperatures. To overcome this a secondary supply of dry air sometimes is admitted independently, and the actual steam-air ratio controlled by adjustment of the dry and saturated supplies.

Variation of Steam required with Load.—Assuming a steady and correct rate of vaporization has been attained for the engine running at a good load, the suction of air over the heated water being regular, when the load is reduced the engine will either miss taking a charge at intervals or draw in a reduced charge, according to the system of governing. At high load the hot zone of the fuel is nearer the vaporizer; for some minutes after the load is reduced it hardly recedes and the gases made are still at their hottest. With a boiler type vaporizer steam hence will be given off as readily as at full load.

If the air were not saturated under normal full-load conditions, due to its relatively high velocity through the vaporizer, the reduction in velocity caused by the less frequent inspirations will cause it to become more highly or completely saturated, leading to more rapid cooling of the fire than otherwise would be the case; but, as has been shown, this is of no moment, for the demand for the best possible gas has ceased. After a time the temperature of the vaporizer would fall, due to the lowering of the depth of the incandescent zone, and the lower average temperature of the gases and the steam supply would become adjusted ultimately.

On application of the load, the air is drawn over the water in the vaporizer more rapidly, a low steam ratio is attained, the water-gas reaction is diminished, and the air-carbon reaction accelerated. Consequently, although poorer gas is obtained for some minutes, which may fail even to give ignition, the requisite temperature in the producer is attained more quickly.

The foregoing remarks apply to producers with vaporizers containing water in bulk. On theoretical grounds the amount of water supplied should be proportional to the work demanded of the engine; at full loads the gas should have the highest calorific value, which is to be attained by the increased ratio of the water-gas reaction. For this reason "flash" type vaporizers are employed in many forms of suction plant, this being the only pattern available which can respond readily to variation of the supply of water. In many cases the actual amount vaporized is determined automatically, almost invariably by the suction effect from the cylinder on drawing a gas charge.

Again, with sudden change from good load to the extreme of no load, the cutting off of the water supply has no effect on the running of the engine; it keeps the fuel bed better up to temperature for a time in two ways—first, the endothermic steam-carbon reaction is reduced; second, the gas is poorer since it contains a greater proportion of air-carbon gas, and the engine makes more frequent charging strokes, so a more rapid draught is maintained. The fire is more ready to respond once again to full-load conditions, if the demand arises in a reasonably short interval.

On the other hand, supposing the plant to have been standing or running on no load for some time, the fire is under least favourable conditions for the production of good gas. Air alone would bring it most quickly up to the requisite temperature and depth, but if the automatic suction control comes into operation the full steam supply is admitted at the very time when the fire is in the most unsuitable condition to have the strongly endothermic steam-carbon reaction thrust upon it, and would take longer to reach proper conditions.

Opinion differs greatly as to the advantages of boiler type and flash type vaporizers, and with the latter as to whether or not the supply should be controlled automatically. In view of the number of plants working with every satisfaction on either system there does not appear to be any marked advantage with either. If operated intelligently the most favourable results ought to be attained with hand adjustment to a flash type vaporizer with visible water supply, but whether the average attendant, often very unskilled, could give the proper attention is open to question. The saving clause in practice is that wide and sudden variations in the load are the exception, and that for ordinary working fluctuations the natural self-adjustment of the producer conditions to the demand is sufficient.

An ingenious form of steam regulator is that made by the Empire Oil Engine Syndicate (see *Eng.*, 1911, **91**, 719), especially for marine suction plants, where far wider fluctuations have to be provided for than in factory use.

In the air supply pipe to the producer a copper coil containing methyl alcohol is fixed. The coil bends over at the top and communicates with a flat chamber filled with heavy oil; this actuates a flexible diaphragm and, through suitable levers, the balanced steam valve controlling the supply generated in a separate boiler and admitted to the air trunk. At full load the proper air-steam ratio is provided ; the load falls and less air passes through, owing to the greater quantity of steam now present the temperature in the air supply pipe rises, the methyl alcohol exerts a much higher vapour pressure, and the steam quickly is shut off.

Exhaust Gases in Lieu of Steam.—Owing to the increased liability to pre-ignition to which it is claimed a gas containing hydrogen is liable, which limits the compression and hence efficiency of an engine, it has been proposed to replace steam in the blast by the exhaust gases from the engine. These consist of carbon dioxide and nitrogen (water vapour in this case being negligible), and the interaction of the carbon dioxide with more carbon once again generates carbon monoxide, by an endothermic reaction.

The calorific value of the gas produced is about one-third lower than ordinary suction gas, but this is not regarded as important since the calorific value per cubic foot of the mixture supplied to the cylinder is in any case reduced to about half that of the gas itself, say, 60 B.Th.U. G. M. S. Tait found that with ordinary suction gas at the usual compression the output of a particular producer plant was 106 H.P.; with the exhaust gas system the compression was raised to 200 lbs., when the output attained was 126 H.P.

Fuel however always contains hydrogen and some moisture; moreover, the air drawn in is never dry, so that hydrogen cannot be eliminated as a constituent of the gas, although its amount is reducible. With ordinary suction gas the hydrogen content would not exceed 15 per cent. with proper steam-air ratio, and hence the cylinder charge would contain 7·5 per cent. as a maximum.

Fuel Consumption in Suction Plants.—The low fuel consumption per B.H.P. is one of the outstanding features of the suction gas plant, and astonishingly low consumptions have been attained in special tests. Under ordinary running conditions at or near maximum load, the average consumption of anthracite is between 0·7 and 0·8 lb. per B.H.P.-hour, but taking all conditions of load, an estimate of 1 lb. is a safe figure to take. Bituminous fuel plants will give a consumption of 1 lb. at good load; with peat (theoretically dry) about 2 lbs.; with average wood containing 50 per cent. moisture, 3–4 lbs.; hard dry woods, such as oak, ash, etc., require little over 2 lbs.; spent tan, with 50 per cent. moisture, about 4-5 lbs.

The composition and calorific value of the gases from peat and wood respectively are—

	Peat, average moisture 45 per cent.	Wood.
Hydrogen	10·5	9·75
Methane	3·2	4·75
Unsaturated hydrocarbons	?	2·42
Carbon monoxide	26·3	17·45
Carbon dioxide	7·5	13·57
Nitrogen (difference)	52·5	52·06
Total combustibles	40·0	34·37
B.Th.U. per cub. ft. at 60° F. (calc.) *gross*	151·7	192·8
B.Th.U. per cub. ft. at 60° F. (calc.) *net*	142·7	179·1

With good anthracite the yield of gas in a suction plant is about 90 cub. ft. per lb., and its calorific value about 130 B.Th.U. per cub. ft. Coke yields about 75 cub. ft. of much the same calorific value. With anthracite of 14,000 B.Th.U. and coke of 12,500 B.Th.U. per lb. the thermal efficiency with anthracite is 84 per cent., with coke 78 per cent.

It is convenient to remember that for approximate computations 1 B.H.P.-hour is equivalent to the round figure of 10,000 B.Th.U. supplied to a gas engine. With the figures given in the preceding paragraph, the number of cubic feet of gas per B.H.P.-hour is 77·5.

The consumption of fuel in a suction gas plant is somewhat greater in small sized units than in large plants, but above some 25–30 H.P. the consumption diminishes but little per H.P. hour with the larger sized plants. It is well known that at reduced loads the relative fuel consumption per H.P. hour is greater than at full loads. In the Derby trials of the Royal Agricultural Society the average consumption at half load was 1·6 times greater per H.P. hour than the consumption per H.P. hour at full load. Haeder has given results which show that the fuel consumption at 70 per cent. of the maximum load was 1·2 times greater per H.P. hour than at the maximum, and at 50 per cent. of the maximum 1·48 times as great.

As the fuel costs vary with the load the selection of the plant of suitable rating for the average demand for power is important; working a plant at low percentage output is clearly uneconomical.

Control of Gas Plants by Analysis, etc.—Where a large plant is installed regular analysis of the gas should be made in order to keep a proper control over the working and ensure the best results. A complete analysis is quite unnecessary; in general the carbon dioxide alone will afford valuable information as to the course of the reactions, and this is the simplest of gases to estimate. By the use of a carbon dioxide recorder, of the type used for estimating the excess air in flue gases (see Chapter XIX.), a continuous record of the working of the plant could be kept, and once a standard of composition had been established for a particular class of fuel, the adjustment of the conditions of air and steam supply to give such gas would be readily made.

Frequent tests of calorific power should also be taken with a suitable gas calorimeter. No doubt the recently introduced recording type of these instruments would be worth installing for a large plant.

Even with small units, such as suction producers, a frequent determination of the carbon dioxide in a sample, which may be carried out in a very simple form of apparatus, would prove a good guide in working to get the best results.

BLAST FURNACE GAS

This secondary product in the extraction of pig iron in the blast furnace is a fuel of great importance, not only by reason of its utilization in that particular industry, but because there is, when economic appliances are introduced, a vast amount of energy available for outside use.

For generations iron was obtained in the old open-throat furnaces and the gases burned to waste. With the introduction of the hot blast much of the heat energy of the waste gases was returned to the furnace in the blast, and another portion utilized in raising steam for the blowers and for operating the plant. This method is very uneconomical, but with the introduction of large gas engines of direct action for supplying the blast and for generating electric current, such great reduction of the waste gas consumption for the entire blast furnace plant is possible that a large surplus is available for outside purposes.

The consumption of fuel for iron and steel production in this country is estimated to be between 10–12 million tons per annum, and it may be claimed safely that a saving of some 20–25 per cent. would be effected if all plants were equipped with modern gas engines or steam turbo-generating machinery. The difficulty is, of course, largely one of capital expenditure and distribution of the surplus energy at a remunerative figure, when the high capital charges for such distribution are taken into account; and even with poor methods of utilizing the gases, by burning under boilers and using the steam in reciprocating blowing engines, there is always plenty of surplus gas, so that economy is of little use without profitable outlet for the increased surplus. On the North-East coast large quantities of coke-oven gas and blast furnace gas are being used for the generation of electricity, which is being distributed throughout the district.

According to Mr. A. E. L. Chorlton the relative proportion of blast furnace gas made and utilized profitably in Germany and this country was (1911)—

	Germany.	England.	
Producible .	1,340,000	1,060,000	B.H.P.
Utilized . .	448,000	23,300	,,

W. Dixon (*Times Eng. Suppl.*, Oct. 25th, 1911) gives the total power production from blast furnace gas in large gas engines as 1,033,509 B.H.P., of which Germany contributes 46·5 per cent.; America, 32·5; France, 5·4; Belgium, 4·6; Austria-Hungary, 2·4; Great Britain, 2·4; and other countries, 6·2 per cent.

The cost of electricity produced from blast furnace gas varies considerably with the locality. It may range from about $\frac{1}{10}$ to $\frac{1}{4}$ of a penny per kilo-watt-hour. In the Westphalian district surplus gas is taken by the electrical power company, the public supply price varying from 0·36 to 0·42*d.* per K.W.-hour.

Composition of Blast Furnace Gas.—The bulk of the iron ore in this country is smelted with coke as fuel. In some districts of Scotland splint coal is employed. Since the furnaces are worked with an air blast without steam the gases partake more closely of the character of simple producer gas; where coal is employed, the gas will be a mixture of producer gas with the coal gas resulting from the distillation of the raw fuel. Necessarily, with different furnace conditions considerable variation in the gas is found, but the following figures are a fair average:—

	With coke fuel.	With hard coal.
Carbon monoxide . . .	27–30	27–30
Hydrogen	1·0–2·5	4–5·5
Methane	—	2·5–4·0
Carbon dioxide	9·0–12·0	8·0–10·0
Nitrogen	57·0–60·0	55·0–58·0

The calorific value usually will be from 95–105 B.Th.U. per cubic foot. The mean of samples from 78 Continental furnaces is given by A. Witz as 110 B.Th.U.

Estimate of Surplus Gas and Power Available.—With modern blast furnace practice a little less than one ton of coke is required in the production of one ton of pig iron. Some of the carbon of the charge passes out in the pig iron, but against this may be set the carbon derived from the limestone ($CaCO_3$) flux added, which passes out in the gases either as carbon dioxide or carbon monoxide. For all practical purposes, it may be computed then that for one ton of pig iron obtained, one ton of carbon appears in the gases, and at ordinary temperatures there will be from 140,000–160,000 cub. ft. of gas per ton.

Taking as a convenient example a furnace capable of giving an output of 1000 tons of pig iron per week (168 hours), the iron per hour is 5·95 tons.

Then, gas produced per hour = 150,000 cub. ft. × 5·95 = 892,500 cub. ft. For heating the blast about 45 per cent. of the gases must be employed, and for power purposes connected with operating the furnace about 10 per cent. of the gas when utilized in gas engines. The surplus gas will be found from:—

	Per ton.	Per hour.
Gas for stoves . .	$\frac{150{,}000 \times 45}{100} = 67{,}500$	$\frac{892{,}500 \times 45}{100} = 400{,}000$
Gas for engines .	$\frac{150{,}000 \times 10}{100} = 15{,}000$	$\frac{892{,}500 \times 10}{100} = 89{,}250$
Total gas utilized for plant . .	82,500 cub. ft.	489,250 cub. ft.
Surplus gas	67,500 ,,	403,250 ,,
Total gas produced . .	150,000 ,,	892,500 ,,

For ascertaining the distribution of the heat units and the available power from the surplus gas, the calorific value may be taken as 100 B.Th.U. per cub. ft., and of the coke charged as 12,000 B.Th.U. per lb.

Total heat units in coke per hour $= 12{,}000 \times 2240 \times 5{\cdot}95 = 159{,}000{,}000$

,, ,, gas ,, $= 892{,}500 \times 100 = 89{,}250{,}000$

$$\text{Percentage of total heat units in gas} = \frac{89{,}250{,}000 \times 100}{159{,}000{,}000} = 56 \text{ per cent.}$$

Surplus heat units per hour $= 403{,}250 \times 100 = 40{,}325{,}000$ B.Th.U.

For estimating the power available, the round figure 10,000 B.Th.U. per hour to give 1 B.H.P. in a large gas engine, with the high compression possible with such gas, is approximately correct, then

$$\text{B.H.P. per hour} = \frac{40{,}325{,}000}{10{,}000} = 4000 \text{ B.H.P. (approx.).}$$

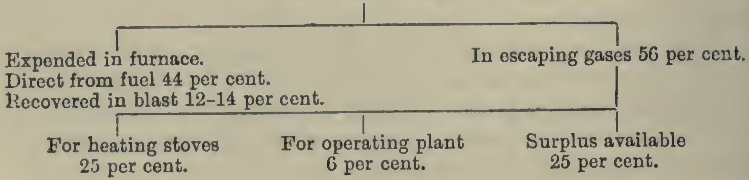
Converted into electric energy, with 90 per cent. efficiency, this equals 3600 E.H.P. per hour. The equivalent per ton per hour is 670 B.H.P. or 605 E.H.P.

On this basis every ton of pig iron produced per day will give an output of $\frac{4000}{5{\cdot}95 \times 24} = 28$ H.P., a figure in fair agreement with estimates by several authorities. The annual output of pig iron in this country is between 10,000,000 and 12,000,000 tons, so that the available H.P. on the mean figure would be

$$\frac{11{,}000{,}000 \times 28}{365} = 840{,}000 \text{ H.P. per day per ton.}$$

The approximate distribution of the heat units from the furnace is given below—

Distribution of Heat Units
from Blast Furnace.



Cleansing Blast Furnace Gas.—As the gas leaves the furnace it is hot, the actual temperature depending on a variety of conditions, and in addition carries considerable quantities of fine dust, which must be removed almost completely before the gas is fit for use in engines. The amount of dust is very variable, depending on the character of the flux, the ore, and the fuel. Manganiferous ores, for example, generally give a high dust content.

E. Huberdick (*J. C. S. I.*, 1905, 691) states that with solid ore the dust is from to 2–4 grams per cub. metre (0·88–1·76 grains per cub. ft.), and with loose ore 4–6 grams per cub. metre (1·76–2·64 grains per cub. ft.). R. Pokorny (*Times Eng. Supp.*, April 12, 1911) says that it is economical to use fairly clean gas for boilers or stoves; the boiler power may be reduced 40 per cent. by the heating surfaces becoming coated with dust and dirt. Stoves working with 90° C. fall in temperature can remain three hours in blast with clean gas, and only two hours with dirty gas.

For use in engines the gas should be cooled to 20° C. (68° F.), and should never contain more than 0·1 grain of dust per cub. ft.

Pokorny, in dealing with German practice, says the usual method is to pass the gas to large chambers, where the heavier particles are deposited, thence the gas, containing from 2·62 to 3·5 grains of dust per cub. ft., passès to vertical cooling chambers, where it meets with a water spray, and further dust is removed, the gas leaving at a temperature of 77° F. Then come centrifugal fans with water spray, which reduce the dust to about 0·13 grain per cub. ft., and with this content it is employed for stoves and boilers. For engine use, the gas passes through a second set of fans, where the dust is reduced to 0·008 to 0·003 grain. At the Deutscher Kaiser Iron and Steel Works, Bruckhausen, a plant of this type deals with over 14 million cub. ft. of gas hourly, the power required is 1800 H.P., and 400,000 gallons of water are used for this quantity. After settling and cooling the water is used again.

At Saarbrucken, Pokorny states, a dry cleaning plant, dealing with 176,600 cub. ft. per hour, is in operation. The initial temperature of the gases is 175–250° F.; these are conducted into a large vertical chamber, coarse dust deposited, and the temperature reduced to 120–140° F. The gases are now raised in temperature by some 20–40°, steam heat or the exhaust from gas engines being used; this "dry" gas is then passed through conical cotton fabric filters, by means of induced draught, and the dust reduced to 0·004 grain per cub. ft. and even less. When the filters become choked a current of compressed gas is sent through them in the reverse direction, the filter bags being agitated. This cleansing takes place automatically every four minutes. The total cost of cleansing (including capital charges) by the first process is given as 1*d*. per 10,000 cub. ft., and by the second process as less than one halfpenny.

At the Barrow Hæmatite Iron and Steel Co.'s works, the gases are sent into a conveniently-situated old furnace, where heavier dust deposits, and then through a long length of large diameter main arranged vertically on a W system, so that the gas is air-cooled and its direction repeatedly changed, thus depositing much further dust. In the washer house Theisen washers are installed, each capable of dealing with 5300 cub. ft. per minute; the gas is cleaned until it contains about 0·065 grain per cub. ft. The clean gas is sent to the engines through a 10-ft. main, 210 ft. in length, which abolishes fluctuations in the pressure.

At Barrow fuel costs are very high, and the estimated coal saving for the first week the plant was running was 1000 tons at 14*s*., the estimated total economy £1000 per week. The yield of gas per ton of iron is given as 170,000 cub. ft., which is higher than usual, so that the total gas from the four furnaces of 1200 tons capacity weekly is enormous.

Chapter XVI

FUEL CONSUMPTIONS AND GENERAL CONSIDERATIONS IN POWER PRODUCTION

Fuel Consumptions.—A vast amount of information on the consumption of fuel is scattered throughout the literature dealing with power production. It is impossible to convert the whole of the heat energy of the fuel into useful work, and the proportion which can be converted, even under the best conditions, varies over a wide range for plant of different type. This proportionate conversion of heat into work is expressed as the "efficiency" of the plant. The over-all efficiency includes that of the boiler and steam engine, or, in the case of gaseous fuels, of the producer and gas engine. In the case of the steam plant the efficiency of the boiler will vary with the type, but for any type will depend very largely on the proper control of the combustion process, a subject discussed at length in a subsequent chapter.

As already indicated, the consumption per H.P. generated is least the nearer the plant is working to the maximum output. Figures have been given already for consumption in suction gas plants at full and reduced loads (p. 277). Here an attempt is made to correlate average consumptions for plants of different type, when working under every-day conditions at full or nearly full loads, but including stand-by charges, etc. Of course better results are obtained every day in test runs, but a plant does not reach such perfection in ordinary use.

In order to give a general comparison of the relative value for power of the various fuels already dealt with in previous chapters, Table XLV. has been arranged, based upon the theoretical horsepower obtainable in a perfect heat engine. Since 1 H.P. is equal to 33,000 ft.-lbs. per minute, the H.P.-hour is equivalent to 33,000 × 60 = 1,980,000 ft.-lbs. The B.Th.U. is equivalent to 778 ft.-lbs. Hence with the perfect heat engine

$$\text{B.Th.U. per H.P.-hour} = \frac{1,980,000}{778} = 2560.$$

TABLE XLV.

Comparative Consumption of Fuels at Various Thermal Efficiencies.

(*Based on the perfect heat engine requiring* 2560 *B.Th.U. per H.P.*

Thermal efficiency per cent.	Type of engine of this efficiency.	Equivalent in B.Th.U.	Quantity of different fuels to provide these units.				
			Coal. 12,500 B.Th.U. per lb.	Oil and petrol. 19,000 B.Th.U. per lb.	Coal gas. 600 B.Th.U. per cub. ft.	Producer gas. 140 B.Th.U. per cub. ft.	Blast furnace gas. 90 B.Th.U. per cub. ft.
40	Diesel engines	6,450	0·512	**0·336**	10·4	45·7	57·5
35		7,320	0·586	**0·385**	12·2	47·0	81·3
30	Large gas engines	8,530	0·683	0·450	14·2	**61·0**	**94·8**
25		10,240	**0·819** (*a*)	**0·540**	**17·0**	**3·2**	114·0
20	Gas engines, ordinary oil and petrol motors	12,800	1·024	**0·675**	21·6	91·4	142·5
15	Large turbine sets, over-type superheated steam	17,050	**1·365**	**0·90**	28·4	122·0	189·5
12·5	Small turbine sets, high-speed reciprocating condensing .	20,500	**1·640**	**1·08**	34·3	146·5	228·0
10·0	Ordinary expansion condensing	25,600	**2·08**	**1·35**	42·7	183·0	285·0
7·5		34,200	**2·73**	1·80	57·0	244·0	380·0
5·0	Small reciprocating non-condensing.	51,200	**4·10**	2·59	85·4	366·0	570·0

Note.—Figures in heavier type indicate the usual fuel and the average consumption.

(*a*) When gasified in producers.

Captain Sankey (*J. Roy. Soc. Arts.*, 110, 3127, p. 1089) gave the data reproduced in Table XLVI. for the fuel consumption in various types of plants at varying loads.

TABLE XLVI.

Fuel Consumptions at Various Loads (Capt. Sankey).

Description of plant.	Calorific value of fuel B.Th.U. per lb.	Total fuel required—lbs. per hour at various proportions of full load.				
		Quarter load 25.	Half load 50.	Full load 100 B.H.P.	10 per cent. Overload 110.	50 per cent. Overload 150.
Non-condensing steam plant	13,000	150	190	270	290	—
		200	240	320	340	410
Condensing steam plant . .	13,000	95	120	190	210	310
Overtype superheated condensing steam plant . .	13,000	55	75	130	150	230
Gas engine, pressure producer	13,000	37	57	93	—	—
		53	70	104	110	140
Gas engine, suction producer	14,000	34	53	85	—	—
		49	64	96	104	130
Oil engine	19,000	26	40	65	—	—
		33	46	72	78	97
Diesel engine	18,500	16	25	45	51	—
		19	27	45	50	69

Where two sets of figures are given for the same class of engine, the upper is for 100 H.P. plant, the lower for 150 H.P.

Under ordinary conditions in practice the figures in Table XLVII. have been deduced from a large number of records. The over-all efficiency in the case of steam plants includes boilers and engines; in the case of gas plants it includes the producer, cleansing plant, and engine efficiency. Of course, the consumption per B.H.P.-hour is greater for small power engines, but with internal combustion engines the increase is very much less than with steam plant.

TABLE XLVII.

OVER-ALL CONSUMPTION OF FUEL PER B.H.P. AT FULL LOAD UNDER RUNNING CONDITIONS.

Steam Plants.

Type of engine.	Approx. overall efficiency.	Lbs. of fuel.	
		Coal.	Oil fuel.
Small reciprocating non-condensing . .	5	4–5	—
Large multiple expansion condensing . .	6–7	3–4	2–2·5
Small turbine sets and over-type super-heat condensing	12–15	1·4–1·7	0·9–1·1
Large turbine sets	15	1·4	0·9

Gas Plants, Town gas, Blast furnace gas.

		Lbs. of fuel in generator.	Cubic ft. of gas.
Pressure producers	20	0·9–1·1	80–90
Suction producers	22	0·8–1·0	80–90
Town gas	25–27	—	16–18
Coke oven gas . . .	25–27	—	20–21
Blast furnace gas	25–27	—	100–110

Oil Engines.

		Nature of fuel and and sp. gr.	Lbs.	Pints.
Petrol motor	18–22	Petrol (0·722)	0·63	0·7
Ordinary oil engines . .	18–25	Kerosene (0·825)	0·61–0·875	0·60–0·85
Semi-Diesel engines . .	25–27	Fuel oil (0·920)	0·63–0·69	0·55–0·60
Diesel type engines . . .	30–33	Fuel oil (0·920)	0·45–0·50	0·39–0·43

Mr. A. J. J. Pfeiffer, in an important paper on Medium-sized Power Plants (*Inst. Elec. Eng.*, 1909, 43, 557) gives the fuel consumption in Table XLVIII. for high-speed vertical type steam plant, gas plant with producers, and Diesel oil engines with a maximum load factor of 1600 K.W.

TABLE XLVIII.

FUEL CONSUMPTIONS IN STEAM, GAS PLANT AND DIESEL ENGINES FOR GENERATING ELECTRIC CURRENT. (A. J. J. Pfeiffer.)

Load factor.			Steam plant.		Gas plant.		Diesel engines.
			Lbs. coal per unit.		Lbs. coal per unit.		Lbs. oil per unit.
17·5 (Lighting.)	(1)		2·69		1·660		0·652
	(2)		1·20		0·216		0·000
			3·89		1·876		0·652
		+ 20 %	0·78	+ 20 %	0·375	+ 10 %	0·065
	Total fuel . . .		4·67		2·251		0·717
33·0 (Light and power.)	(1)		2·65		1·630		0·630
	(2)		0·44		0·089		0·000
			3·09		1·719		0·630
		+ 15 %	0·46	+ 15 %	0·260	+ 7·5 %	0·047
	Total fuel . . .		3·55		1·979		0·677
	Over-all thermo-dynamic efficiency.		*7·30*		*13·30*		*27·30*
52·0 (Traction.)	(1)		2·60		1·62		0·63
	(2)		0·20		0·04		0·00
			2·80		1·66		0·63
		+ 10 %	0·28	+ 10 %	0·16	+ 5 %	0·03
	Total fuel . . .		3·08		1·82		0·66
	Over-all thermo-dynamic efficiency.		*8·7*		*14·5*		*27·8*

(1) Fuel required for effective work.
(2) Fuel to cover stand by losses.
Percentage additions are to cover inefficient operating, losses in efficiency, etc., of every-day practice.

Comparison between Gas and Steam Plants.—In comparison with even the best boiler performances a gas producer shows a somewhat higher efficiency; it responds more readily to changing demands, and requires less upkeep. Producers show a better efficiency because for a given output they are smaller than boilers; there is less material to heat up and less loss by radiation. With suction plants and smaller pressure plants producers are simpler to operate, but larger-sized plants are regarded generally as requiring more attention and skill, and hence more difficult to work. This is due probably in a measure to the more general acquaintance with steam plants of the class of men available.

With a gas plant the transmission of the gas over comparatively long distances is a simple matter; there is no loss by condensation in pipes, and the pressures involved are but little above atmospheric so that the pipe system is cheap as compared with steam piping These considerations enable a central gas-generating plant to be arranged with distribution to engines over a wide area. The corresponding centralization with steam can be accomplished by electric distribution of power.

The following scheme shows the relative consumption of the total heat units in the fuel in a first-class steam plant and good average producer gas-power plant. Authorities differs greatly as to the relative heat losses in the exhaust, cooling arrangements, etc., of a gas engine, but these considerations are of no moment in such a comparison; the total loss being all that is requisite. In the steam engine the high efficiency of 15 per cent. is adopted; in the gas engine an efficiency of 28 per cent.

Steam plant.					Gas plant.		
			B.Th.U.	Per cent. on fuel.	B.Th.U.	Per cent. on fuel.	
Heat units per lb. of fuel. 12,500 B.Th.U.	Boiler 75 per cent. efficiency.	Losses .	3125	25	2500	20	Producer 80 per cent. efficiency.
		Engine	9374	75	10,000	80	
			12,500	100	12,500	100	
	Engine 15 per cent. efficiency.	Losses .	8250	66	7200	57·4	Engine 28 per cent. efficiency.
		As effective work .	1125	9	2800	22·6	
			9375	75	10,000	80	

The over-all relative efficiencies are as 2·5 : 1.

Very complete comparative tests between producer and steam plants were carried out in the United States laboratories, and valuable results obtained. In all 138 bituminous coals, 9 subbituminous coals, 10 lignite and 11 miscellaneous fuels were examined. For the bituminous coals the minimum consumption per B.H.P.-hour was 0·84 lb., the maximum 1·48. The average was 1·36. With lignites an average of 1·99 lbs. was found.

Comparative tests on 75 bituminous coals in gas producers with engines and with water-tube boilers and reciprocating plant gave an average ratio of fuel consumption of 2·7 : 1. Low grade coals and lignites of little or no value under boilers gave excellent results in producers.

Stand-by Fuel Consumptions.—In most power plants this is an important factor in any consideration of the total fuel consumption, and when comparisons are made between steam plants and gas plants, still further emphasizes the lower fuel consumptions in the latter.

Mr. Dowson (*Inst. Mech. Eng.*, 1911) gives results for stand-by consumptions with steam plants; the lowest is at the rate of 0·11 lb. per boiler H.P., the highest 0·36, the average being 0·2 lb. With producers the highest was 0·021, the lowest 0·055, the average about 0·014 lb. per producer H.P. Approximately, the stand-by consumption with boilers is 14 times as great as with producers.

According to Mr. S. Donkin, Sir A. Kennedy gave the figure 5·75 lbs. of coal per hour for boilers of 1000 lb. per hour evaporative capacity, but this is an outside figure for both small marine dry back and small water-tube boilers. Mr. Donkin's own test, on a water-tube boiler with a maximum output of 30,000 lbs. steam per hour, with pressure kept constant throughout the test, gave a stand-by consumption of 2·5 lbs. of coal per hour per 1000 lbs. per hour evaporative capacity.

The stand-by consumption in a 1000 H.P. Mond plant during 14 hours has been stated as 3 cwt., which on this rating would be equivalent to 0·023 lb. per H.P.-hour.

GENERAL CONSIDERATIONS IN POWER PRODUCTION

The particular plant most suitable for power production under the very varying conditions in practice is often difficult to arrive at; indeed, as in most things, sharp lines of demarcation are frequently absent, and when all costs of installation, fuel charges and operating are taken into account, there is often little to choose between rival systems.

It is not within the scope of a book on fuel to discuss cost of plant, weight and space, which are important in the ratio they bear to fuel consumption and cost, but certain general considerations may be referred to briefly.

A very large proportion of the total fuel for power purposes is required in small plants, say, up to 100 H.P., and with such plants there is great latitude of choice. The small steam engine, especially if non-condensing, as is often the case, is notoriously inefficient, quite justifying its appellation of a "coal eater." This disadvantage at once places it so far behind the suction gas plant, gas engine on town supply, oil engine and, often, the electric motor, that it need be considered no longer as a competitor. With some of the most modern over-type superheat engines such low coal consumptions are attained that, taking cost, etc., into consideration, they are serious competitors to the suction gas plants working on anthracite, which is now an expensive fuel.

In districts not supplied with town gas the small consumer has the choice between suction gas and oil engines. With anthracite at 28*s*. per ton the B.H.P.-hour costs about 0·15*d*. Oil at 8*d*. a gallon gives a cost of 0·7*d*. For the usual small power rating of ordinary oil engines their cost, small space occupied and ease of operation give them advantages which more than compensate for extra fuel costs; they find great favour then in country districts, especially for farm use, etc.

Where coal gas can be obtain at a reasonably low figure the question of its competition with suction gas plant is important. Coal gas offers certain advantages; there is a constant supply available of a fuel of very constant composition, the gas is perfectly clean, so that no water charges for purification are incurred, or attention to scrubbers, etc., there are no stand-by costs, which for intermittent work is important, and the capital expenditure is limited to the engine, with sometimes the meter.

Mr. W. A. Tookey has given the following comparison between the cost of suction gas and town gas, based on an estimated demand of 10,000 B.Th.U. per H.P. generated. The plant was 60 H.P.

Suction gas.	Coal gas.
B.Th.U. per cub. ft. 130.	B.Th.U. per cub. ft. 600.
1 lb. anthracite = 77 cub. ft.	Cub. ft. per 10,000 B.Th.U. (1 B.H.P.)
and 77 × 130 = 10,000 B.Th.U. (1 B.H.P.)	$= \frac{10,000}{60} = 16·7$ cub. ft.
Or 60 lbs. anthracite for 600,000 B.Th.U.	Or 1,000 cub. ft. gas for 600,000 B.Th.U

	Cost on fuel alone.		Cost on all charges and loss.[1]				
60 lbs. anthracite at	37*s*. 6*d*.	or	29*s*.	equals	1000 cub. ft. gas	at	1*s*. 0*d*.
,, ,,	56*s*. 0*d*.	,,	44*s*.	,,	,,	,,	1*s*. 6*d*.
,, ,,	75*s*. 0*d*.	,,	59*s*.	,,	,,	,,	2*s*. 0*d*.

The writer has prepared the estimate in Table XLIX. of costs for plants of 20 and 40 B.H.P. on suction gas and coal gas respectively—

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[1] The charges, losses, etc., in the suction plant are supposed to be covered by an addition of 25 per cent. to the fuel costs. For coal gas an addition of 1*s*. per hour, as working expenses, should be made.

TABLE XLIX.

Estimated Cost per annum and per B.H.P.-hour for Suction Gas and Coal Gas.

	Suction gas.		Coal gas.	
	20 B.H.P.	40 B.H.P.	20 B.H.P.	40 B.H.P.
	£	£	£	£
First cost—producer	110	130	—	—
First cost—engine	150	250	150	250
Extra charges—foundations, etc., 10 % extra	26	38	15	25
Total cost £	286	418	165	275
Plant running 52 weeks of 54 hours. Total B.H.P. per annum	56,160	112,320	56,160	112,320
	£ *s.* *d.*	£ *s.* *d.*	£ *s.* *d.*	£ *s.* *d.*
Interest, depreciation, etc., at 10 %	28 5 0	41 10 0	16 5 0	27 5 0
Anthracite :—1·1 lbs. per B.H.P. at 32*s.* 6*d.* per ton	44 16 6	89 13 0	—	—
Coal gas :—18 cub. ft. at 1*s.* 7½d. per 1000	—	—	82 4 0	164 8 0
Water for vaporizer, scrubbers, etc. 2 gals. per B.H.P. at 9*d.* per 1000	4 4 0	8 8 0	—	—
Oil :—1½ gals. per week at 1*s.* 9*d.*	6 16 0	6 16 0	6 16 0	6 16 0
Labour[1]	20 16 0	20 16 0	5 4 0	5 4 0
Total cost per annum £	104 17 6	167 3 0	110 9 0	203 13 0
Cost per B.H.P. hour	0·448*d.*	0·357*d.*	0·472*d.*	0·435*d.*

[1] For suction plant :—1 whole day for cleaning out producer, etc., and 2 hours per day for 5 days = 2 days weekly at 24*s.*
For town gas :—½ day per week at 24*s.*

It will be clear that for small plants of about 20 H.P. the cost of coal gas compares very favourably with suction gas, and when all its advantages, enumerated above, are taken into account, it has decided preferential claims. As the size of the plant increases, the advantages of suction gas become evidenced, but it is impossible to say at what point the many advantages of coal gas are more than counterbalanced by the lower total costs of suction gas per H.P.; so much depends on the price of the fuels in the particular locality. Under any circumstances coal gas appears unlikely to prove superior to suction gas where the power exceeds some 50–60 H.P.

In nearly all suction gas plants which may be regarded as entering into competition with coal gas, anthracite is the fuel employed. The cheaper fuels, coke and possibly bituminous coals, do not find their application in these smaller plants.

The competition between suction gas plants, coal gas, oil and electricity has been discussed widely, and the relative merits of each not overlooked by their respective advocates. A comparison of the consumption for each is arrived at easily from data already given, and a comparison of costs deduced. The consumption per B.H.P. may be taken as—

Anthracite in suction gas plants (including stand-by consumption)	1·1 lbs.
Coal gas	17 cub. ft.
Oil	0·7 pint.
Electricity	0·7 unit.

Taking various prices within the normal range for the different fuels, the cost in price per B.H.P. is given in Table L.

TABLE L.

COST OF FUELS AND ELECTRICITY IN PENCE PER B.H.P. PER HOUR.

Anthracite. 1·1 lbs. per B.H.P.		Coal gas. 17 cub. ft. per B.H.P.		Oil (Kerosene). 0·7 pint per B.H.P.		Electricity. 0·7 unit for B.H.P.	
Price per ton.	Pence per B.H.P.	Price per 1000.	Pence per B.H.P.	Price per gal.	Pence per B.H.P.	Price per unit.	Pence per B.H.P.
28*s.*	0·165	1*s.* 0*d.*	0·204	6*d.*	0·502	¾*d.*	0·525
30*s.*	0·176	1*s.* 3*d.*	0·255	7*d.*	0·610	1*d.*	0·700
32*s.*	0·187	1*s.* 6*d.*	0·306	8*d.*	0·700	1½*d.*	1·050
34*s.*	0·200	1*s.* 9*d.*	0·357	9*d.*	0·790	2*d.*	1·400
36*s.*	0·212	2*s.* 0*d.*	0·408	10*d.*	0·875	2½*d.*	1·750

Mr. C. E. Teasdale (*J. Gas Ltg.*, 1910, **109**, 505) gave the following costs per B.H.P.-hour with gas at 1*s.* per 1000 cub. ft. and electricity at 1*d.* per unit—

Size in H.P.	Mechanical efficiency.		Cost in pence per B.H.P.-hour.	
	Electric motor.	Gas engine.	Electricity.	Gas.
30	91	89	0·820	0·18
800	93	90	0·803	0·18
1000	95	91	0·790	0·18

The consumption of gas per B.H.P. is taken as 9000 B.Th.U., a better figure than is usual under ordinary running conditions. Further, although gas can be obtained at the above rate in certain towns, the average cost for power is about 1*s.* 7*d.* To meet these altered conditions the figures under gas cost should be multiplied by 1·8.

Very valuable tables of the cost of fuel in small and medium installations per unit of electricity generated were given by Mr. J. F. C. Snell before the Institute of Electrical Engineers (1908, 40, 291). The figures given in Table LI. represent the actual cost as obtained in independent installations. The price of anthracite is much below current rates and might well be increased 50 per cent.

TABLE LI.

COST OF GENERATING ONE ELECTRICAL UNIT IN PENCE (*J. F. C. Snell*).

Installations up to 100 *H.P.*

Load factor.	Equivalent hours per annum.	Suction or producer gas. Anthracite at 22*s*. per ton.	Town gas, at 2*s*. per 1000.	Oil engines, oil at 42*s*. 6*d*. per ton.	Steam (or small peas) coal, at 10*s*.
30	2628	0·812	0·944	0·650	0·705
40	3504	0·694	0·844	0·563	0·598
50	4380	0·625	0·791	0·511	0·542
60	5256	0·576	0·745	0·475	0·498
70	6132	0·540	0·706	0·448	0·460
80	7008	0·514	0·670	0·426	0·429

Installations from 100–500 *H.P.*

Load factor.	Equivalent hours per annum.	Suction or producer gas. Anthracite at 22*s*. per ton.	Town gas, at 2*s*. per 1000.	Oil engines, oil at 42*s*. 6*d*. per ton.	Steam (or small peas) coal, at 10*s*.
30	2628	0·596	—	0·536	0·534
40	3504	0·502	—	0·469	0·464
50	4380	0·447	—	0 430	0·421
60	5256	0·406	—	0·404	0·393
70	6132	0·377	—	0·382	0·373
80	7008	0·358	—	3·366	0·357

In Berlin suction gas plants are employed in generating current for lighting independent blocks of buildings on a consumption of 1·75 lbs. anthracite per K.W.

Whilst low fuel consumption must be a factor of great importance in any power plant, it can be the deciding factor between different systems only when all costs, capital expenditure, depreciation, operating costs, etc., are all about equal. The advantages accruing to lower fuel consumption are in some cases more than counterbalanced by the lower fixed charges on some other system with somewhat higher fuel consumption. The consideration of all these contingent costs is clearly beyond the scope of this work; indeed, in nearly every case it depends on such special factors that each requires careful individual consideration.

One point which frequently is overlooked is that low fuel consumption involves, on the one hand, carrying less stock of fuel, with less capital expenditure in suitable stores, lower handling costs of the fuel and ashes, and frequently less loss by deterioration. On the other hand, where about the same stock is carried, the consumer is provided with far larger reserves of fuel for operating the plant when supplies may be interrupted through colliery strikes or transport difficulties.

With gaseous fuels the inability of the engine to carry any great overload is important, especially in conjunction with the greatly reduced efficiency at largely-diminished loads. This means that individual units should be provided to work as nearly as possible up to the rated load for maximum efficiency. With modern methods of starting gas-engines on compressed air or electricity, no difficulty arises in putting other units into operation as required. On the other hand, the gas-producer plant offers this great advantage over steam, viz., that the efficiency is almost as good in small plants as in large, which is in marked contradistinction to most steam plants. Further, the United States tests have shown that whilst the consumption of low-grade fuels under boilers increases very rapidly with diminution in quality, the consumption in producers does not increase in anything like the same proportion.

Suction and Pressure Systems.—In general the Suction gas plant is operated on non-bituminous fuels, the Pressure gas on either non-bituminous or bituminous. Each has its own field more or less broadly defined, but it is impossible to fix definite outlines to these fields.

The suction gas plant usually forms a separate unit with its own gas engine. Its special features are the compactness of the plant, the ease of operating and the low fuel costs. Because of the simple form which the purifying portion of the plant must take, the ordinary suction plant is unable to deal with fuels evolving tarry matter. The gas being always under reduced pressure, leakage of poisonous carbon monoxide is impossible. Owing also to this reduced pressure the gas charge per unit volume of cylinder capacity is lower than with pressure gas. If the absolute pressure of the gas is reduced (say by some obstruction) from 11 lbs. to 7 lbs., there is a reduction of the charge by 50 per cent.

Where the producer and cleansing plant are operated by fan suction, the gas being sent at something above 15 lbs. absolute pressure to the engine, these drawbacks are overcome. Fans also serve to eliminate tar fog and, by a return valve system, suction plants are often made to deliver gas for heating purposes.

With pressure plants, the process being more continuous than with suction plants, since it is independent of fluctuations in the load, the gas is of more uniform composition. A gas-holder usually provides a reserve of gas for distribution and minimizes fluctuations in pressure. After the producers have been standing-by, the holder preserves a supply of good gas until once more they are making good gas, the poor gas meanwhile being sent to waste. A gas-holder, without being of impracticable dimensions, can hold only a small supply of such low power gases.

In many pressure plants, especially on the Continent, the gas-holder is abolished; automatic control of the make to meet varying demands is obtained by a fan driving in the air blast instead of by the use of steam injectors; large mains minimize pressure variations.

With the marked increase in the size of suction gas plants and the use of bituminous coals in such plants, pressure plants for non-bituminous fuels are unlikely to find extended use. The field previously covered by such plants is now within the scope of suction gas plants; units up to 500 H.P. are not uncommon.

Pressure plants for bituminous fuels find their special application where the demand for gas is high, and especially where gas is required for heating as well as power purposes. The higher capital outlay and operating charges are far more than counterbalanced by the very low fuel costs possible when low grade bituminous coals are employed. Further, the gas has a higher calorific value from bituminous fuels.

The great reduction in fuel costs possible through ammonia recovery has been referred to already. At what point in gas output it pays to install recovery plant can be decided only by a careful consideration of the consumption, initial outlay, and character of the fuel, especially the average nitrogen content. Seven shillings per ton of fuel from ammonium sulphate is a figure often realized in practice as a set-off against the first cost of the fuel.

Summarized, the present position of the different systems of the application of gas power may be expressed on these broad lines. Up to 50 H.P. coal gas below 2*s.* per 1000 cub. ft. is a serious competitor with suction gas from anthracite, which is employed almost universally in such plants in spite of its high cost. Suction gas finds its application in all plants up to about 400–500 H.P. units. For the higher ratings, the use of coke or bituminous coals, if available of suitable character, owing to their relatively low cost as compared with anthracite, is necessary if fuel costs are to be kept down. From this point upwards, pressure plants working on cheap non-caking bituminous fuels are general. At about 1000 H.P., the upper limit depending largely on capital cost of the installation, the claims of ammonia recovery plant call for consideration, which may be said to be invariably economical at 2000 H.P. output.

The rival claims of the large gas plant and steam turbines for the production of electricity offer a big field, and have been dealt with adequately in a paper by Andrews and Porter before the Institute of Electrical Engineers (1909). This paper, together with the important discussion thereon, should be referred to. The general deduction is that the fuel consumption per K.W.-hour for steam turbine machinery at its best is about 3 lbs.; for gas plant 2 lbs. The relative price of plant per K.W. installed is about £14 for boilers and turbines, and £17 10*s*. for a gas installation.

The question of further economy in a steam plant through the use of engines of high economy with the exhaust steam passing through low pressure turbines was discussed by Mr. T. M. Chance (*Eng. Record*, 1909), who gave the following estimated consumptions for a 1000 K.W. plant of each type:—

Load factor.	Pounds of Coal Gas.	Pounds of Coal Steam.
40 per cent.	2·1	2·45
60 „	1·8	2·15
80 „	1·7	2·00
100 „	1·7	1·95

In the "Memorandum" for the year 1911 issued of Mr. Stromeyer, the Chief Engineer of the Manchester Steam Users' Association, the relative cost of burning fuel or oil under boilers and employing oil or gas in internal combustion engines is dealt with. With the price of oil then ruling, it was not profitable to burn it in preference to coal until the cost of this had risen to 38*s*. per ton; but oil could be used profitably in internal combustion engines whenever and wherever the price of coal exceeded 15*s*. per ton. The following comparisons are made: roughly stated, a first class modern steam engine utilizes about 12 per cent. of the available heat in the coal, from 1·6–1·7 lbs. of fuel per B.H.P. per hour for a week's work of 55 hours. If the boilers are fired by producer gas, for which purpose slack and dust can be used, then each B.H.P. will require about 2–2·2 lbs. of coal. Internally-fired gas and oil engines are approximately twice as efficient as steam engines, which means that they utilize about 25 per cent. of the available heat. Crude oil being 37 per cent. better than good ordinary coal, oil engines should use only about $\frac{3}{8}$ of the quantities of coal mentioned above—say, about 0·6 lb. per B.H.P. Then, however, as there are no boiler radiation losses overnight, a material saving result, and the oil consumption per week of 55 hours may be about 0·5 lb. per B.H.P. Petrol and similar internal combustion engines would require about 0·4 lb. (?). Gas engines have also about the same efficiency as oil engines; but as there is a loss of about 20 per cent. in the producers, if these work day and night, and another loss of quite 10 per cent. if they have to stand idle overnight, the efficiency of gas engines is only about 40 per cent. better than that of first-class steam engines.

PART IV

FUEL ANALYSIS, CALORIMETRY AND CONTROL OF FUEL SUPPLY

Chapter XVII

FUEL ANALYSIS

Space does not permit of exhaustive treatment of methods of analysis, neither is it necessary, for the usual determinations required in commercial work are fairly simple and will be described as far as necessary. More elaborate determinations, such as those involved in arriving at the ultimate composition of a fuel, are carried out by the well-known methods of organic analysis, familiar to all chemists, and such work is hardly likely to be undertaken by others.

Whilst for technical work on fuels reasonable accuracy is demanded, the tendency to strain after excessive accuracy in determining the important factors of moisture, volatile matter and ash in fuels—which are all that are usually required in addition to calorific value—is often ridiculous in view of the difficulty of sampling large bulks of fuel. The present vogue is to strain at the gnat of accuracy, whilst the camel of inaccuracy through difficulties of sampling is swallowed without murmur.

Sampling.—This is a point to which special attention must be directed, for the sample examined must represent always as far as possible the bulk from which it is drawn, and enough of the original must be dealt with to ensure this.

When coal is handled the lump and small coal readily separate, and since the small generally yields more ash and is often much wetter than the lump, care must be taken to get a proper proportion of each. Again, slaty portions are very unevenly distributed. In general, the larger the pieces the more important it is to take a good quantity—at least 3–4 cwt.—to start with, drawn from different parts of the bulk or trucks.

All must be broken down next to pieces no larger than a hen's egg, mixed and piled in a heap. This is divided into quadrants of four equal portions, one portion being taken. This selected portion should be broken down to the size of walnuts, again mixed and quartered. It should undergo then a further crushing until all passes a ¼-in. mesh sieve. After thorough mixing, about 2 lbs. should be put into an air-tight vessel for the analyst's sample. Where duplicate samples are required, it is most important to see that they are identical. Jars with air-tight lever lids are very convenient, or, if tins are used, these should be soldered down if they are to be sent away.

A rock crusher is always employed by the author for the reduction of coarse samples, and is very convenient. After quartering from this, 100 grams of the coarse powder should be weighed out in a shallow metal tray, and the moisture lost by air-drying for 24 hours at ordinary temperatures determined.

For analysis, the air-dried sample is put through an ordinary coffee mill, which experience shows is the readiest and simplest method of getting a fine sample. About half should be preserved in a stoppered bottle, to serve as the general sample. From this about 25 grams are taken and ground until the whole passes a 60-mesh sieve. Many employ a suitable ball mill for the final grinding, in which case a larger quantity may be reduced.

The advantage of taking moisture by an air-drying on the coarse material is threefold: wet coal cannot be ground properly; in the somewhat prolonged process of grinding and sieving moisture would be lost; finally, drying wet coal in an oven may give fallacious result.

The question of coal sampling has been discussed fully by E. G. Bailey (*J. Ind. and Eng. Chem.*, 1909, **1**, 161.

Peat is very difficult to sample fairly, especially when very wet and soft. It should be broken up well by hand on a metal tray, mixed, quartered and the moisture determined by drying at a low temperature on a tray. It is convenient to support the tray about one inch above the top of an ordinary steam oven. The dried material now may be broken up, and a fair sample obtained for the analysis.

Heavy oil in bulk should be sampled by taking "cores" from two or three parts of the tank or waggon, as is possible usually. A long iron tube of ¾ to 1 in. in diameter is fitted at the bottom end with a wooden plug, from which a wire leads to the top of the tube. This is pushed down to the bottom of the tank, the plug is pulled into place by the wire and fixed by a sharp blow on the bottom of the tank.

For U.S. official methods of sampling, see Bureau of Mines Bulls. 63 and 116 (also *Times Eng. Sup.*, 26th Jan. 1917).

PROXIMATE ANALYSIS OF COAL

(*Moisture, Volatile Matter, Fixed Carbon, Ash.*)

For technical purposes these determinations, together with an accurate estimate of the calorific value, are all that are required. It is only in exceptional cases that the ultimate analysis—carbon, hydrogen, oxygen, etc.—is demanded, although very essential for the complete study of a particular coal. Sulphur and nitrogen, however, are often of importance, and their estimation will be dealt with.

Moisture.—The sample should be air-dried previously, the moisture lost in this being recorded and added to that determined by subsequent drying at 105° C. for one hour, to give the total moisture.

Most coals undergo other changes than the mere loss of moisture on drying. It is found frequently that after a loss of weight is noted for some time, then there is an increase. This is due to oxidation of constituents. Further, small quantities of material, other than moisture, are lost at 105° C., but the loss through this has been shown to be negligible. By drying at 105° C. under suitable conditions the loss in one hour corresponds very closely with the moisture determined by actually absorbing the evolved water and making a careful estimation. The process of oven-drying really gives good results by a balance of errors.

One gram of the sample should be weighed out in a shallow pattern stoppered weighing-bottle, in order that a thin layer may be obtained. A pair of 2-in. watch glasses with suitable clamp may be used also. The sample is heated for one hour, cooled in a desiccator, and the loss determined.

An air oven heated by a good ring burner is usually employed, with suitable thermostat and thermometer. It is preferable to use an oven heated by either a liquid or vapour jacket; more uniform distribution of temperature in the oven is attained. Toluene is a suitable liquid for vapour heating, but the ovens used in the United States Official Laboratories are the best. They consist of a double-walled copper cylinder, closed at one end, and having a double-wall door at the other. The space between the walls is filled with a glycerin-water mixture (sp. gr. 1·19 at 15° C.) of such concentration that when boiling the oven is maintained at 105° C. A reflux condenser keeps the concentration of the solution constant.

When a gas-heated oven is employed, it should be fairly capacious, and the bottle should be placed as nearly as convenient to the middle of the oven, and not in direct contact with the shelf on which it stands, as this is generally overheated by conduction. A good plan is to bend the wires of a pipe-clay triangle downwards, place an asbestos card on this, and the bottle on the card.

An ordinary water oven never attains a sufficiently high temperature for the estimation of moisture in fuels.

For a full consideration of the question of moisture determination, especially in coal, the paper by G. N. Huntley and J. H. Coste (*J. S. C. I.*, 1913, 62) should be consulted.

Volatile Matter and Coke.—The determination of the loss by distilling off at a high temperature all the volatile matter from powdered coal under such conditions that air does not find access to the sample, at first sight, would appear to be a simple proposition, but a number of factors interferes with the result. The maximum temperature attained and the rate of heating are the principal. Slow heating gives a higher coke-yield than a quick heat. The nature of the crucible and its size will affect this considerably, and platinum should be employed always. It is found that even a polished crucible gives a different result from a dull crucible.

It is next to impossible to obtain in the laboratory with a small sample the conditions existing in a gas retort or coke oven; it is better to find that procedure which gives a coke most closely resembling in composition that obtained from coals on a large scale of working, and standardize the method to give consistent results.

The standard American method best fulfils these conditions, and is adopted almost universally. The details are:—"One gram of the fresh (air-dried) powdered coal is heated in a platinum crucible of 20–30 grams weight, provided with a closely-fitting lid, for 7 minutes over the full flame of a bunsen burner. The flame when burning free should be 20 cm. high, and must be protected from draughts. The crucible should be supported in a platinum wire triangle so that its bottom is 6 to 8 cm. above the top of the tube of the burner. The crucible must be allowed always to cool sufficiently for transference to a desiccator without disturbance of the lid. The under surface of the lid should be covered with carbon, but the upper surface should be free from it."

The various methods of determining the volatile matter have been compared by Constam (see *J. Gas Ltg.*, 1909, 108, 184), who pronounced on the American method as being most accurate. The method of Heinrichos of heating for 3½ mins. over a bunsen and 3½ mins. over a blowpipe, gives practically the same results as the American method. A. J. Cox (*J. Amer. Chem. Soc.*, 1907, 29, 775) states that while the official American method gives satisfactory results with coking coals (and others of lower volatile content), for more bituminous coals there is some mechanical loss. Cox recommends a preliminary period of "smoking off," which in his opinion could be adopted advantageously for all coals.

In the U.S. Bureau of Mines Laboratories (*Tech. Paper No.* 8, 1912) this smoking-off by 4–6 minutes' preliminary heating before the final 7 minutes at full temperature has been adopted for lignites and coals high in moisture.

This agrees with the experience of the writer, who has adopted the following modified procedure in all cases—two bunsens are employed, one 4½ in. high, adjusted so that the tip of its flame just touches the bottom of the crucible; the other 6 in. high, adjusted to the American conditions. The smaller flame is applied for 3½ min., and then replaced immediately by the full burner for 7 min. It is better to employ two bunsens than to attempt the adjustment of the one.

S. W. Parr recommends moistening 1 gram of the coal with 10–15 drops of kerosene to avoid mechanical loss.

The physical nature of the coked residue affords considerable information as to the character of the coal, and should be noted always in a report. It is true that the conditions with the small weight and a metal crucible are not comparable with practice, and an improved method, specially designed to afford more specific information as to the character of the coke, is due to R. Lessing (*J. S. C. I.*, 1912, 465). The apparatus is constructed throughout of quartz glass, and consists of an outer heating tube, around which a spiral of platinum wire is wound, the coils being close together at the lower end, and gradually opening out higher up. This outer tube is embedded in kieselguhr, as an insulating material. The decomposition tube fits closely into the heater, and again inside this a plunger-like tube is fitted. One gram of the sample is used in the apparatus.

Very consistent results are obtained with the same coal in a series of experiments. It has been put forward as an objection to Lessing's method that because a cold start is made, it does not agree with the conditions in practice, coal invariably being charged into a heated retort. From numerous determinations by Euchêne, Bond and others, it is known that heat travels but slowly through the coal in retorts or coke ovens, and it is established that only the superficial layers in contact with the fireclay heat up quickly. The rapid heat penetration in a crucible is really a weak point. It is well known that the coking properties of many coals are dependent largely on the rate of heating; when rapid some will give no coherent coke, whilst by heating slowly the coke is quite good.

It appears therefore that a method such as Lessing's, where great control of the rate of heating and temperature of great uniformity are attainable through the use of the electric current, offers many advantages over gas-heating. With experience it should be possible to get results in close agreement with those obtained on a large scale. From figures given in the paper the quantitative results are in excellent agreement with those of the American method.

Campredon's test for the coking power of coal has been described on p. 57.

Ash.—The residue left in the crucible gives the "Coke-yield." After weighing the crucible lid is removed, the crucible placed well on its side in the triangle, and the carbon burnt away entirely by the bunsen burner. Spreading the coal into the thinnest possible layer shortens the time required. The residue left consists of the ash.

The loss of weight which the coked residue suffers is regarded as "fixed carbon."

The determination of the ash is liable to certain errors. Alix and Bay (*J. S. C. I.*, 1904, 800) say that in six samples of coal examined there was a mean content of 4·99 per cent. of calcium carbonate ($CaCO_3$), equal to 2·06 per cent. of carbon dioxide. This gas would be driven off during incineration of the coke, and a low result obtained. It is important to note that this would also raise the percentage of carbon determined in an ultimate analysis. J. W. Cobb (*J. S. C. I.*, 1904, 12) found also, when determining the unburnt carbon in ash and clinker, that the loss on ignition may be due in part to the escape of sulphur.

The fusibility of the coal ash is often an important point, and reference to the composition in relation to fusibility has been made on p. 41. A practical test on this point is often of value, and may be made on the well-known Seger cone principle for determining high temperature. J. W. Cobb (*J. S. C. I.*, 1904, 11) grinds the ash until it will pass a sieve with 100 meshes to the linear inch, moistens the powder and builds a pyramid 1 in. square at the base, and 3 in. high, with one side vertical. The cones are heated in a muffle furnace until one softens and turns down. Heating must be uniform throughout the muffle. Comparison may be made between a standard ash sample or relatively between different samples.

An electric resistance muffle furnace would be certainly most suitable, and it would be preferable to record actual temperatures, as taken by a thermo-junction.

Sulphur.—By far the most convenient and accurate process for coals, and in the writer's experience, the only really good one for oils, is that of burning the fuel in a bomb calorimeter with an oxygen pressure of not less than 20 atmospheres. A little distilled water is put in the bottom of the bomb, and after combustion the gases are allowed to remain for 10 minutes to give proper absorption. Since the calorific value generally has to be taken, the sulphur determination is carried out simultaneously.

Sulphur is converted into the trioxide on combustion at these pressures and rapidly absorbed by the water. The water and washings are filtered, and the sulphuric acid precipitated in the nearly boiling solution by hot barium chloride. An important point to note is that with small quantities of sulphur precipitation is by no means so rapid as usually assumed; the liquid always should stand in a warm place for at least six hours.

Innumerable other methods of determining sulphur in fuels are in use, and as a bomb is not always available, the principal of these must be discussed.

The Eschka process is to be preferred in such a case. A mixture of 1 part of pure dry sodium carbonate and 2 parts of pure calcined magnesia (MgO) is prepared. It is often very difficult to obtain the latter free from sulphate, and some prefer to use pure lime. One gram of coal is mixed intimately with 1·5 grams of this mixture in a platinum crucible, and the mixture heated, commencing with a gentle heat applied to the bottom of the crucible and increasing gradually. When all carbon has been burnt, shown by there being no black specks in the residue, the contents are emptied into a beaker, and the crucible washed out, about 50 c.c. of water being used. 15 c.c. of saturated bromine water are added, and the solution boiled for five minutes in order to oxidize sulphurous acid to sulphuric. The insoluble residue is allowed to settle, the clear liquid poured off, and the residue washed twice by boiling with more water. The total clear liquid is acidified with hydrochloric acid, boiled to expel the bromine, and the sulphuric acid precipitated from the nearly boiling solution by hot barium chloride.

Since coal gas is liable to lead to contamination of the contents of the crucible, a spirit flame frequently is preferred for heating.

Bender (*J. S. C. I.*, 1905, 293) carries out the ignition in a hard glass tube 18 cm. long, 2·8–3 cm. diameter, with the same object. Brunck (*J. S. C. I.*, 1905, 1086) used cobalt oxide instead of magnesia, in the same proportion. Heating may be carried out in a platinum crucible, but is conducted preferably in a porcelain boat heated in a tube through which oxygen is passed. The process is completed in 15 minutes. The gases may be passed through hydrogen peroxide to recover any escaping sulphur dioxide.

Parr (*J. Amer. Chem. Soc.*, **22**, 646) and others have employed sodium peroxide as the oxidizing substance. About 0·7 gram of the sample is mixed with 13 grams of peroxide in a 30 c.c. crucible. This is placed in water, so that the bottom is kept cool, the cover placed on, and the mixture fired by nitrated wick. The contents are dissolved in water, filtered, acidified with hydrochloric acid, and the sulphur estimation carried on as described.

Comparisons of the various methods have been made by C. W. Stoddart (*J. Amer. Chem. Soc.*, 1902, **24**, (9), 852) and Holliger (*J. S. C. I.*, 1909, 357). Both agree that the bomb is most accurate, but the latter states that with high ash some sulphur may be retained in it. Holliger says Eschka's method may be inaccurate when there is over 2 per cent. of sulphur, and Stoddart that silica in solution should be removed always by evaporation of the acid solution. Both agree that the sodium peroxide method is liable to give low results, and Holliger considers it should be used only where speed rather than accuracy is aimed at.

Sulphur in Oils, etc.—As already mentioned, the bomb method is far the most satisfactory, but alternatives must be considered. Hodgson regards the Carius method, commonly employed in organic analysis, as suitable for accurate results. Goetzl (*J. S. C. I.*, 1905, 1086) places 2–3 grams of the oil in a large platinum crucible, 4 c.c. of fuming nitric acid are floated on top, the cover put on, and the liquids allowed to mix gradually and then stand over-night. The mixture is heated on the water-bath, and, when action ceases, evaporated to dryness. The dry residue is mixed with 5 grams of dry sodium carbonate and 1 gram of potassium nitrate, a layer of the same mixture being placed on the top, and the whole heated until white. The residue is dissolved in water, and the sulphur determined.

Garrett and Lomax (*J. S. C. I.*, 1905, 1212) employ a modification of the Eschka method. 0·7 to 1·5 grams of the sample are mixed intimately with 3–4 grams of a mixture consisting of 4 parts of pure lime and 1 part of dry sodium carbonate. The crucible is then filled up with this mixture. A larger platinum crucible is then placed over the smaller one, the two inverted, and the space between the two filled with the mixture.

The mouth of the crucible is covered with a thick pad of asbestos board, and the two crucibles placed in a muffle already heated. The asbestos prevents radiation from the top of the muffle heating the substance until the soda-lime packing is hot. In two minutes distillation commences, the asbestos may then be removed, and heating continued for two hours. The process is completed as in Eschka's method. Results are said to be good when compared with those by the Carius method.

Nitrogen.—By far the most convenient method for solid fuels is that of Kjeldahl. With coal, it is very desirable to reduce the sample to as fine a state of division as possible; time spent over this is repaid amply by the shortening of the solution period. The method adopted in the Laboratory of the U.S. Bureau of Mines is as follows:—

1 gram of the sample is boiled with 30 c.c. of concentrated sulphuric acid, and 0·6 gram of mercury, until the solution has become straw-coloured. Potassium permanganate is then added in small quantities, until a permanent green colour is produced. After dilution to about 200 c.c. and the addition of 25 c.c. of potassium sulphide solution (40 grams per litre) to precipitate the mercury, 1 gram of granulated zinc is put in, to prevent bumping, and a small fragment of paraffin wax, to prevent frothing, the excess of strong sodium hydroxide solution is added, and the ammonia driven off into standard sulphuric acid, as usual.

EXAMINATION OF LIQUID FUELS

Specific Gravity.—This may be taken by any of the usual methods, but with very thick oils is determined best in a 250 c.c. graduated flask, the weight of which and the water content have been ascertained previously.

In many cases, with heavy fuel oils, the weight delivered is computed from the volume, and temperature will be clearly of the greatest importance. It is usual to make a correction of ± 0·0006 to the specific gravity for each degree above or below 15° C. The coefficient of expansion for different petroleum distillates has been given on p. 110.

The specific gravity at 15° C. having been ascertained, the weight of the barrel of oil, whether in United States or Imperial gallons, can be determined as described on p. 109.

Flash Point.—This is defined as the lowest temperature at which vapour is given off from the oil in sufficient quantities to be ignited by a flame.

The *ignition point* is defined as that temperature at which sufficient vapour is given off not only to be ignited, but with sufficient rapidity for the oil to continue burning.

Clearly the flash point will be dependent upon, first, the vapour pressure of the oil, which to a minor degree will be dependent on the barometric pressure; secondly, the proportion of oil vapour in air requisite to form an ignitable mixture. This proportion will vary little for the different petroleum distillates, but several factors will determine when the requisite quantity is reached. If the apparatus is open to the air it will be reached only at a higher temperature than in an enclosed apparatus. In the latter the ratio of the air space to the surface of oil exposed will influence the result, so that standard sizes for closed testers must be adhered to rigidly if results are to be comparable. Again, in a closed apparatus, when the test flame is lowered through the testing port, the air and vapour inside are replaced by fresh air drawn down through the other open ports provided, and if testing is performed at regular temperature increments, but at different rates of heating the time given for sufficient vapour to diffuse into the air will vary and hence also the result.

These points are mentioned in order to emphasize the necessity for adopting standardized apparatus and procedure, if discrepancies are to be avoided.

The *open flash test* is clearly liable to considerable variation and is only an approximate test, though often of value for crude oils and residues. The apparatus should consist of a porcelain crucible 2½–2¾ ins. diameter at the top, ¾ in. across the bottom, and 1¾ ins. deep. It is placed in a hole cut in asbestos board so that the bottom of the crucible projects below about ¼ in., and a small heating flame should just touch the bottom. The oil should reach to within ½ in. of the top of the crucible. It is important to see that the bulb of the thermometer is properly adjusted to the centre of the oil. Many ordinary cylindrical bulb thermometers have too long a bulb to permit this.

The most convenient test flame is a tiny jet of gas burning at the end of an ordinary mouth-blowpipe. Draughts must be excluded carefully.

Closed Tests.—The *Abel apparatus* has become a legally standardized tester in this country and the Colonies, and is employed for ordinary burning oils. The apparatus, together with dimensions for the principal parts is shown in diagrammatic section in Fig. 54. The cup A is insulated from direct contact with the heating vessel B by a vulcanite ring *v*, on which the flange rests. There is an air space C ½ in. across between the sides and bottom of the cup and the wall of the heater, so that with water always at one temperature in the latter when commencing, the rise of temperature of the oil is always regular, though not uniform for equal increments of time.

The procedure for legal testing is laid down strictly, but need not be detailed here. For ordinary purposes the following directions will suffice—

The heater is filled with water at a temperature of 130° F. The oil cup is placed on a level surface and filled to the proper level, care being taken that none is splashed on the sides.

The cover is placed on the oil cup, the thermometer inserted, and the test flame adjusted to the size of the bead provided and mounted on the cup.

The cup is placed carefully into position in the heater, the whole apparatus being in a situation free from draughts. Testing is commenced at 66° F., the slide being drawn open *slowly* and closed *quickly*. This is repeated at every degree rise of temperature until a flash is obtained.

If a flash occurs between 66 and 73° F. (the lower legal limit) a fresh portion of the oil is cooled to 55° F. before putting in the cup, and testing is commenced at 60° F.

If no flash is given before 95° F. the bath is emptied and refilled with water at 95° F., also the air space to a depth of $1\frac{1}{2}$ ins.; fresh oil is taken, and the whole warmed up by the burner, testing being carried out at degree intervals.

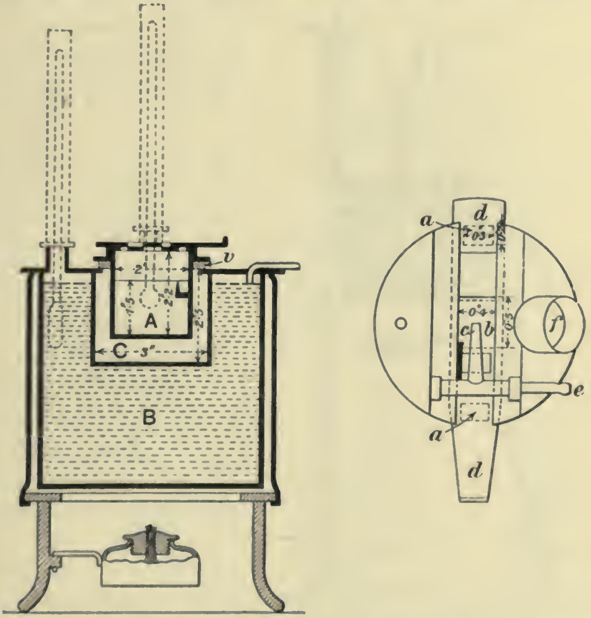

FIG. 54.—Abel flash-point apparatus.

With very low flashing oils the sample may be cooled to 32° F. in melting ice, also the oil cup itself, before filling. The cup may be mounted conveniently through a sheet of asbestos card, so that it extends into a beaker containing water (with ice) at 32° F. If there is no flash under these conditions the temperature is raised slowly until the proper flash point is reached. A special thermometer will require to be fitted by means of a cork, as the one supplied with the apparatus does not record these low temperatures.

Where special accuracy is demanded, the flash point is corrected for barometric pressure, 1·6° F. being added or subtracted for each inch above or below 30 ins.

The *Abel-Pensky* apparatus has been adopted officially by the International Petroleum Commission. In this form the opening and closing of the ports and the application of the test flame is operated by clockwork. The results are 3° F. higher than with the original Abel.

The *Pensky-Marten tester* is the most suitable for heavy oils flashing above temperatures attainable in the Abel tester. With these oils it is necessary to provide a stirrer in the oil, and also one to mix the heavy vapours with the air. A mass of iron is employed instead of water for the heaters. The apparatus is illustrated in Fig. 55. The stirrer is operated by means of a flexible wire, and the cup ports opened, the test flame inserted and the ports closed by turning the milled head on the upright pillar.

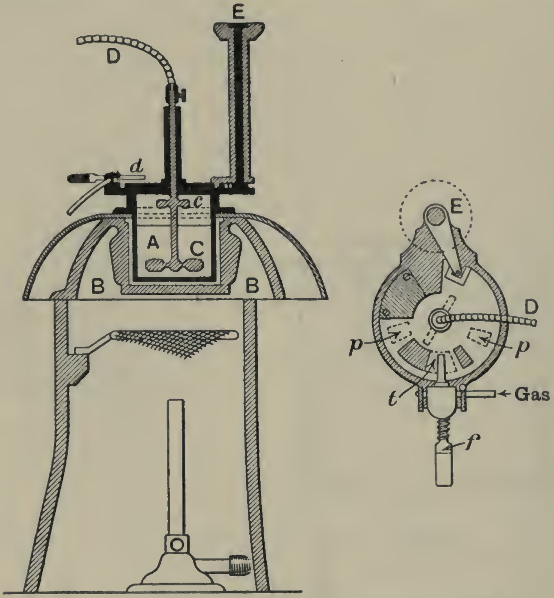

FIG. 55.—Pensky-Marten flash-point apparatus.

A, Oil cup; B, Cast-iron heater; C, Oil stirrer; *c*, Vapour stirrer; D, Flexible wire to operate stirrer; E, Milled head for operating cap; *d*, Test jet; *f*, Flame regulator; *t*, Test flame port; *pp*, Air ports.

The rate of heating should not exceed 10° F. per minute; below this rate it has no appreciable influence on the result.

Gray (*J. S. C. I.*, 1891, 343) has described a modified form of this tester, which is used largely. In this a gear wheel is provided which operates the stirrer. It is important that this wheel is rotated only slowly; there is a great temptation to stir rapidly, because of the small handle which is fitted. If this is done the oil is swirled up the sides of the cup, too big a surface is exposed, and the results are frequently 2–3° below those with the Pensky-Marten tester.

It is most important with all these testers to see that oil does not remain between the sliding and fixed plates forming the cover. These should be separated and thoroughly cleaned if necessary.

Messrs. Harker and Higgins have carried out comparative tests with types of flash-point apparatus at the National Physical Laboratory. Their results are recorded in the *Petroleum World*, 1911, pp. 303, 351, 397.

Viscosity.[1] — The viscosity of an oil hitherto has been of most importance from the point of view of lubrication. With the extending use of oils for internal combustion the viscosity, or mobility, at different temperatures is of increased importance from this wider outlook. For ordinary fuel oils for burning, laboratory instruments are not generally suitable; the orifice or diameter of the tube employed is too small and the head of pressure too low. A practical test through a pipe under a given head of pressure is preferable. The American Navy Board takes a pipe 4 ins. diameter and 10 ft. long, and the oil under a head of 1 ft. (p. 108).

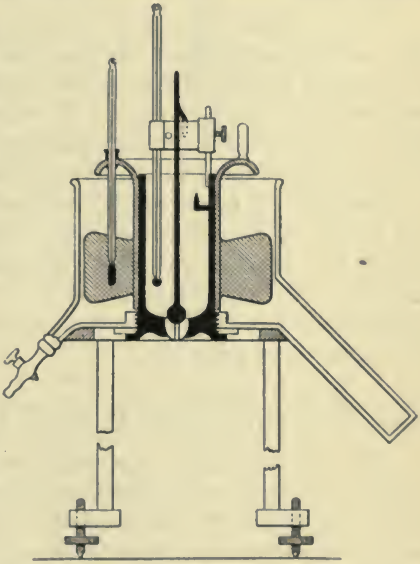

FIG. 56.—Redwood viscometer.

The *Redwood viscometer* has been adopted generally in this country for laboratory determinations of viscosity. It is illustrated in Fig. 56, The oil is contained in a central cup, having an orifice at the bottom drilled through a piece of agate. This is kept closed by a simple ball valve until the experimental conditions are realized. The water in the jacket is brought to any desired temperature by a burner placed

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[1] In the commercial sense the viscosity of an oil is the time of flow through a given orifice in a specified apparatus at a given temperature. Hence it is a function of the apparatus; whilst the true viscosity is independent of the form of apparatus.

under the extension limb, and paddles for stirring the water are provided, these centring round the oil cup.

Owing to the bad heat conduction and sluggish convection currents in most oils, it is always advisable to bring the oil to within a degree or so of the required temperature before filling the oil cup. This is done best by using a flask of about twice the volume of oil required for the test, a little more than half filling with the sample, and immersing in a large beaker of water at the proper temperature. The oil then can be shaken about and brought quickly to the bath temperature.

Having filled the cup to the top of the gauge point and obtained the correct temperature, the ball valve is opened, and 50 c.c. of oil run into a graduated flask placed below, the time being taken by a stop-watch. Samples should be run over a range of temperatures, and a curve plotted for time and temperature. It is of course very important that the oil shall be free from all suspended matter.

Rape oil is taken as the standard in the Redwood viscometer. At 60° F. 50 c.c. of this oil will average 535 seconds for the flow. Since the head of pressure with different oils will vary with the gravity, this must be taken also at the same temperatures as the viscosity determinations are carried out. Then, relatively to rape oil, the viscosity is given by—

$$\frac{\text{Time in seconds at } t^\circ}{\text{Seconds for rape oil at } 60^\circ\text{ F. } (535)} \times \frac{\text{Sp. Gr. at } t^\circ}{\text{Sp. Gr. rape oil at } 60^\circ\text{ F. } (0{\cdot}915)}.$$

The *Redwood Standard Admiralty pattern viscometer* for fuel oils is similar in design to the above, but the oil flows through an agate tube 5 cm. long about 3·5 mm. diameter. The oil cylinder is raised on legs so that it and the full length of the agate tube are surrounded by the broken ice contained in the outer vessel. Each instrument has to be standardized by experiment.

Water in Oils.—The determination of water in viscous oils often is attended with much difficulty. A sample should always be tested by enclosing in a stoppered 200-c.c. cylinder, tying in the stopper, and standing overnight in a deep beaker of water kept warm in an oven, or, what is infinitely better, on an electrically-heated hot plate.

If there is suspended water in a crude oil, in a distillation test the fractions below 150° C. will contain practically the whole of it, and the quantity may be estimated very fairly in a graduated cylinder. Drying by evaporation of the water is very unsatisfactory, and is of course inadmissible with all oils which lose by vaporization of hydrocarbons.

A very accurate method is described by Allen and Jacobs, who mix 100 grams of the oil with 200 c.c. of benzene, toluene or xylene, preferably the latter, and distil, the water separating in the distillate being measured. The liquids not being miscible, constant attention is required during the distillation, and a long and efficient condenser is employed.

Distillation Test.—With crude oils a distillation test is intended to afford information as to the relative proportion of light spirit burning oils, etc. Distillation on a large scale varies greatly in procedure, owing to the widely varying character of the crude oils and the market for products of different grades. A small scale distillation test must give sufficient separation of these to enable a sound judgment to be formed of the general character of the oil and the probable yield of the products.

The importance of the distillation test in the case of motor spirit has been pointed out, and also the great influence which the form of apparatus employed has on the result, which is true likewise of crude oils.

In the *Engler system*, 100 c.c. of the oil are distilled from an ordinary distillation flask with a side lead. The important dimensions of the flask are—diameter of bulb 6·5 cm., total length of neck 15 cm., side lead 10 cm. long, and making an angle of 75° with the neck. The bulb of the thermometer in all distillation tests must be arranged so that the top part is just below the level of the side tube. Distillation is carried out at the rate of 2–2·5 c.c. per minute. When the temperature is reached at which the volume is to be measured, the light is removed and the oil allowed to cool some few degrees, when it is again distilled up to the temperature, and so on until no more distillate is obtained.

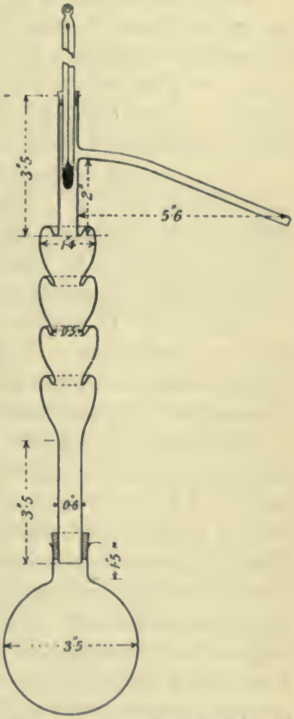

Fig. 57.—Distillation apparatus for oils.

The process gives good results, but is tedious, and the use of suitable fractionating bulbs greatly simplifies the process and gives equally good results. For crude oils and heavier distillates the writer has found the following apparatus and method excellent.

The apparatus, with essential dimensions, is shown in Fig. 57. It consists of a short-necked Jena glass flask with a 4-bulb Young column, which the researches of Prof. S. Young have shown to be one of the most efficient forms. Two hundred c.c. of the oil are used, a long Liebig condenser is attached to the bulbs, and the distillate collected in narrow graduated cylinders. No gauze is employed to protect the flask, the tip of a bunsen flame playing directly on the glass. An important point is to maintain a uniform rate of distillation throughout the run; 60 drops per minute is best.

The temperature is noted at which the first drop of liquid leaves the end of the side tube, then the volume collected at 75°, 100°, 125° C., and so on at every 25° is noted. At 150° the measure is changed, and up to this point the distillates are classed, as by Engler, as light spirits. From 150–300° C. the burning oils are collected. At about 200° the stream of water to the condenser should be cut off.

For purposes connected with fuel it is seldom necessary to go higher than 300° C. The contents of the flask are allowed to cool, drained into a measure and the volume read. By using 200 c.c. it is generally possible to obtain sufficient of the light spirit, burning oil and residuum for estimation of the specific gravity to be made.

Above 300° C. condensation in the bulbs is too great to permit of further distillation. When required to higher temperatures the Young bulbs are removed, and a plain distillation head with one cylindrical bulb substituted.

Distillation of Motor Spirit.—For this purpose a flask of the same dimensions as before is employed, but instead of the plain bulb column a 5-bulb Young dephlegmator, the efficiency of which for low boiling liquids has been demonstrated so amply. With petrols, distillation usually is carried up to 150° C., if sufficient liquid still remains, and the residue in the flask and draining from the dephlegmator in every case measured. With the introduction of various mixtures, such as petrol with benzene, or light petrols (0·680) with heavier grade oils, a carefully conducted distillation test is very necessary, and the determination of the specific gravity of the fractions essential. The volume collected over each 10° C. should be noted, and results very conveniently may be plotted on squared paper for comparison with a standard spirit.

The results for a standard sample of petrol are given below, and may serve as a basis of comparison:—

Petrol (*Pratt's*), Sp. Gr. 0·7088.
First drop at 30° C.

Temperature.	Vol. per cent.	Temperature.	Vol. per cent.
Below 50° C.	1·50	Below 100° C.	57·25
„ 60	7·25	„ 110	70·25
„ 70	19·25	„ 120	79·50
„ 80	28·75	„ 130	86·50
„ 90	42·25	„ 140	91·00

Residue above 140° C. 6·0 per cent., Loss 3·0 per cent.

CHAPTER XVIII

DETERMINATION OF CALORIFIC VALUES

DEFINITIONS of the units employed and a discussion on gross and net calorific values have been given in Chapter I. Here it remains only to consider methods by which the calorific value may be arrived at. These methods may be divided into those based upon calculations from the heating values of the constituents, or obtained by direct determination in some suitable calorimeter.

Calculated Calorific Values.—For coals the calorific value may be calculated on a basis of the elementary constituents, or on the proximate constituents. For oils, on the elementary constituents; for gases, from the values for the individual combustible gaseous constituents.

In calculating on the ultimate composition of the coal it is assumed that the elements have the same heating value as they have in the free uncombined state, and that oxygen is present in combination with its equivalent of hydrogen in the form of water, assumptions which are inherent to the method but certainly not justifiable. It involves likewise the assumption that heat is neither expended nor evolved in rendering the atoms of the constituent elements free to enter into fresh combinations with oxygen on combustion. Since coals low in oxygen have been shown to be only slightly endothermic in formation, it so happens that no heat is demanded for this, which explains the otherwise anomalous fact that calculated results in the majority of cases do agree fairly well with the determined values.

The best known formula is that of Dulong, of which numerous modifications have been proposed. Its original form was—

$$\frac{8080\,C \times \left(H - \frac{O}{8}\right) 34{,}400}{100}$$

where C, H and O are the percentages by weight of these elements

In its most complete form, with values for carbon and hydrogen due to Berthelot, it becomes—

$$\frac{8137\ \mathrm{C} + 34{,}500\left(\mathrm{H} - \frac{(\mathrm{O} + \mathrm{N}) - 1}{8}\right) + 2220\ \mathrm{S}}{100} = \text{gross calories.}$$

It being assumed that the oxygen is wholly in combination with hydrogen, the available surplus of hydrogen for combustion is equal to $\left(\text{Total Hydrogen} - \frac{\text{Oxygen}}{8}\right)$. In ordinary analyses oxygen and nitrogen are found usually by difference, and since the average nitrogen content is about 1 per cent., this deduction is made from the "difference," and the remainder $(\mathrm{O} + \mathrm{N}) - 1$, represents the oxygen.

By taking the net calorific value of hydrogen and introducing a correction for heat expended in evaporating any moisture (the round number 600, as approximately representing the latent and sensible heat in the steam at 100° C.), the formula becomes modified further to—

$$\frac{8137\ \mathrm{C} + 28{,}780\left(\mathrm{H} - \frac{(\mathrm{O} + \mathrm{N} - 1)}{8}\right) + 2220\ \mathrm{S} - (\mathrm{H_2O} \times 600)}{100}$$

= net value.

The modification of the Dulong formula adopted in Germany is—

$$81\ \mathrm{C} + 290\left(\mathrm{H} - \frac{\mathrm{O} + \mathrm{N}}{8}\right) + 25\ \mathrm{S} - 6\ \mathrm{H_2O} = \text{net value.}$$

A simplified formula for the evaporative value from and at 212° F. frequently used in this country is—

$$\mathrm{E} = 0{\cdot}15\left\{\mathrm{C} + 4{\cdot}28\left(\mathrm{H} - \frac{\mathrm{O}}{8}\right)\right\}$$

It is derived thus :—Calorific value of hydrogen is to calorific value of carbon as 34,400 is to 8080 = 4·28; the evaporative value of carbon is $\frac{8080}{100 \times 536{\cdot}5} = 0{\cdot}15$ lb. from and at 212° F.

Calculated values are always open to objection. In the first place, small analytical errors are multiplied largely; secondly, the calorific value for the same element varies somewhat as determined by different observers; thirdly, in the case of carbon, different varieties from different sources exhibit considerable variation in calorific value, depending largely on their density. Uncertainty must always exist therefore as to which value should be chosen.

Whilst with coals containing low oxygen results are generally in good agreement with those determined in a bomb calorimeter, they are often wide of the truth when the oxygen content is high. Brame and Cowan (*J. S. C. I.*, 1903, 1230), found the calculated values were from 0·7 per cent., in the case of an anthracite, to 4·8 per cent. *below* the determined value, in the case of a bituminous coal containing 10·57 per cent. of oxygen. Gray and Robertson (*J. S. C. I.*, 1904, 704) found differences ranging from +0·9 to −2 per cent. with a series of 12 coals. Bunte found differences ranging from −3·7 to +2·0 per cent., and other results might be quoted.

W. Inchley (*The Eng.*, 1911, 111, 155) reviews the question of calculated values, and puts forward the following modifications of the Dulong formula as giving more correct results :—

$$\begin{array}{c}\text{For solid}\\\text{fuels}\end{array}\left\{\begin{array}{l} 8000\,C + 33{,}830\,H = \text{gross calories per gram.}\\ 14{,}000\,C + 60{,}890\,H = \text{gross B.Th.U. per lb.}\\ 14{,}000\,C + 52{,}196\,H = \text{net B.Th.U. per lb.}\end{array}\right.$$

$$\begin{array}{c}\text{For liquid}\\\text{fuels}\end{array}\left\{\begin{array}{l} 7500\,C + 33{,}830\,H = \text{gross calories per gram.}\\ 13{,}500\,C + 60{,}890\,H = \text{gross B.Th.U. per lb.}\end{array}\right.$$

The author has applied the formula for solid fuels to all the coals analyzed by Cowan and himself and by Gray and Robertson in their comparisons of different calorimeters. Results, in percentage difference from the bomb, range from −2·42 to + 3·8. The formula for liquid fuels gives results in general within 1 per cent. of the determined value. From calculations on the German Dulong formula applied to a series of petroleum oils, W. H. Patterson (*J. S. C. I.*, 1913, 213) found the *net* calorific value from 1·25–4·2 per cent. *too high*. With two gas (? tar) oils, containing respectively 5·98 and 7·29 hydrogen, the results were 3·85 and 2·97 per cent. *too low*.

The discrepancy between calculated and determined results, which is more apparent when the oxygen content is high, has been recognized by Mahler, who proposed the following formula—

$$\frac{8140\,C + 34{,}500\,H - 3000\,(O + N)}{100} = \text{gross calories}$$

Summarized, the conclusions as to calculated values on ultimate analysis are that although good agreement (say, within 1 per cent.) is found with most coals and liquid fuels, there is always the liability of a far greater error occurring. In view of the much greater labour of conducting the ultimate analysis, which is required so seldom for technical work, and the simplicity of obtaining correct values in a good calorimeter, little can be said in favour of calculated values for solid and liquid fuels. Calculated values can be justified only when facilities do not exist for making an accurate practical determination of the heating value, and that the values are calculated should be stated clearly always.

Calculation from Proximate Analysis.—Goutal claims that a relationship between the amount of fixed carbon and volatile matter and the calorific value may be traced in coals. This he deduced for a large number of French coals by comparison with the calorific value determined in a bomb calorimeter, constants for varying amounts of volatile matter being determined. These constants must necessarily be calculated on the dry and ash-free coal, *i.e.*, on the pure combustible. Goutal's formula is $82C + aV$, where C represents the fixed carbon, a the constant, and V the volatile matter found on the whole coal.

The values for the constant a, for different values of V^1 (the volatile matter in the pure coal substance, which equals $\left.\frac{V \times 100}{C + V}\right)$ are :—

V^1	5	10	15	20	25	30	35	38	40
a	145	130	117	109	103	98	94	85	80

Applied to Brame and Cowan's coals (*loc. cit.*), these errors amount to $-2{\cdot}15$ to $+1{\cdot}88$.

Constam and Kolbe have shown that with English coals there is often a very wide difference between the heating value for coals containing the same amount of volatile matter, and whilst the heating value of the coke is practically always the same, there must be a big variation in the heating value of the volatile matter, due to difference of composition. Goutal's formula can apply only when there is a definite relation between the heat of combustion of the volatile constituents and their amount. This is frequently the case but by no means invariably, so this method of calculation is unreliable.

Calculation for Gaseous Fuels.—In the case of gaseous fuels, in such mechanical mixtures the constituent gases preserve their heating value, and the calculated results are reliable within fair limits. If one could ascertain the exact proportion of methane, ethane, etc., constituting the "saturated hydrocarbons," and ethylene, propylene, etc., constituting the "unsaturated," with accurate analyses results should be absolutely correct. In practice it is usual and, indeed, almost impossible to do more than state the total saturated and unsaturated hydrocarbons. It is generally assumed in the calculations that the former have the same calorific value as methane, and this is approximately correct, but small quantities of other members of the same series of hydrocarbons are present. The assumption, however, that the unsaturated hydrocarbons are wholly ethylene leads to low results.

Coste (*J. S. C. I.*, 1909, 1231) shows that with coal gas and coal gas-water gas mixtures, ascribing the calorific value of propylene to the whole of the unsaturated hydrocarbons gives results in good accord with practical determinations.

With gases, again, the trouble of making the analysis and the liability to error, for with complex mixtures errors are very apt to occur, cannot compare in simplicity with a direct determination, even although the former results may be good. There are cases, however, where only a small sample is available, when the calorific value must be deduced from the analysis.

CALORIMETRY

The general principle of all calorimeters which find wide application is the transference of the total heat of the combustion of a known weight of the fuel to a known weight of water; from the rise of temperature of the latter the calorific value is deduced. Not only is the water raised in temperature, but the whole of the instrument in contact with it also, and it is necessary to know the heat utilized in doing this, measured in terms of water. This is known as the *water equivalent* of the instrument, and must be determined accurately once for all.

The method of Berthier, based on Welter's rule which assumes that the heat of combustion is proportional to the oxygen used, has been proved for so long to be worthless that it need not be considered. It is mentioned only because it is still described in some books relating to steam production.

For the direct determination of the heating value of fuel certain essential conditions must be fulfilled for accurate results. Combustion must be complete; hence there must be no smoke, no carbon monoxide formed, and no invisible unburnt hydrocarbon gases escaping. The heat must be transferred completely to the water, losses by radiation from the calorimeter must be corrected for, and finally the rise of the temperature of the water must be determined with great accuracy, since the mass of fuel used is very small as compared with the mass of water heated. Very few calorimeters actually fulfil all these conditions.

Calorimeters may be classified broadly as follows:—

1. Where combustion is achieved by admixture of the fuel with a solid oxidizing agent.
    (a) A mixture of nitrate and chlorate of potassium (Lewis Thompson).
    (b) With sodium peroxide (Na_2O_2) (Parr and Wild).

2 By combustion with oxygen at ordinary pressures.
  (a) Where the temperature of the escaping products can be ascertained (Favre and Silbermann, Fischer, etc.).
  (b) Where the products escape through water, and are assumed to be cooled to its temperature (William Thomson and innumerable modifications).
3 By combustion with oxygen at high pressures (Berthelot-Mahler bomb calorimeter and all modifications).

It is proposed to deal only with typical calorimeters of each of these classes, finally considering the relative merits of each system.

Lewis Thompson Calorimeter.—This instrument has been, and probably still is, employed more extensively than any other on account of its low cost, simplicity, rapidity, and not requiring more skill than the average workman possesses to operate. As will be shown conclusively later, it is next to worthless.

Two grams of the coal are mixed with 22 grams of a mixture of potassium chlorate (3 parts) and potassium nitrate (1 part). The chlorate evolves heat on decomposition, the nitrate absorbs heat, and the two are supposed to balance. The mixture is placed in a copper tube, a piece of slow-match inserted, and fired. The copper diving bell provided is slipped over the clips in the stand holding the tube, and, when combustion is started, the whole is immersed in 1934 grams of water. At the conclusion the tap at the top of the tube extending from the bell is opened, water admitted, the whole stirred, and the temperature rise noted.

Since the weight of coal is 2 grams, and the water taken equal to twice the latent heat of steam (967 B.Th.U.), the rise of temperature gives directly the evaporative value of the fuel.

The results are "corrected" by the addition of 10 per cent. (one authority says 15 per cent.) to cover losses by the gases not being cooled properly, the heat of solution of the products, radiation, unburnt fuel, etc.

Calorimeters of the Parr Type.—In these the fuel is mixed with sodium peroxide (Na_2O_2), which readily yields one oxygen atom per molecule for the combustion of the fuel. Sodium oxide (Na_2O) is left, with which the water formed on combustion combines to form sodium hydroxide ($NaHO$), and carbon dioxide in the products of combustion to form sodium carbonate. No products therefore escape. Heat is evolved, however, in these chemical reactions, and a factor must be employed to convert the rise in temperature in degrees into calories; 73 per cent. of the heat is due to the combustible, and 27 per cent. to other chemical reactions.

Sodium peroxide is extremely hygroscopic, and the degree of moisture absorbed influences the result. It must therefore be protected carefully from the air. Further, it has been shown that the factor for the same coal may vary 3 per cent. with difference in quality and fineness of the peroxide.

Parr has stated that "Any results based upon the use of peroxide which has been sifted, ground or otherwise handled in any manner to permit of the absorption of moisture from the atmosphere are open to question," and further that "for variable or unknown peroxide it is necessary to standardize it."

Theoretically perfect as the process is, sodium peroxide alone is not sufficient to complete the combustion of many fuels, such as anthracites. "Accelerators" (such as persulphates) and, with anthracite tartaric acid also, are employed in addition, and different "factors" are required for different oxidizing mixtures. S. W. Parr has stated that "even then for anthracites and similar difficult combustible materials the unburnt carbon must always be filtered off and estimated."

Certainly the residue always should be dissolved in water and hydrochloric acid, and the solution examined for unburnt carbon.

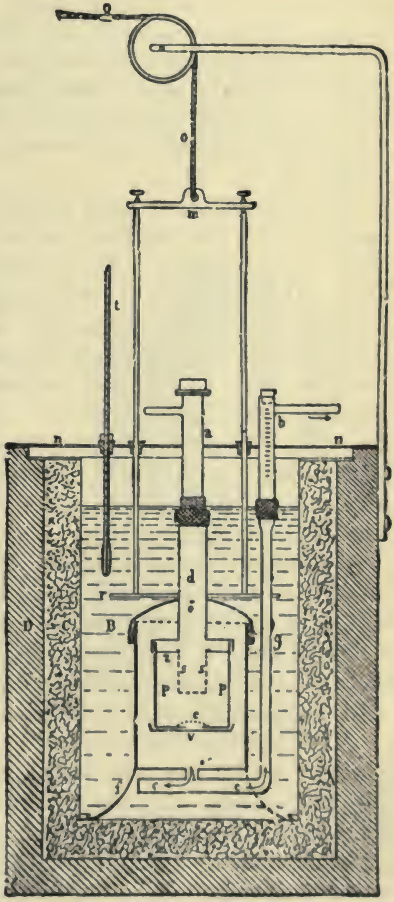

FIG. 58.—Sectional diagram, F. Fischer calorimeter.

Constam and Rougeot (*J. S. C. I.*, 1906, 1082), compared the results with the Parr calorimeter with those in a bomb calorimeter, and in addition to noting the variation in the factor for variation in the peroxide, state the magnitude of the errors renders it superfluous to correct for radiation; that there is closest agreement with the bomb when an excess of finely ground peroxide together with persulphate is used; and conclude by stating that in no circumstances have they obtained complete combustion of coal, and do not regard the results as sufficiently trustworthy to form the basis for a decision as to the calorific value of a coal.

COMBUSTION IN FREE OXYGEN

F. Fischer Calorimeter.—Of the several modifications, leading to greater simplicity and reduced cost, made on the instrument with which Favre and Silbermann conducted their classical researches, this is in all probability the best type. A sectional diagram is given in Fig. 58.

The calorimeter vessel is packed in eiderdown C, in a circular oak case D. The combustion chamber is of silver, the cover carrying the inlet tube *d* being held on the main body by the tight fit of the two. At the bottom of the chamber a flat circular chamber *cc* is provided to cool the gases, and further cooling takes place in the flattened tube *g*, from which the gases pass out through a glass piece with side lead. A thermometer is placed here to check the temperature of the exit gases.

Inside the combustion chamber there is another chamber *pp* made of thin platinum foil, with a bottom piece *v* so fitted that the gases may escape. The coal sample is in pellet form, and is carried on a platinum gauze basket *ss*.

The sample is pressed into cylindrical shape by means of a small steel mortar, and placed in the platinum basket. The carrier is fitted to top of combustion chamber, and the cover made air- and water-tight by luting it with grease, and the chamber fastened to the base of the calorimeter by its tripod feet. The calorimeter is filled with 1,500 cubic centimetres of water, and the cover placed in position.

The stirrer is now worked until the thermometer remains stationary. During this time a slow current of oxygen has been passing through the combustion chamber, and as soon as the temperature is constant the sample is ignited, either by electricity or by means of a small particle of incandescent charcoal. The current of oxygen is now increased to 2 to 4 litres per minute. As the combustion approaches the finish, the amount is reduced to $1\frac{1}{2}$ litres per minute.

The time occupied in burning the fuel is usually from 7 to 10 mins. Temperature readings should be made at minute intervals until the maximum is reached.

Modified W. Thomson Calorimeters.—The original instrument was described first by Thomson in 1886, and was clearly an adaptation of the Lewis Thompson apparatus, for use with free oxygen in lieu of the combined oxygen of a chlorate-nitrate mixture. Numerous modifications in the detail of construction have been made, and the *Rosenhain and Darling patterns* have been selected for description as typical of good forms of the instrument. The former is illustrated in Fig. 59.

The apparatus consists essentially of two parts, the calorimeter vessel containing the water, and the combustion chamber in which the coal sample is burned. The combustion chamber is formed from a glass lamp chimney, closed at the top and bottom by brass clamping plates, which are separated from the glass by rubber washers.

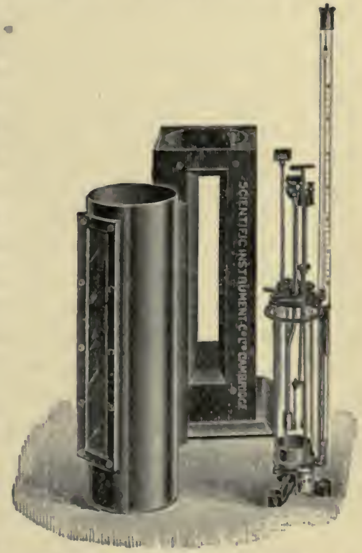

FIG. 59.—Thomson-Rosenhain calorimeter.

The plates are drawn together by means of screws on three brass uprights fixed to the lower plate. A ball containing a stuffing box is mounted on the upper plate through which a tube passes carrying the electric ignition device.

The upper plate also carries a tube for admitting oxygen into the combustion chamber. A wire-gauze nozzle is fitted to the end of this tube to prevent the oxygen jet from breaking up the coal sample.

The combustion chamber communicates with the exterior by means of an aperture, thus permitting the products of combustion to pass from the vessel to the surrounding water. This aperture is closed by a ball valve, which allows the gases to pass from the combustion chamber to the surrounding water, but prevents the water entering the chamber. An arrangement is fitted by means of which the ball can be raised and so allow some water to enter. This water is then forced out by the oxygen and mixed with the rest of the water, thus ensuring that the calorimeter and its contents are brought to one temperature. To prevent radiation, the calorimeter vessel is enclosed in a wooden case, through openings in the sides of which the progress of the combustion may be watched.

For standardizing the instrument, briquettes of coal of known calorific value can be obtained from the makers, and the water equivalent is determined best in this manner also.

The coal is made into a pellet in the press provided and introduced into the calorimeter, the platinum wire of the electric ignition device being placed in contact with the coal. The water in the calorimeter (2500 c.c.) being at room temperature, the oxygen supply is connected up, a small stream of oxygen turned on, and the combustion chamber lowered into the calorimeter vessel. The thermometer is then placed in position, and the initial temperature of the water noted.

Connection is now made for a definite period—say, 10 seconds—with the firing battery. The current of oxygen is kept slow at first, but as the ash accumulates and tends to retard the combustion towards the end, the stream of oxygen is increased gradually as the experiment proceeds; very violent combustion is to be avoided, as smoke is liable to be formed; it is also apt to injure the platinum igniting wire. The duration of the combustion varies from 10 to 15 minutes; the end of the combustion is generally well defined. When all combustion has ceased, the oxygen supply is cut off, the valve raised, and the tap in the upper outlet tube opened; the water then flows into the combustion chamber and is allowed to fill it completely; as soon as this is accomplished the valve is lowered and the oxygen again turned on. The water is forced out through the valve at the base of the combustion chamber, and the bubbles of gas effectively stir the water. The thermometer is now read carefully at short intervals until its maximum reading is attained, which is generally the case a few seconds after the water has been expelled from the combustion chamber. This reading and the time are noted, and the entire instrument is allowed to cool, with a slight current of oxygen still passing, for a period of time equal to half of that which has elapsed between the commencement of the combustion and the maximum reading of the thermometer; the fall of temperature during this time is added, as a radiation correction, to the apparent rise of temperature observed between the initial and maximum readings of the thermometer.

Then, if m be the weight of coal, W the weight of water taken, w the water equivalent, T the rise of temperature, and t the correction for radiation—

$$\text{Calories} = \frac{(\text{W} + w) \times (\text{T} + t)}{m}$$

Pellets of dry compressed cellulose are employed for absorbing oils for calorific determinations; the pellets weigh about 1 grm., and have a calorific value of 4270 calories per grm. About 0·5 grm. of oil is used.

W. Rosenhain (*J. S. C. I.*, 1906, 239) describes the method of applying this pattern calorimeter to petrols and other volatile liquids. The petrol is absorbed in a dry cellulose pellet, which is wrapped immediately in thin tinfoil, to prevent loss by evaporation. There is slow evaporation, but this can be allowed for. The tinfoil burns, evolving 2200 cals. per grm.; with the weight actually used about 400 cals. are involved. There is a possible source of error in the fact that the tin is not completely burnt, but on an average this would amount to an error of 20 cals. only.

Whilst the rate of evaporation is low with petrol, which consists of hydrocarbons of widely different vapour tension, it would involve the loss of the most volatile portions—principally hexane—but this is inevitable in most processes. It is important to note that benzene had not at that date been burnt without deposition of carbon.

Other modifications of the Thomson pattern which are extensively employed are those of Darling (*Eng.*, 1902, 801) and Gray (*J. S. C. I.*, 1906, 409). In 1906 Darling described in the same journal a modified pattern for use with liquid fuels, which are burnt in a lamp with suitable wick.

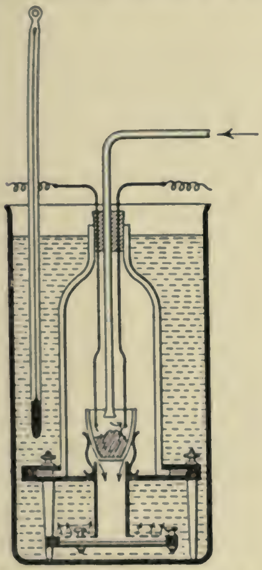

Fig. 60.—Thomson-Darling calorimeter for solid fuels.

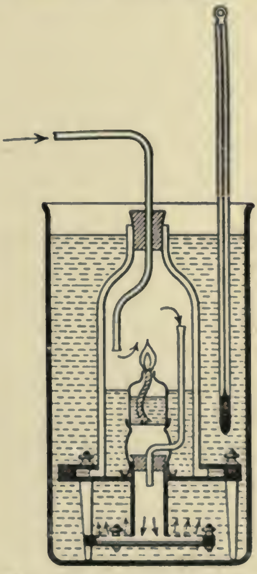

Fig. 61.—Thomson-Darling calorimeter for oils.

The Darling solid fuel calorimeter is illustrated in Fig. 60. A small glass bell-jar forms the combustion chamber, the flange of this being clamped in a brass base ring, and the joint being made tight with rubber rings. The products of combustion pass down through the wide glass tube into a flat circular chamber, the top plate of which is perforated with a number of small holes, so that the gases issue in several fine streams.

For liquid fuel (Fig. 61) a small brass lamp furnished with an asbestos wick is employed, and is kept cool by the water, which is allowed to rise to a suitable height. The products of combustion are led off into the collecting chamber by a bent glass tube. It is stated that with a very narrow wick ($\frac{1}{16}$th inch in diameter) light petrols may be burnt safely, whilst for alcohol and ordinary petroleum the diameter may be $\frac{3}{16}$th inch. It is very doubtful whether a heavy oil fuel can ever be burnt with a wick.

Rawles (*J. S. C. I.*, 1907, 665) has described a further modification of Darling's instrument, specially designed for petrol.

Certain points must be attended to carefully in order to ensure the best results with any calorimeter using oxygen at ordinary pressures. In the first place, the coal is burnt preferably in pellet form. The ordinary crucibles supplied with this pattern instrument are nearly always too massive, and if the coal is burnt in the loose form, towards the end of the combustion isolated portions become extinguished in contact with the crucible, which does not get very hot. The author finds a shallow cone, made of thin platinum foil, is to be preferred to the crucibles supplied, it being mounted as free from metallic contact with the metal stand as can be arranged. With pellets there is not this trouble.

Further, oxygen almost always is derived from the ordinary cylinders, and is practically dry. It is well known that combustion is never so complete with a dry gas. With a Wm. Thomson instrument, Adams (*J. S. C. I.*, 1901, 972) found that results with dry oxygen were some 126 calories lower than with wet; in some more carefully conducted experiments 220 calories lower. Further, the use of dry oxygen causes evaporation as it passes through the water, and the latent heat of the water thus evaporated is abstracted. In all cases, then, the oxygen should be sent through water in a suitable wash-bottle before use.

Another possible error is introduced by the lower temperature of oxygen taken direct from a cylinder, due to its expansion. With a sufficiently large water-bottle this becomes negligible, but it is a good plan to interpose between the oxygen cylinder and the wash-bottle a coil of metal piping of sufficient length to ensure the oxygen reaching the room temperature.

The correction for radiation is usually made by adding to the observed rise of temperature the fall noted during the prolongation of the experiment through half the number of minutes occupied in the actual combustion. A small stream of oxygen should still be passed through the apparatus. An alternative method is to start with the water in the calorimeter as much below the room temperature as the expected final temperature will be above it.

Although it is claimed that combustion is complete in calorimeters of this type, this is very doubtful in the case of coals. Favre and Silbermann in their classical experiments recognized this, and always passed the products of combustion through a heated copper oxide tube, and made corrections for the unburnt hydrocarbons. It is very seldom that some smoke is not seen to escape during an experiment, and the smell of the escaping products is generally sufficient proof of the incompleteness of the combustion.

Bomb Calorimeters.—These are all developments and modifications of the original "bomb" pressure calorimeter, which Berthelot employed first to measure the heat evolution on firing explosives. A lighter form of bomb was constructed for him later, and used for fuels. Many other patterns have followed the original model.

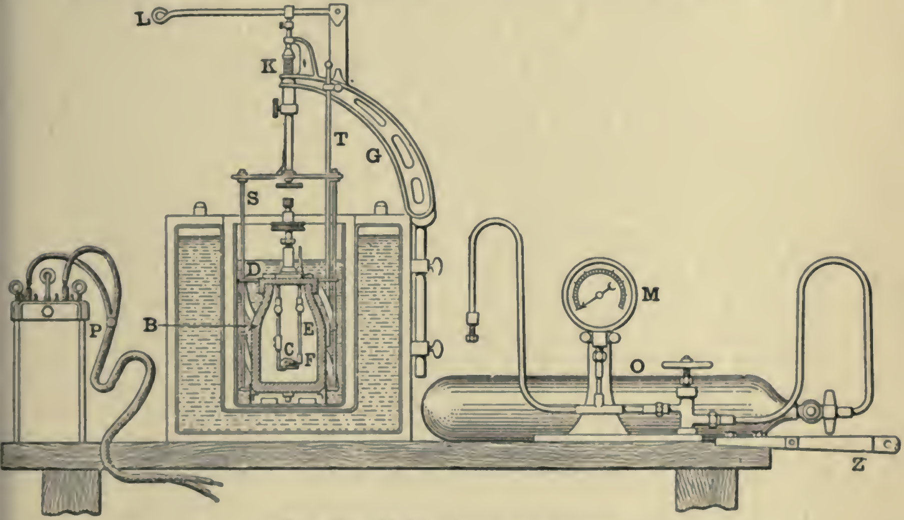

FIG. 62.—Mahler bomb calorimeter.

In all bomb calorimeters oxygen always is employed at several atmospheres pressure; combustion is thus always complete. Further, no products escape during the experiment; and, since the combustion vessel is immersed almost completely in water, the whole of the heat is transferred for measurement. Calorimeters of this type are probably as perfect as possible, but their high cost is frequently prohibitive.

The application of the term "bomb" to calorimeters of the Parr type is very misleading.

The pattern chosen as illustrative of the "bomb" type is that of Mahler. The complete apparatus is depicted in Fig. 62.

The bomb (B) is of steel, lined with an enamel to prevent corrosion.

In some more expensive forms platinum or gold is employed, but an instrument with enamel lining has been in constant use by the author for twelve years, and the enamel is still perfect. The cap screws on to the top of the bomb, and is made gas-tight by suitable lead rings, the whole being screwed home by means of a large spanner whilst the bomb is gripped in the lead-lined clamp Z. At the centre of the cap an inlet valve for the oxygen is provided, and from the underside two platinum rods extend; one of these (E) is connected with a piece passing to the exterior, but electrically insulated from the metal of the cap, and the other carries the flat platinum capsule (C) in which the fuel is placed. A length of about 2 inches of fine platinum wire (0·002 inch diameter) is wound round the terminals of the rods, forming a loose loop which is in contact with the fuel. Iron wire is sometimes recommended, but is best avoided. The oxide formed fuses in globules on the lining and quickly ruins it, and, moreover, entails a correction for its heat of combustion. In the long run, the fine platinum wire is most economical.

The charged bomb is immersed, as shown, in the water vessel of the calorimeter, being kept clear at the bottom by a perforated stand, into which it springs. There must be a free circulation of water right round the bomb. The calorimeter vessel is insulated from the capacious surrounding water vessel by a triangular wooden stand.

Oxygen is supplied from the cylinder O, which is connected by fine-bore copper tubing with a valve and the manometer M. For filling, the bomb is attached at the top of the inlet valve to the end of the copper tube by a screw union.

The stirrer S is carried by the arm G, and operated by the lever L. Helical blades are provided on the stirrer, which moves up and down, and at the same time is given a rotary motion by the thread cut at K. The battery for firing is shown at P; a two-cell accumulator is most convenient.

In operating, the firing wire should be arranged and always tested first with *one* cell, the two being used for firing. The fuel is weighed into the capsule, which is fixed in position by the small clamp on the rod. A little distilled water being put in the bomb, it is then gripped in the clamp, and the cap carrying the capsule, etc., is screwed home carefully. Connection is now made to the oxygen pipe, the admission valve to the bomb opened two turns, and the manometer valve tightly closed. *Now* the valve in the oxygen cylinder is opened *fully*, and gas admitted by operating the manometer valve, which is closed when 25 atmospheres is reached, the cap valve being then closed also.

It is important to operate the valves as described, and always to open the oxygen cylinder valve sufficiently. Cases of burst pressure gauges have occurred through neglect to have the manometer valve properly closed before the cylinder valve has been opened; also through partially opening the latter at the start, then, finding the pressure ceases to rise, opening out further so that the full pressure from the cylinder is thrown on the gauge. Hence, *always close the manometer valve before making any alteration to the oxygen cylinder valve.*

The bomb being charged, attach the small stand, place centrally in the calorimeter vessel, into which the requisite quantity of water has been *weighed*, attach the stirrer, and see that all works smoothly, and that the stirrer will clear the thermometer. Finally, the thermometer is placed in position.

The water is stirred regularly, and the temperature noted every minute. It is a good plan to keep a large vessel of water in the room always, from which to fill the calorimeter vessel; then a constant temperature is reached very quickly. When the rate of rise, or a constant temperature, has been ascertained, attach one wire to the insulated pole, touch the top of the admission valve with the other wire, and fire the fuel. Stir regularly, noting the rise of temperature each half-minute, and continuing every minute for 6 or 8 minutes after the maximum, to obtain data for the radiation correction. A high class thermometer, reading easily to $\frac{1}{100}$th° C. must be employed. Some prefer one of the Beckmann type. For a full consideration of the suitability of the different types of thermometer see Huntley (*J. S. C. I.*, 1910, 917).

After removal from the apparatus the valve is opened, the gases being allowed to escape. The bomb and cover are rinsed thoroughly with water, which is preserved when necessary for the estimation of the sulphuric and nitric acids formed.

Corrections required and calculation of the results.—Combustible sulphur in the fuel burns to sulphur dioxide, which at the high pressures is oxidized further to sulphur trioxide, and this combining with water gives a further evolution of heat. As these two last exothermic actions do not occur with oxygen at normal pressures, a correction must be applied in accurate work. Further, nitrogen in the fuel and nitrogen in the residual air in the bomb form nitric acid at the high temperature reached and in the presence of water, heat being evolved again which must be corrected for.

The heat of formation of nitric acid is 227 calories per gram, hence 0·0044 gram = 1 calorie. A solution of sodium carbonate, containing 3·706 grams of the pure dry salt per litre, will give directly the number of calories to be deducted by the number of cubic centimetres used to titrate the acid washings; methyl orange is a suitable indicator.

The excess heat from the reaction $SO_2 + O + aqua$ is equal to 22·5 calories for each 1 per cent. of sulphur.

The washings from the bomb are titrated with sodium carbonate of the above strength, then the solution is acidified, boiled, and the sulphur estimated by barium chloride as usual. Since in the titration the carbonate was used partly to neutralize the nitric acid and partly the sulphuric acid, the heat of formation of the latter in terms of nitric acid must be subtracted from the total c.c. of carbonate used. This value is given approximately correctly by the weight of barium sulphate × 100.[1]

Hence, nitric acid correction =

$$\text{c.c. standard sodium carbonate} - 100(BaSO_4)$$

$$\text{Sulphuric acid correction} = \frac{22{\cdot}5 \times \text{per cent. sulphur in fuel}^{2}}{1}$$

The magnitude of these corrections, and hence the value of taking them into account, must be stated briefly. The nitric acid deduction will be usually of the order of 15 calories, and sulphur about 20 calories; say, 35 in all. On a coal of 7000 calories this is equal to 0·5 per cent.

Radiation.—Elaborate systems of correction for this have been proposed, and for research work are necessary, the Stohmann modification of Regnault and Pflaunder's formula giving absolutely correct results. All systems of correction which are not purely arbitrary are based on Newton's law, that the rate is proportional to difference in temperature between two bodies, and this holds for all such temperatures as are involved in calorimetric work.

The following example will make clear the simple form of correction required for most technical work; the water had reached a constant temperature before the fuel was fired.

Initial temperature (t'), 15·52°.

Time after firing.	Thermometer reading.	Mean temperature of minute.	Mean difference from initial t.
1 minute	17·37	16·445	0·925
2 minutes	17·94	17·665	2·135
2½ ,,	17·95	17·945	2·425
3 ,,	17·95 (t^2)	17·945	2·425
4 ,,	17·945	—	—
5 ,,	17·935	—	—
10 ,,	17·860	—	—

---

[1] The latent heat of formation of nitric acid (227 cals. per gram) being approximately equal to the molecular weight of $BaSO_4$ (233).

[2] *i.e.*, as found in the acid liquid and calculated on the weight of fuel.

$$\text{Rise} = 17{\cdot}95 - 15{\cdot}52 = 2{\cdot}43$$

$$\text{Loss per minute} = \frac{17{\cdot}935^{1} - 17{\cdot}860}{5} = 0{\cdot}015$$

$$\begin{aligned}
\text{Loss in 1st minute} &= 2{\cdot}43 : 0{\cdot}015 :: 0{\cdot}925 = 0{\cdot}006\\
\text{,, 2nd ,,} &= 2{\cdot}43 : 0{\cdot}015 :: 2{\cdot}135 = 0{\cdot}013\\
\text{,, 3rd ,,} &= 2{\cdot}43 : 0{\cdot}015 :: 2{\cdot}425 = \underline{0{\cdot}015}\\
\text{Total correction . .} &\quad 0{\cdot}034
\end{aligned}$$

$$\text{Corrected rise of temperature} = 2{\cdot}43 + 0{\cdot}034 = 2{\cdot}464^\circ$$

As pointed out by G. N. Huntley, a calorimeter should not be surrounded by a vessel with the object of preventing radiation; this is impossible, but it should be surrounded by a medium which makes the loss by radiation *constant*, and for which corrections can be applied. A large mass of water fulfils this condition best, and wooden tubs and similar devices are not applicable.

The true rise of temperature may be obtained also graphically (see E. A. Allcut, *Eng.*, 1910, 90, 755).

With the Mahler calorimeter, the maximum invariably being reached in from 2½ to 3 minutes, the following empirical correction is stated to apply—

1. The decrease in temperature after the maximum represents the loss of heat of the calorimeter before the maximum and for a certain minute, with the condition that the mean temperature of this minute does not differ more than 1° from the maximum.
2. If the mean temperature differs more than 1° but less than 2° from the maximum, the rate of loss at the maximum *less* 0·005° will give the required correction.

In the above example the application of this rule involves a difference well below the possible limits of experimental error, and for general technical work the method is sufficiently accurate. Clearly it would not apply to a form of bomb calorimeter where the rise to the maximum is extended over several minutes.

The calorific value of the fuel is then calculated from the formula—

$$\text{calories} = \frac{(\mathrm{T} + t) \times (\mathrm{W} + w) - (\mathrm{HNO_3}\ \text{correction} + \mathrm{S}\ \text{correction})}{\text{weight of coal in grams}}$$

T = observed rise $\qquad \mathrm{W}$ = weight of water

t = radiation correction $\qquad w$ = water equivalent

---

[1] At the minute when the maximum temperature is reached and for the succeeding minute or two heat is still passing out from the bomb, more or less balancing the loss by radiation. To ascertain the true loss per minute by radiation alone, the temperature at which the rate becomes uniform must be taken.

The effect of lowering the initial oxygen pressure with a bomb calorimeter has been investigated by E. A. Allcut (*loc. cit.*). With the sample of coal used the theoretical oxygen required was 1·33 grams per gram. The following results show the importance of working with at least 20 atmospheres inital pressure :—

Pressure	25	20·0	15·0	13·0	11·3	9·0	7·0	5·0	3·2
Weight of oxygen in bomb	19	15·2	11·4	9·94	8·64	6·9	5·41	3·92	2·42
Percentage of maximum calorific value . . .	100	99·7	98·6	97·7	97·0	95·0	90·0	71·7	59·6

It is most important to note that, judged by the calorific value, at 3·2 atmospheres with nearly twice the theoretical oxygen the results are 40 per cent. below the truth. Unfortunately Allcut did not estimate the unburnt carbon, which at 13 atmospheres was first visible in the residue, neither were the products of combustion examined. The coal employed was anthracite—"because it was nearly pure carbon"—a bituminous coal would have given probably more complete combustion at the lower pressure.

With coals having a very fusible ash it is important to note that some carbon may be included in the fused residue. Huntley found the maximum error due to this equal to 3 per cent. on the calorific value. With a low ash content such error is generally negligible, but with a high ash of fusible character the possibility must not be overlooked.

Liquid and Gaseous Fuels in Bomb Calorimeters.—With the Mahler pattern heavier oils burn very completely on the shallow pattern tray employed; for lighter oils (kerosene, etc.) the author has found absorption of the oil by kieselguhr very satisfactory. The tray is half filled with this material (previously ignited, as it always contains organic matter), the surface corrugated, the whole weighed, and the oil distributed over the kieselguhr and reweighed. More dry kieselguhr is then spread over the surface, and an almost "dry" oil-impregnated mass obtained. Some kieselguhrs are very fusible and are unsuitable for this use, for a considerable proportion of carbon may remain in the fused mass, which should be examined carefully at the conclusion of the experiment. The porous absorbent blocks of cellulose already mentioned also may be employed, but this reduces considerably the amount of oil which can be taken.

With very volatile liquids, such as petrol, great caution should be observed, as in a few cases there has been such violent explosion that the thread of the cover has been stripped. Berthelot employed a deep platinum cup entirely enclosed in celluloid for such liquids, this preventing evaporation and ensuring complete combustion. By weighing the petrol in a **U** tube having fine capillary tubes on either limb, blowing out sufficient on to kieselguhr in the dish already fixed in position on the rod with the firing wire ready, and immediately screwing the top of the bomb on at the balance before finally weighing the tube to ascertain the amount of petrol taken, the loss by evaporation is so small that good results are obtained. The ignition always should be made from a safe distance.

With such volatile liquids Watson's method (*J. Soc. Arts*, 1910, 58, 990) of vaporizing the petrol and burning carburetted air in a suitable gas calorimeter is greatly to be perferred to other methods.

The calorific value of a gas may be determined in a bomb, but so many calorimeters of a far more suitable type are available that the bomb is used but seldom. The small quantity of gas it is possible to employ is against the method.

Benedict and Fletcher (*J. Amer. Chem. Soc.*, 1907, 29, 739) burnt a number of substances in a bomb calorimeter, and found that with an initial pressure of 300 lbs (20 atmospheres) the maximum pressure exceeded 700 lbs.

DETERMINATION OF THE WATER EQUIVALENT OF CALORIMETERS

This determination must be made with every possible degree of accuracy for any type of calorimeter. Several methods may be employed, and it is desirable to employ more than one, to check the result. These methods may be—

1. Calculation from the weight and specific heat of the parts.
2. A practical determination of the specific heat.
3. By the combustion of substances of known calorific value.
4. By imparting heat to the system electrically, and finding the rise of temperature.

The first method can be only approximate; it is often impossible to ascertain the weight of the individual materials of construction, or to be certain of their specific heat. With a glass calorimeter vessel which is only partly filled with water, the proper allowance is impossible to compute.

The practical determination of the specific heat of the whole apparatus subject to rise of temperature is a most useful check and readily carried out.

The last two methods undoubtedly are the best, that of burning a substance of known calorific value being most convenient. The mean rise of three or four results should be taken, when the water value (x) will be found from—

$$\text{Calorific value of pure substance} = (\text{Weight of water} + x) \times \text{Rise of temperature}$$

The following pure substances, with their heat of combustion, have been employed :—

Naphthalene	9622 calories	(±2)
Benzoic acid . . .	6329 ,,	—
Cane sugar	3949 ,,	(±2)

Naphthalene is frequently difficult to burn completely, and benzoic acid and cane sugar, both on account of better combustion and greater certainty of their absolute calorific value, are most suitable.

The electrical method is capable of giving very exact results. C. J. Evans (*Eng.*, 1906, 82, 295) has described this method as applied to a Thomson-Rosenhain calorimeter. A heating coil was arranged in the place that a sample of fuel would occupy normally, connection with it being effected by means of a special insulated terminal and another on the body of the instrument, potential leads being connected just above those for current. The electrical quantities measured were current and potential, the former by a Weston ammeter, and the latter by Poggendorff's method of direct comparison with a Standard Clark Cell. Oxygen was supplied at about the same average rate as during a combustion.

The following data and method of calculation will make the procedure clear :—

Duration of experiment = T = 600 seconds in both cases.
When W = watts

$$\text{Therms } (= \text{gram-degrees C.}) = \frac{WT}{4187} = 143{\cdot}3W$$

[J being $4{\cdot}187 \times 10^7$ (Griffiths adopted) at 15° C., which was the average temperature of the experiments.]

$$\text{Water equivalent grams} = \frac{\text{therms}}{\text{temperature rise }^\circ\text{C.}} = \frac{143{\cdot}3W}{\text{Degrees C}}$$

The necessary allowance must be made when the parts of the apparatus used in the determination are removed, this being calculated from their weight and specific heat.

The following figures are the results of experiments to determine the water equivalent on this system :—

Temperature rise ° C.	Average watts.	Water equivalent grammes.	
5·75	102·9	2564	2566
5·92	106·1	2568	

With calorimeters of the William Thomson type, the constants for the apparatus are determined best by the combustion of standard coal samples, which can be purchased. With three or four coals of varying volatile content an approximate correction covering the water equivalent and errors due to differences in burning may be obtained, the correction stated in a particular case being that for the standard nearest in nature to the sample under examination.

The following figures by the different methods with a Mahler bomb illustrate the degree of accuracy attained:—

By determination of Sp. Ht. (mean of 4) . . .	550·6 cals.
,, calculation of Sp. Ht. from weight of parts .	546·8 ,,
,, combustion of naphthalene	550·0 ,,

COMPARATIVE ACCURACY WITH COAL CALORIMETERS

Comparisons of results obtained with different calorimeters have been given by Brame and Cowan and by Gray and Robertson *J. S. C. I.*, 1903, 1230 and 1904, 704). The former used the Lewis Thompson, William Thomson, Fischer, and Mahler bomb, the latter did not employ a calorimeter of the Fischer type. Five coals, ranging from anthracite to highly bituminous coal, were employed by the first-mentioned authors; in the other laboratory the coals were mainly bituminous.

The results with the Lewis Thompson instrument are of particular importance by reason of its wide use. It has been recognized for a long time that the instrument is worthless as the anthracites are approached, this being due to the large amount of carbon which escapes combustion. Brame and Cowan (*The Engineer*, May, 1905) obtained as an average for a large number of experiments, in which the ratio of oxidizing material to coal was varied, the following results:—

Percentage of volatile matter in dry coal	6·84	9·70	14·08	20·50
Unburnt carbon, per cent.	33·4	24·7	9·7	5·17
Calorific value below truth	35·06	29·40	12·70	8·00

With the bituminous coals, the average unburnt carbon ranged from 4–6 per cent. The instrument is quite incapable of given even approximate results with coals containing under 25 per cent. volatile matter, and with a coal most suited to the instrument, as found by actual tests, and with every precaution which experience showed requisite to give the best results, an error of from 3·5–4·4 per cent. below the true value was found in a series of 28 tests. From the joint researches referred to the results with bituminous coals may be too low by 8 per cent.

It is possible to apply an approximate correction for unburnt coal, but this estimation involves so much labour and time that at once it far more than counterbalances the advantages of simplicity and rapidity which have been the chief asset of these calorimeters. Even with this correction applied, the results in Brame and Cowan's series ranged from 2·3–6·4 per cent. below the true value.

L. L. Lloyd and G. W. Parr (*J. S. C. I.*, 1910, 740) give a few results obtained with the Roland-Wild sodium peroxide calorimeter in comparison with the bomb calorimeter. With long flaming bituminous coals they noted that flame was projected through the valve. The following results for coals may be cited:—

Coal.	Percentage error in determinations.	Mean per cent. error from bomb.
Long flame bituminous	2·2	+ 1·13
,, ,, ...	0·86	+ 3·92
Anthracite	1·52	− 0·068

Salicylic acid gave a result 5·1 per cent. above the bomb value.

W. Thomson, Calorimeter.—The comparative results available are all from the original pattern instrument. Gray and Robertson employed the coal in pellet form, and used electrical ignition, both conditions being more favourable to good results than the method originally described, and which was followed by the author and Cowan. With the former the mean deficit from the bomb results was 1·8 per cent. the difference ranged from 0·7–2·9 per cent. Brame and Cowan's results are summarized below:—

Volatile matter on dry coal . .	6·84	9·70	14·08	20·50	34·00
Maximum below bomb, per cent.	5·86	8·10	5·30	3·85	3·40
Minimum ,, ,, ,,	1·61	5·30	2·26	1·07	0·36
Average	4·00	6·90	3·40	1·92	1·80
Range of experimental error on at least six determinations . . .	4·4	3·0	3·2	1·8	3·1

The general conclusion to be drawn from the joint work is that calorimeters of this type will give results which may not vary more than 2 per cent. below the bomb figure, when the coal is used in pellet form, electrical ignition adopted, the calorimeter standardized by suitable coals, and with the precautions indicated earlier. The results could not be taken as sufficiently accurate to form a basis for purchase on the calorific value. The margin for experimental error is too great, and constant disputes undoubtedly would result. Such calorimeters find useful application when an approximate determination of the calorific value is all that is requisite.

Bomb Calorimeters.—Very large numbers of tests have shown that the bomb calorimeter is the only form capable of giving consistent results with a reasonably high degree of accuracy. Adopting all corrections, Brame and Cowan found an experimental variation ranging from 0·16–0·30 per cent.; Gray and Robertson from 0·06–0·7 per cent. When small corrections are omitted the sum of these may amount to an error of 1 or 2 per cent., but it would be rare for them to be all in the same direction. For example, the omission of a radiation correction is counterbalanced largely by the omission of the nitric-sulphuric acid correction. With both these omitted, in the case of the five coals used by the author and Cowan, the uncorrected value was about 50 calories (0·6 per cent.) below the fully corrected value.

The paper by G. N. Huntley (*J. S. C. I.*, 1910, 917) on the Accuracy obtainable in Fuel Calorimetry should be studied carefully.

One very obvious point, to which it is only necessary to draw attention because it is overlooked so frequently, is the absurdity of returning calorific values to the first and even second decimal place. It is clear that the last significant figure has no real value, even in the most accurately conducted tests.

Probable variation in the sample examined from the bulk of the coal from which it is drawn is of much greater order than the errors in calorimetry with the bomb apparatus. It is clearly very essential to take every step possible to reduce the sampling variation to a minimum.

For a proper estimate of the value attaching to calorimetric values it is essential to know the method by which the result has been arrived at, and this should be stated in every case. In the literature on fuels this is most exceptional, and most of the calorific values must be accepted with some reserve; the reliable data on British coals is very meagre.

CALORIMETRY OF GASES

The most suitable form of calorimeter is one with constant flow of water, and from the volume of gas burnt, the rise of temperature and weight of water heated, the calorific value is obtained at once. Further, as the *net* value has to be recorded in most cases, this form of apparatus readily gives the necessary data, for sufficient gas can be burnt to yield a fair volume of condensed water for the proper deduction from the gross value.

The best known pattern is the *Junker calorimeter*, which is employed almost exclusively on the Continent and in America, and very largely in this country. In the original pattern the thermometers for measuring the temperature of the inlet and outlet water were at great difference of level, which made reading difficult, and no ready means of directing the flow of water into the measuring vessel or to waste as required was furnished. In the latest pattern of the instrument, illustrated in Fig. 63, these defects have been remedied and the design improved on in other respects.

The principle of construction is that the gas burns at a Bunsen burner in a central flue of sufficient diameter to ensure no impingement of the flame against the walls, the hot products of combustion pass to the top of the flue and then descend through small metal tubes arranged in a double circle around the central flue, finally making their exit near the bottom of the instrument. The water is supplied from a constant level tank and flows through the calorimeter in a reverse direction to the gas flow, consequently the exit gas should be cooled to the temperature of the inlet water. It is very necessary to provide proper admixture of the various streams of warm water; this is accomplished by numerous baffles constituting a labyrinth below the exit thermometer.

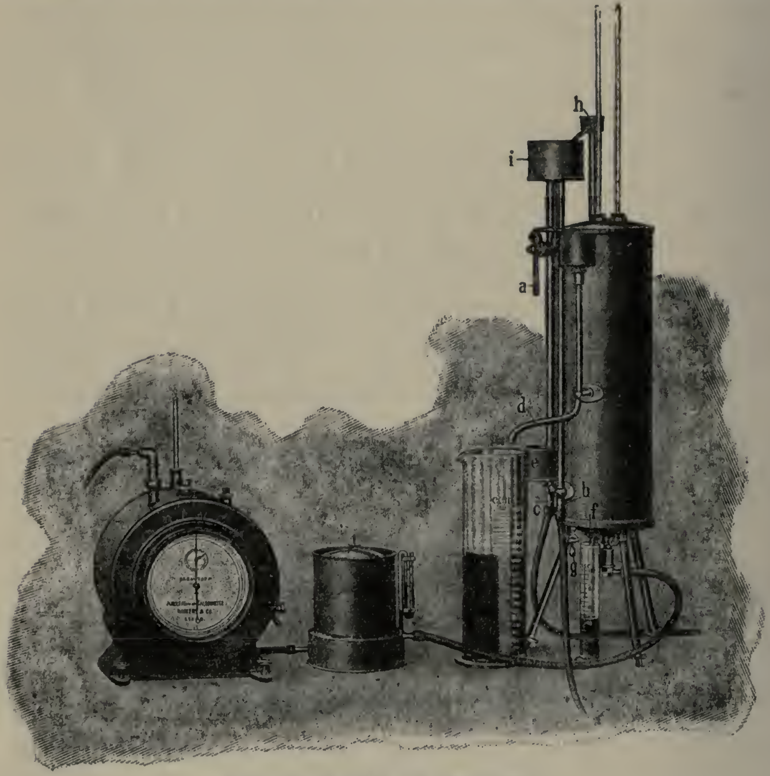

FIG. 63.—Junker gas calorimeter.

The constant level tank is shown at *i* (Fig. 63), water to which is supplied through the tube *b*. The quantity of water flowing through the calorimeter is controlled by the quadrant tap *a*, an excess supply over that really demanded being allowed to escape into the small waste tank *e*, thus indicating that the head is sufficient to overflow the weir in *i*, so maintaining the head constant. From *e* the water passes to waste through the pipe *c*.

The warm outflowing water passes through *d*, which may be turned over *e* to waste, or over the large measuring vessel in which it is collected during an actual test. The water resulting from condensation drains to the lower part of the instrument and is collected in the smaller measuring vessel placed under the spout *f*. A tap *g* for emptying the instrument is provided at the bottom and an air vent through an upright tube at the top, terminating in the small tank *h*.

The *Boys calorimeter* was designed by Prof. C. V. Boys, one of the London Gas Referees, at the time when official tests of the calorific power of the gas supply were introduced. Its essential features are that a very small volume of water is actually in the instrument at any one moment, the heat from the gases being abstracted by this water flowing through two spiral copper pipes in series, these being wound with wires, as in a motor car radiator. The instrument is compact, and when standing on a table both thermometers are at a convenient height for reading. The whole instrument may be lifted from the base, giving ready access to the burner, and the coil system may be lifted out attached to the wooden lid and the coils immersed in dilute alkali to prevent corrosion.

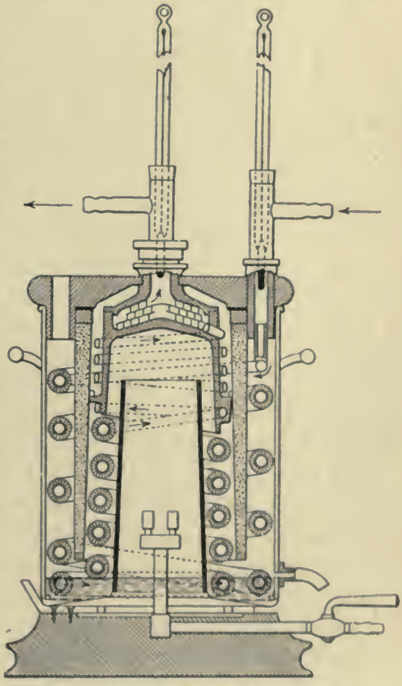
FIG. 64.—Boys gas calorimeter.

A section of the apparatus is shown in Fig. 64.

The inlet water passes first through the outer coils downwards, then returns upwards through the interior coils, which are heat-insulated by a partition from the exterior coils, finally it flows around suitable channels on the exterior of the metal casting immediately above the chimney, and passes into a mixer with a labyrinth formed of coiled brass slips. Into the top of this chamber the outlet thermometer is fixed.

Two luminous flames from suitable jets are employed. The central chimney is always too hot for condensation of water to take place in it. At the commencement water is poured into the bottom of the vessel until it overflows at the spout provided. Proportionately condensation water flows from this spout during a run, and is collected and measured for the net calorific determination.

The calorimeter equipment is completed by an accurate meter (one giving a complete revolution of the main index for $\frac{1}{10}$ of a cubic foot) and suitable pressure regulators. It is advisable to instal one regulator on the supply side of the meter and another between the meter and the instrument. The calorimeter should be fitted with a simple device for directing the water into the large measuring cylinder at the proper moment or to waste, without the operator being obliged to look away from the meter dial. In accurate work the temperature, and pressure at which the gas is supplied to the meter must be noted, and the volume passed corrected to dry gas at 60° F. and 30 ins. barometric pressure. It is very desirable that the water should be supplied at the temperature of the room, which may be arranged for by a supply tank, without ball valve, holding from 30 to 40 gallons.

In operating calorimeters of the flow type the adjustment of the gas and water supplies must be suited to the character of the gas. With coal gas about 6 cub. ft. per hour is suitable; poor power gases may be burnt at 3 to 4 times this rate. The water flow should be regulated so that the products of combustion should leave the instrument at as nearly as possible air temperature. In the Junker calorimeter considerable control of this is possible by alteration of the damper in the exit flue. For the Boys calorimeter a correction of $\frac{1}{6}$ calorie for each degree difference in temperature between the exit gases and the air temperature must be added or subtracted from the results. In general, a difference in thermometer readings of 10° to 12° C. will give a suitable cooling of the exit gases.

A convenient quantity of coal gas to employ in a test is 0·3 cub. ft. The temperature of the inlet water thermometer should be read just before the test, as nearly as possible at the completion of the first and second revolutions of the meter, and immediately after the test. The exit water temperature should be noted at every quarter revolution; in each case the mean temperature from the observations is employed.

The main water supply must be adjusted so that a small quantity is always flowing to waste over the weir in the constant pressure device, and the calorimeter should always be run for from 20 to 30 minutes before taking a test, in order that conditions may become settled. When fresh water has been added to the meter or new rubber tubing employed, gas should be run through for some time in order to saturate them thoroughly.

Some small error is introduced by measuring the water instead of weighing it; in this country measuring is usual, in America the water is weighed. The simplest plan is to calibrate the measure for the weight of water around the average temperature at which it will be collected in practice.

With proper attention to these points the results will be accurate for all practical tests.[1] The thermal efficiency of a flow type calorimeter is about 99·5 per cent.

With a flow calorimeter the calorific value is obtained from the simple equation—

$$\text{Calories per cub. ft.} = \frac{\text{Weight of water in kilos} \times \text{difference of temp.}}{\text{Cub. ft. of gas at } 60^\circ \text{ F. and 30 ins.}}$$

In an actual example—Temp. of gas 68° F.; barometer 29·7; water collected 3·945 kilos (litres); gas burnt 0·3 cub. ft. (= 0·297 at 60° F. and 30 ins.); difference of temperature 11·6° C.

$$\textit{Gross} \text{ calories per cub. ft.} = \frac{3945 \times 11{\cdot}6}{0{\cdot}297} = 154{\cdot}0 \text{ (610 B.Th.U.)}$$

For the *net* calorific value it is desirable to burn at least 1 cub. ft. of gas and measure the quantity of condensed water (in c.c.) collected from the drip pipe; calculate this to the amount obtainable per cub. ft. of gas. The amount of heat to be deducted from the *gross* value per cub. ft. will be obtained with sufficient accuracy by multiplying the number of c.c. of condensed water per cub. ft. of gas by 0·6 Calories (see p. 9).

Example.—In experiment above, water collected from 2 cub. ft. of gas = 42 c.c.

$$\text{Net value} = 154 - \left(\frac{42}{2} \times 0{\cdot}6\right) = 141{\cdot}4 \text{ Cals. (563 B.Th.U.)}$$

Liquid Fuels in Flow-type Calorimeters.—For volatile liquids, such as petrol and benzol, vaporization by some suitable method and admixture with air to form a good combustible mixture which can be

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[1] The conditions affecting the accuracy of flow-type calorimeters have been investigated fully, and the following papers may be referred to:—"Reports of the American Gas Institute Committee," *J. Gas Ltg.*, 1908, **104**, 888, 904: 1910, **109**, 295; **112**, 710; J. B. Klumpp on "Gas Calorimetry in the United States," *J. Gas Ltg.*, 1910, **110**, 823; T. Holgate, "Causes and Ranges of Variation in Calorimeter Tests," *J. Gas Ltg.*, 1910, **110**, 355, 432, 573, 655; J. H. Coste, "Technical Gas Calorimetry," *J.S.C.I.*, 1909, 1231; Coste and James, "Radiation Errors in Flow Calorimeters," *J.S.C.I.*, 1911, 67.

burnt at the gas burner, is probably the most satisfactory way of obtaining their calorific value. In addition to the gross value the net value may be obtained also. Watson (*loc. cit.*) has described a form of apparatus he employed with a Boys calorimeter, which appears very suitable. Of course every precaution must be taken to avoid selective evaporation of the more volatile constituents, *i.e.* the liquid must be vaporized completely in small quantities at a time.

For oils, etc., to be burnt in liquid form, Immenkötter employed a burner of the Primus pattern, modified to permit of its being suspended on knife edges on one arm of a balance.

Still-water Gas Calorimeters.—Where no regular supply of the gas is available it is sometimes convenient to employ a calorimeter with fixed quantity of water. For a description of two patterns of such calorimeters reference should be made to the Strache calorimeter (*J. Gas Ltg.*, 1910, **111**, 387) and Coste and James "On a New Form of Still-water Calorimeter" (*J. S. C. I.*, 1911, 258).

RECORDING GAS CALORIMETERS

With the increased importance very properly attached to the calorific value of coal gas and the absolute importance of this property in the case of power gases, the installation of instruments capable of giving continuous and permanent records is in the case of large gas works or power plants very desirable. Excellent instruments for this purpose are now on the market, and finding extended application as their value is appreciated. For controlling large power plants their use is likely to lead to great improvement in the conditions of operating.

Such instruments are unlikely ever to serve as standards for judging the absolute calorific value; they can seldom have the degree of accuracy possible with a flow-type calorimeter, but find their special sphere in giving continuous records of approximately accurate values.

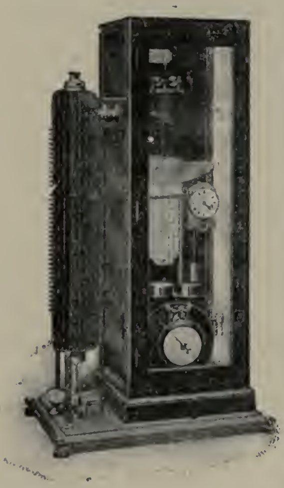

FIG. 65.—Sarco recording gas calorimeter.

Since the results must be dependent always upon very absolute control of the quantity of gas consumed, the proper automatic regulation of the gas supply is one of the most important features. In the Junker pattern (see P. C. Balcon, *J. Gas*

Ltg., 1910, 109, 436), where the flow-type is adhered to, the difference in temperature between the inlet and outlet water being measured by suitably-placed thermo-junctions, the ratio between gas consumed and water supplied must be absolutely constant.

Space permits only of a description of two patterns, both of proved practical value. The "*Sarco*" *Gas Calorimeter* (Beasley patents) is shown in general view in Fig. 65, and its principle of operation will be followed from the diagram, Fig. 66. Two limbs of a U tube contain oil; one of these limbs A jackets the chimney C in which the burner is situated, and this limb communicates with the oil tank D. The other limb B is cold, and communicates with a second tank E. The oil in the hot limb becomes expanded, and oil flows into D, and the difference in level in the two tanks operates on the floats in each, which in turn affect the shaft carrying the pen P through the cords and wheels F and F′, so that as the recording drum G is rotated by its clockwork gearing, the temperature is marked by the pen.

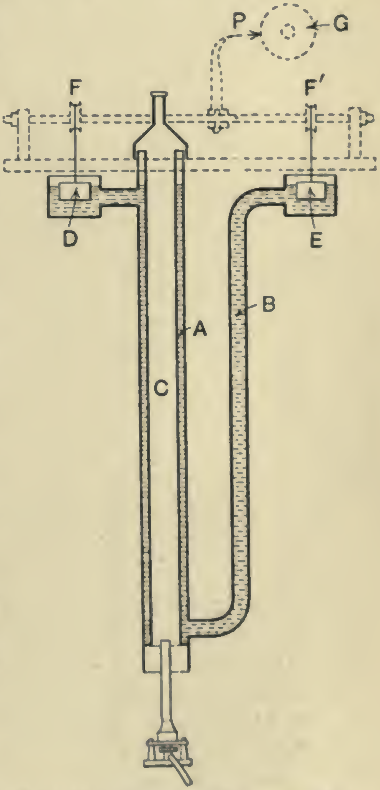

FIG. 66.—Sarco recording gas calorimeter—diagram.

To ensure absolute uniformity in the quantity of gas burnt, a pressure regulator and constant resistance to the flow of gas are provided. The resistance of a jet would serve if no deposit or obstruction could occur, but reliance cannot be placed on this. The gas, therefore, passes first through a pressure regulator and then through a special flow regulator, of meter pattern, shown at the bottom of the case in the view of the apparatus. In this the gas is passed regularly by the meter drum, which works at a constant speed in rectified paraffin oil. The rate of flow being now independent of the size of the burner jet, the latter is made unusually large and so obviates the chance of any deposit being likely to choke it. The jet is easily accessible, and can be removed when required and a clean one substituted.

The cold limb is furnished with circular radiating discs, just visible in the figure projecting slightly beyond the heavy flanged iron casing surrounding the hot limb, this casing acting as a radiator. The float chambers are situated at the top of the instrument, inside the case.

The instruments are standardized by pure hydrogen and carbon monoxide. As the temperature of the flue gases is about 70° C. no condensation of moisture occurs, and hence the *net* value is recorded.

The *Leskole Recording Calorimeter* is the design of Dr. Fahrenheim. The principle of its operation will be followed from the diagram (Fig. 67).

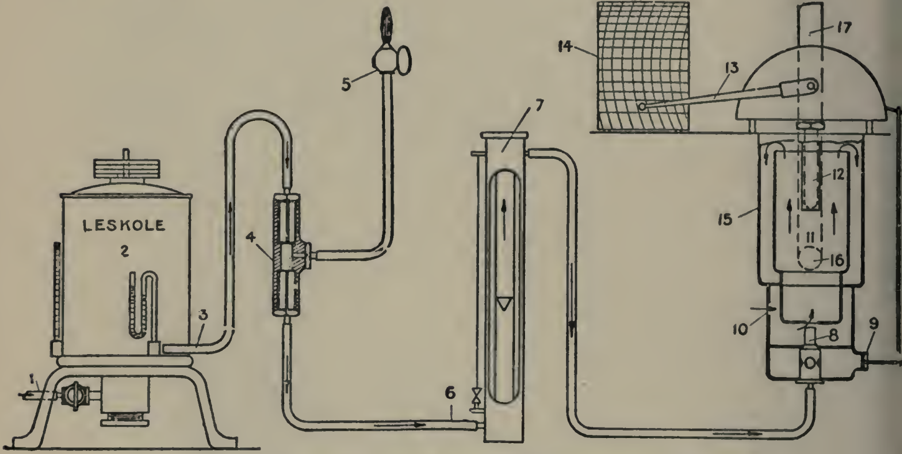

FIG. 67.—Leskole recording gas calorimeter—diagram.

The gas enters the calorimeter system at 1, and passes first through the governor 2, from whence it flows through a system of capillaries 4. This, in conjunction with the auxiliary burner 5, regulates the flow of gas, so that variations in density do not influence the volume of gas furnished to the calorimeter burner in unit time. At 6 the gas enters a specially designed meter 7, by means of which the correct flow to the burner 8 is adjusted.

Air for combustion is admitted through the valve 9, which adjusts itself automatically in accordance with the temperature of the exit gases, and perfect combustion is attained thereby. The hot gases cause expansion of the pyrometer 12, which operates the pen gear 13. After passing the pyrometer the gases pass downwards through the annular space between the outer and inner casings, and make their exit through 16 and the chimney 17. A secondary supply of air is admitted through the aperture 10.

CHAPTER XIX

SCIENTIFIC CONTROL OF THE PURCHASE OF FUEL AND OF ITS COMBUSTION

IN spite of the enormous development of gas power the generation of steam is still the most important method of converting the heat energy of coal into work. The economy of the water-tube boiler in conjunction with turbines has falsified the view put forward with such confidence by some prophets that the steam engine would at an early date be relegated to the museums. Whilst under the best practice a boiler efficiency of 75–80 per cent. is attainable, by operating without some system of scientific control large but easily avoidable losses, which greatly reduce the efficiency, are incurred daily. Further, in the purchase of fuel for large plants very much better value for money can be attained almost invariably by applying common-sense rules.

To quote from an article in the *Times Engineering Supplement* (August 26, 1908):—"There are few materials required in our manufacturing and carrying industries which are purchased on a large scale with such a complete neglect of common-sense rules and precautions as fuels—the majority of our manufacturers still purchase fuel by the rule-of-thumb methods which satisfied the last generation. A user is not purchasing so many tons of a solid of uniform composition, but should be purchasing so many units of heat—in solid form—as a matter of convenience."

From a consumer's point of view the value of a coal is dependent primarily upon its suitability to existing boiler-house conditions, and, secondly, on its calorific value. Its burning character, depending upon its freedom from caking, its average size, etc., will determine whether the requisite quantity can be burnt economically per square foot of grate area to give the steam required. Its calorific value is dependent upon the quantity of combustible matter actually present and the heating value of this combustible part; the percentage of combustible matter being inversely proportional to the moisture and ash of the fuel.

Given that coals of a suitable character are available, it has been proved conclusively in the American laboratories with various kinds of boilers that the practical value of coal for steam-raising is directly proportional to its calorific value as determined in some form of bomb calorimeter (*i.e.*, gross value). Logically, it is as absurd to purchase coal without reference to its heating value (which is always liable to variation from the same seam at the same colliery) as it would be for a metallurgist to pay at a uniform rate per ton for the ore of a precious metal without reference to the actual number of ounces of metal per ton of ore.

There has been naturally an adjustment of price to value; certain coals are so superior for steam-raising to others that they have commanded always a better figure. When such are employed the quality of deliveries is much better sustained when it is known that all deliveries are subjected to sampling and determination of calorific value. Where automatic stoking appliances are installed and control of combustion kept by the adoption of scientific methods, it often will be found that poor coal is quite suitable for use and in reality gives much better value for money than the special quality coals.

Whilst in some cases there is no option, if heavy freight charges are to be avoided, but to employ strictly local coals, it will be very exceptional to find no latitude of choice; some coals are certain to give better value in heat units for a given price than others.

Purchase based on a guarantee of composition and calorific value never can be satisfactory with a natural product like coal; it is so liable to variation in the quantity of combustible matter in different parts of the same seam, although the combustible matter has possibly a fairly uniform heating value, as to be against any guarantee. The simplest method, in cases where consumption does not justify the application of a full scientific system of purchase, will be that of contracting for the coal which, after trials of other deliveries of coals all suiting the conditions of practice, affords the greatest number of heat units per unit of cost, the penny being the most convenient unit of value. Comparison can be made on

$$\frac{\text{B.Th.U. per ton}}{\text{Cost in pence per ton}}$$

Should any deficiency in use become apparent, the calorific value determined on a properly-drawn sample will enable a comparison to be made with the original value on which it was decided to purchase this coal, and it would be possible to sustain a complaint, which with ordinary methods is next to impossible.

A factor which has operated against the system has been the uncertainty of calorimetric determinations, on which payment must be based. In an article in the *Iron and Coal Trades Review*, August 18, 1911, the following results are quoted as obtained by three chemists or engineers for what purported to be the same sample—13,550, 14,050, and 15,360 B.Th.U.! If results one-tenth as divergent as these are liable to be obtained, no one can accept purchase on a calorific value basis, and it is because figures have been put forward in the past showing enormous discrepancies that there is a natural hesitation to be bound in the matter of a guarantee of heating value, or by a contract based on *pro rata* payments on the heat units of the fuel.

Purchase on a scientific basis can become general only when confidence is established in the accuracy of the tests, which, of course, involves fair and accurate sampling. Reference has been made already to the large errors with certain commonly employed types of calorimeters, and it has been proved conclusively that in the hands of a competent operator an error of less than half a per cent. is possible with the bomb calorimeter. Unfortunately the idea has been fostered that any engineer or other not specially-trained person can get the true calorific value of a fuel in some of the simpler calorimeters, an idea which, after many years' experience with most commercial calorimeters, the writer disputes unhesitatingly. For the same class of coal good comparative figures are obtainable, but the results can never have the degree of accuracy to serve as a basis for purchase; some form of bomb calorimeter in the hands of an experienced operator alone can furnish sufficiently trustworthy results.

Two alternatives are open in arranging for the proper testing of the samples, presuming the specified directions for proper sampling have been certified as adopted. Three identical samples may be sealed up, one of these being examined for the consumer; if demanded, the other must be returned to the producer for his determinations, and a third preserved for reference to an independent expert, whose decision shall be final. On the other hand, as this might entail considerable expense, the parties may agree to accept the report of an independent authority in every case, on a certificate that sampling has been carried out exactly as specified, and with a provision for the independent expert to take his own sample if he considered it advisable.

Where contracts based primarily upon *pro rata* payments in accordance with calorific value have been running, it has been found invariably that the total economies resulting are much greater proportionately than the mere per cent. allowance. The United States Government are very large purchasers on this system, and their collected experience is that a saving of 20 per cent. is effected. Herein lies the great value of the system; not only is the price paid strictly proportional to the quality, but the knowledge that all deliveries are subject to constant sampling and determination of calorific value ensures that a much better average coal for steam-raising is supplied than under the old system.

Primarily then the price paid will be strictly proportional to the calorific value as delivered, a standard price per ton being arrived at in conjunction with the calorific value of the bulk sample submitted for trial. It is not desirable to make too fine a differentiation on the calorific value results or payments based on them in view of errors in calorimeter determinations in commercial practice possibly reaching half a per cent., whilst with really good sampling a further error of the order of 1 per cent. is probable. Allowing a fair margin it would be reasonable to make 2 per cent. differences on the calorific value the usual practice, and this is the system adopted by the United States authorities. With average values for the calorific value of coals for boiler use and average prices, a deduction or bonus at the rate of 1*d.* per 100 B.Th.U. variation from the standard would be approximately correct, and nearer than 100 B.Th.U. it is undesirable to draft a contract. One large Power Corporation in the States makes an allowance at the rate of 1 cent. for every 50 B.Th.U., which is almost in the same proportion, but assumes an impossible degree of accuracy in sampling and calorimetry.

The point has been raised whether the gross or net calorific value should be taken. The fallacy of regarding the latter as the true practical value has been dealt with already, but it is desirable to consider whether the net value is preferable as the basis. In the first place, the gross value is the one obtained in all calorimetric work with solid fuels, although one form of bomb calorimeter is said to be adapted for determining directly the water formed on combustion, but this must entail many difficulties which add greatly to the work involved. In practically every case the net calorific value can be arrived at only by a knowledge of the percentage of hydrogen in the fuel, and this again is ascertained accurately only by the tedious and generally unnecessary process of ultimate analysis.

Attempts have been made to calculate the hydrogen from the amount of volatile matter, but no satisfactory relationship has been established. It pre-supposes that the compounds yielding volatile constituents are similar in all cases, which is manifestly not the case.

Seyler has proposed the formula—

$$H = 1{\cdot}72 + 2{\cdot}43 \log V$$

where V is the volatile matter on the dry, ash-free coal, this being claimed to hold between 3 and 40 per cent. volatile matter. Applying this formula to the very carefully analyzed coals used by the author and Cowan and Gray and Watson, the error ranges from $-0{\cdot}14$ to $+0{\cdot}84$; practically 1 per cent. This error is greater than the hydrogen variation in coals of about the same character, and clearly indicates that recourse must always be had to the tedious process of ultimate analysis for a correct result.

Taking the very large series of analyses summarized in Table XVII. it will be seen that, excluding anthracites, which are not used for steam-raising, the extreme variation in hydrogen hardly ever exceeds 1·5 per cent., and in general with steam-raising coals will be under 1 per cent. To obtain the net value the deduction for hydrogen required to be made from the gross value is 87 B.Th.U. per 1 per cent., with 1·5 per cent. difference in hydrogen; this means a deduction of 130 B.Th.U., or about 1 per cent. on the heating value.

The difference between the gross value and the real practical value as compared with the difference between the net value and the same real practical value is, within the limits of variation in the amount of hydrogen found in coals, so nearly constant, certainly well within the combined limits of error of sampling and calorimetry, that the extra trouble involved in arriving at the net value is not commensurate with any slight gain. The gross value as determined by the bomb is all that is required.

Free moisture, however, demands very careful consideration. Heat will be expended in its evaporation and be lost through the steam produced escaping at flue gas temperatures. For the *net* calorific value of the sample as delivered a deduction would have to be made for this, but there are very good reasons for not taking this into account except in very abnormal circumstances. In the first place, the net calorific value is calculated always on the assumption that the products of combustion are at a temperature of 212° F., which is never the case, and this net value is no more the real available value than the gross is; it is only a little nearer the practical.

The heat involved for evaporation may be calculated from—

(a) Heat raising water from air temperature to 212° $(212 - t^1)$.
(b) Heat to convert to steam from and at 212° (967).
(c) Heat to raise steam from 212° to flue gas temperature (t^2).
$(t^2 - 212) \times$ specific heat steam (0·48).

Then—

$$\text{Weight of water per lb. of coal} \times [(212 - t^1) + 967 + 0{\cdot}48\,(t^2 - 212)]$$

The magnitude of the values will be appreciated best by taking an actual example.

With coal: Ash 7·5 per cent. Calorific value on dry, 13,000; on combustible, 14,050: Air temperature, 60° F; Flue gases at 500° F.

Moisture.	Calorific value on wet coal.	Additional B.Th.U. expended on evaporating moisture.	Percentage loss of calorific value.
5·0 per cent.	12,350	62·5	0·50
7·5	12,025	93·7	0·78
10·0	11,700	125·0	1·06
12·5	11,375	156·2	1·37
15·0	11,050	187·5	1·70

The correction for heat expended in vaporizing this water to flue gas temperature will approximate in percentage lowering of calorific value to one-tenth only of the percentage of moisture. Hence, unless the delivery is exceptionally wet as compared with the standard coal, this additional factor hardly demands consideration. As further reasons for neglecting this there is the variation in the distribution of moisture throughout a large bulk of coal, for which it is not always possible to correct in sampling, and the fact that the coal as burnt is often much drier after storage than when delivered.

Moisture is throughout the most difficult point to deal with satisfactorily. In many cases it would be obviously unfair to saddle a contractor with penalties for what might be beyond his control, such as open trucks standing in the rain for some hours before unloading, but, of course, the converse is sometimes the case, and the sample is drier than on loading. Over a period it would in all probability give a balance if the sliding scale of payment was based on the calorific value of the dry coal, taking a certain determined percentage of water as normal, and therefore the standard, and making an additional allowance by calculating the actual delivery as so much per cent. above or below the quantity weighed in as the percentage of moisture is below or above the standard of moisture agreed upon.

The percentage of ash is another important point. It is allowed for *pro rata* with the lower calorific value, but above a certain amount ash is detrimental in far greater ratio than the actual percentage will show, and a *pro rata* deduction does not compensate the consumer properly when the ash is much above the standard.

There is additional trouble in the handling and disposal of ashes; if of a clinkering character it will be very troublesome; it leads to deposition of much dust in tubes and flues; it interferes with proper combustion on the grate, and it may be difficult to maintain the required output from the boilers. Above a certain amount then ash may well be subject to a penalty increasing more rapidly than the actual percentage increase, with right of rejection when a certain limit is exceeded. In the American Government contracts the sliding scale for ash ranges from 2 cents per ton with low ash to 18 cents for high ash content.

The percentage of small coal again is sometimes taken into consideration, for if this is high it interferes with the proper air supply through the grate and larger carbon losses in the ash, etc., result. It is very difficult to make proper allowance for this in terms of money value. The London County Council contract given below takes this factor into consideration.

Whilst the factors other than calorific value have been discussed in their relation to purchase on a scientific basis and are of importance, in the draft of contracts for what is largely an innovation on generations of practice, and of the fairness of which it is still necessary to convince many producers, the importance of simplicity in the terms cannot be over-rated. One would be disposed therefore to forego many of these minor considerations for the great advantage to be gained by the general acceptance of the main principle of purchase *pro rata* on calorific value.

In developing any scheme of purchase based strictly on calorific value the primary object which should be kept in mind is that the consumer shall obtain regularly coal of the desired quality, and that the contract shall be so drawn that it is to the best financial interests of the producer to supply this quality. If below the standard the consumer shall not be called upon to pay more than a fair price, but, on the other hand, the producer must be assured of receiving what is fairly due to him should he supply coal honestly worth more than the standard price, and it is certainly to the interests of the consumer to obtain such fuel.

It is mainly because proposed contracts in this country have been drawn purely with a view of benefiting the consumer that very natural opposition has arisen to such a system of purchase on the part of the producer. If the latter can be shown that he is to be treated fairly, and that if he supplies coal of higher heating value than the average value taken as the basis of the contract he is going to obtain a higher price, in fact that the contract is perfectly equitable between both parties, this opposition will disappear.

When the author first laid stress on the necessity for bonus as well as penalty clauses in contracts, Mr. G. C. Locket, Chairman of the Coal Merchants Society wrote—

"It is the first time in my experience, that any one of authority has put forward the proposition that contract conditions should be perfectly equitable as between buyer and seller. Personally, I am disposed to favour the principle of selling fuel according to its calorific value, provided the method of sampling, the form of calorimeter used, the method of taking the analysis, and the adoption of a premium as well as a fine, is settled on a fair and equitable basis."

That these principles are receiving recognition is shown by the agreement on tenders recently entered into between the principal London firms of coal contractors and the Associated Municipal Electrical Engineers of Greater London. (See *Iron and Coal Trades Review*, March, 1913.) Two alternative specifications are given, A for named coal, or coal of a particular description, B for coal guaranted to have definite qualites as a fuel for steam-raising. The standards adopted are given in Table LII.

TABLE LII.

STANDARDS FOR GUARANTEED COALS.

Washed Coals.

Description.	Calorific value in B.Th.U.	Moisture.	Small coal.
Durham and Yorks. (bituminous).			
Double nuts	13,250	8	15·0 per cent. through ¼ in.[1]
Single ,, ...	13,000	9	17·5 ,, ,, ⅜ ,,
Peas	12,750	10	20·0 ,, ,, ¼ ,,
Scotch (bituminous).			
Double nuts	12,750	10	15·0 ,, ,, ½ ,,
Single ,, ...	12,500	11	20·0 ,, ,, ⅜ ,,
Peas	12,000	13	20·0 ,, ,, 3/16 ,,
Welsh (semi-bituminous and pseudo-anthracitic).			
Large nuts	14,300	5	15·0 ,, ,, ½ ,,
Small ,, ...	13,900	6	20·0 ,, ,, ⅜ ,,
Peas	13,350	6	20·0 ,, ,, 3/16 ,,
Dry Screened Coals.			
Durham and Yorks. (bituminous).			
Double nuts	12,750	5	17·5 ,, ,, ½ ,,
Single ,, ...	12,500	6	25·0 ,, ,, ⅜ ,,
Peas	12,250	6	25·0 ,, ,, ¼ ,,
Derby and Notts (bituminous).			
Double nuts	12,250	9	15·0 ,, ,, ½ ,,
Doubled screened small nuts .	12,000	9	20 0 ,, ,, ⅜ ,,
Pea nuts	11,500	10	20·0 ,, ,, 3/16 ,,
Leicester, Warwick and South Staffs.			
Double nuts	12,000	10	15·0 ,, ,, ½ ,,
Double screened small nuts .	11,750	10	20·0 ,, ,, — ,,
Pea nuts	11,250	12	20·0 ,, ,, 3/16 ,,

Payment under B is on a *pro rata* scale based on the calorific value with suitable modifications of the quantity paid for as delivered according to the moisture and small coal. No variation in the contract price is made for variations in the calorific value from the standard not exceeding one-twentieth of the figures in the table. The calorific value is to be determined on the coal after drying for 1 hour at 104·4° C. (220° F.).

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[1] *Sieves shall be square mesh with openings in the clear to the sizes given.*

The allowance for moisture is arranged as in the County Council Contract below, and small coal on a very similar basis. If the percentage of small coal be above (or below) the standard, the quantity weighed out shall be decreased (or increased) by a quarter of the percentage increase (or decrease) of small coal—percentage being taken on the bulk and not on the standard. Right of rejection of a consignment may be exercised if the moisture is more than 1½ times the standard or the proportion of small coal exceeds 25 per cent. by weight—taken on the bulk. The percentage of sulphur on the coal as received must not exceed 2 per cent.

Two other contracts may be cited. Mr. Rider (*Jour. Inst. Elec. Engs.*, 1909, 43, 197, 241) gave the following particulars as to the contract for the London County Council Power Station.

The specified standards are—

Calorific value	12,500 B.Th.U.
Small (passing through ⅜ square mesh sieve)	20 per cent. by measurement
Moisture	10 per cent. by weight.

The calorific value and moisture are measured by the County Council chemist on samples taken from every 100 tons brought over the pier head, the calorific value being determined by a Mahler bomb Calorimeter on samples dried at 100° C. Moisture is determined on a weighed portion of the sample taken from an air-tight tin.

Small coal is ascertained on the pier on a sample of about 50 lbs. in weight, taken at the option of the Council, either from the hold, or from the quantity unloaded from the grabs.

If the quality of the coal in any cargo, as ascertained by the samples tested be found different as regards calorific value, moisture or small from the above standards, the price paid to the contractor is varied as follows—

(a) If the calorific value exceed 12,500 B.Th.U. the price per ton is increased in the same percentage ratio as the increase in calorific value.

(b) If the calorific value is less than 12,500 B.Th.U. the price is decreased in the same percentage ratio. The Council, however, has the right to reject the whole of the cargo if the calorific value be less than 10,500 B.Th.U.

(c) If the moisture is less than 10 per cent. by weight, the quantity of coal to be paid for is increased beyond the quantity weighed in by a percentage equal to the percentage decrease of moisture.

(d) If the moisture exceed 10 per cent. by weight, the weight of coal to be paid for is decreased below the quantity weighed in by a percentage equal to the percentage increase in moisture. The Council, however, has the right to reject the whole cargo if the moisture exceed 13 per cent.

(e) If the proportion of small be less than 20 per cent. by weight, the weight of coal to be paid for is increased beyond the quantity actually weighed in by a percentage equal to a quarter of the percentage decrease of small coal.

(f) If the proportion of small coal exceed 20 per cent. by weight, the weight of coal to be paid for is decreased below the quantity actually weighed in by a percentage equal to a quarter of the percentage increase of small coal. The Council, however, has the right to reject the whole cargo if the proportion of small coal exceed 25 per cent. by weight.

"The coal merchants were at first a little chary at accepting a contract with such conditions, but, after a little experience, they found that they were easily able to meet them, and the result has been that an increased price is paid for practically every cargo of coal because it is better than the standard. This is a gain to the Council in every way, as not only is the quality and size of the coal very uniform, but, being so, its handling and burning become an easy matter."

Mr. L. P. Crecilius has given the following particulars of the system adopted by the Municipal Traction Company of Cleveland (U.S.A.)—

Each day's consignment of coal furnished to each power plant by the contractor is sampled and analyzed to determine its heating value. The price paid by the company per ton per car of coal is based on a table of heat values for excess or deficiency on the standard contained in the contract, but subject to further deductions for ash and sulphur.

The table of penalties is so proportioned as to make it most profitable for the dealer to supply bituminous slack of a value ranging from 12,500 B.Th.U., the standard in the contract, to 13,125 B.Th.U., 5 per cent. above the standard.

A small quantity of coal is taken from at least five different places in each car received, by driving into the coal a 5-foot ram, before the car is unloaded. The quantities thus received from each car of coal of the day's consignment are thrown into a receptacle provided for the purpose and thoroughly mixed, and a properly selected sample of the mixture is taken for chemical analysis. Half the sample of the average mixture is labelled and held at the Company's laboratory for a period of two weeks after unloading the cars. The other half is analyzed as soon as possible after being taken. No other samples are recognized.

Tests of the sample taken from the average mixture are made by the Company's chemist. Should the contractor question the result of the test, the duplicate sample is forwarded to an independent laboratory. The results obtained from the second test are considered to be final and conclusive. In case the disputed values as obtained in the Company's test are found by the second test to be 2 per cent. or less in error, the cost of the second test is borne by the contractor; but if the disputed value is found to be more than 2 per cent. the cost is borne by the Company.

Coal which is shown by analysis to contain less than 15 per cent. of ash and 3·5 per cent. of sulphur is accepted without any deduction from the basic contract price, plus or minus an amount of excess or deficiency of B.Th.U. value. When the analysis gives amounts in excess of these quantities, deductions are made from the basic contract price in accordance with the penalties provided in the contract, plus or minus the amount for excess or deficiency of the standard value.

Almost immediately after the contract came in force there was a marked difference in the cost of maintaining the efficiency of the entire plant, accompanied by an improvement of some 8 per cent. in the consumption of coal per kilowatt-hour.

CONTROL OF COMBUSTION THROUGH COMPOSITION OF FLUE GASES

The method of calculating the amount of air required theoretically for the combustion of fuel of given composition and the theoretical composition of the flue gases have been given in Chapter I, and full data for such calculations in Table II, Appendix.

When the combustion of a fuel is complete the whole of the carbon should appear in the flue gases as carbon dioxide, accompanied by the nitrogen previously associated with the oxygen in the air. If this were attainable without excess air carbon dioxide and nitrogen alone would constitute the flue gases. With excess air, as must be the case always with a solid or liquid fuel, free oxygen will be present in addition. On the other hand, when combustion is not complete carbon will be found in the flue gases partly as carbon monoxide and partly as hydrocarbons; theoretically there should be no free oxygen.

The efficiency of the combustion process is dependent upon two main factors—

1. Complete development of the maximum number of heat units of the fuel, attainable only by complete combustion.
2. Maximum utilization of these units, attainable only by avoiding all preventable waste.

The first condition is very important. All carbon appearing as the monoxide leads to serious loss, for 1 lb. of carbon then develops only 4,420 B.Th.U. per lb., instead of 14,650, as it does when burnt to carbon dioxide. Further, incomplete combustion of the volatile constituents (or products resulting from their decomposition by heat) leads to escape of hydrocarbon gases. From Table I, Appendix, it will be seen that such hydrocarbons have very high thermal values.

In general these losses through incomplete combustion can be avoided only by admission of a certain excess of air over that demanded theoretically, and necessarily this entails losses through sensible heat units carried by the flue gases, which up to a certain limit are unavoidable. For maximum practical efficiency a course must be steered clear on the one hand of the losses through incomplete combustion, without on the other hand running the risk of still bigger losses through unnecessary excess of air. Heat units must be sacrificed; the important point is to adjust conditions of air supply so that this sacrifice is reduced to the minimum.

Assuming combustion were perfect with the theoretical air, heat would still be lost through the hot flue gases, the actual loss depending on the weight of the gases, their specific heat and temperature, or

$$m \times \text{Sp. ht.}\ (t^1 - t^2) = \text{B.Th.U.}$$

where m is the weight of gases per lb. of fuel, t^1 the temperature of the flue gases, t^2 the temperature of the air supply. Excess of air which must be allowed, as shown already, increases m, and the losses become proportionately large as $(t^1 - t^2)$ becomes greater. In addition to losses in the flue gases excess air causes direct cooling in the furnace, and reduces the efficiency of the heat transmission to the water.

It is clear then that the control of the amount of air actually employed in the combustion process is essential to good results, and consequently the means by which a proper judgment of the actual air supply can be ascertained must be considered carefully.

These methods include (*a*) complete analysis of the flue gases; (*b*) intermittent ("snap") determinations of carbon dioxide, only; (*c*) continuous recording apparatus for carbon dioxide; (*d*) indirect estimation of carbon dioxide from density of the gases.

From the complete analysis of the flue gases, carried out usually in an Orsatt apparatus, a better computation of the conditions can be arrived at than by other methods. This method has the special, advantage of giving readily both the carbon dioxide and free oxygen. and if the amount of carbon monoxide and hydrocarbons is sufficient, as should not be the case, a fair approximation as to their amount. If the quantity of these products of partial combustion is small, more delicate means of analysis is required for their estimation. The complete analysis is invaluable in many cases, but for general control in practice much simpler methods are preferable.

Carbon dioxide alone is a sufficiently good guide in general. Pure carbon on combustion with the theoretical air yields a volume of carbon dioxide equal to the volume of oxygen with which it combines; hence, as air contains approximately 21 per cent. of oxygen, the gaseous products consist of 21 per cent. of carbon dioxide and 79 per cent. of nitrogen. For a fuel containing x per cent. carbon the flue gases will contain $\frac{21 \times x}{100} = y =$ carbon dioxide per cent.

The excess air with pure carbon will be found from

$$\left(\frac{21}{CO_2 \text{ found}} - 1\right)100.$$

For a fuel consisting of carbon only as the combustible together with non-combustible constituents, the excess air will equal $\left(\frac{y}{CO_2 \text{ found}} - 1\right)100$. In the case of a fuel containing hydrogen, a slight modification would be required, because the hydrogen burns with oxygen, forming water, which is condensed, and the carbon dioxide is estimated always in the gases after this condensation; but for practical purposes this may be neglected, and the last formula applied as giving a sufficiently accurate approximation. It is not possible, however, always to obtain the composition of the coal from which y is calculated, but, taking coals generally, the amount of carbon dioxide present in the flue gases with theoretical air supply will lie between 18·5 and 19 per cent. On the basis then of $\left(\frac{18{\cdot}5}{CO_2 \text{ found}} - 1\right)100$, the excess of air may be ascertained approximately, and for a given heating value of the coal and flue gas temperature the loss of heat units for different excess quantities of air calculated. In the diagram (Fig. 68) curves for a typical case are given for three different flue gas temperatures.

It will be seen that the rate of increase of loss through excess air down to 12 per cent. of carbon dioxide is not great, but below this figure the losses may increase rapidly. In an attempt to work with too high a carbon dioxide figure great risk is run of incurring far more serious losses through incomplete combustion, and a safe maximum for carbon dioxide may well be fixed at 14 per cent.

Several simple forms of apparatus are available for the rapid estimation of carbon dioxide in flue gases, and the application of these is often a valuable guide, but conditions during operation of a boiler plant, especially with hand-firing, vary so from time to time that these intermittent tests have nothing like the value which a continuous recording apparatus has.

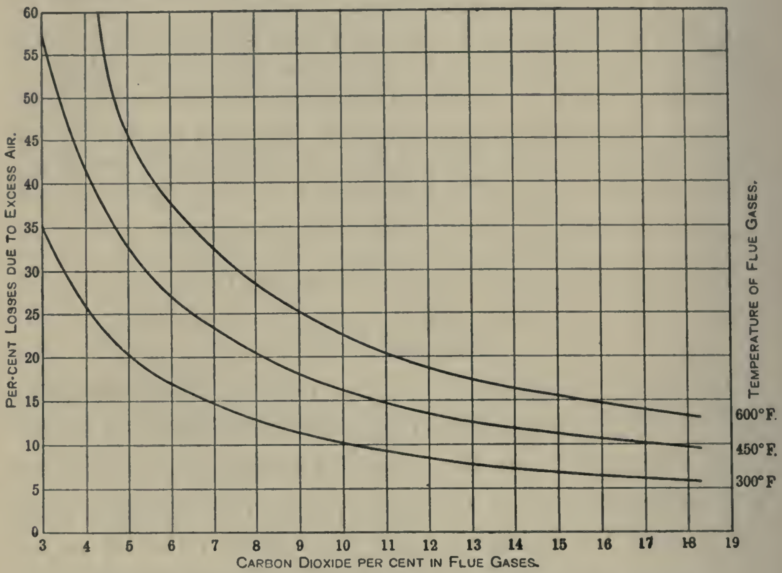

FIG. 68.—Loss of heat in flue gases with different CO_2 percentage.

Calculated for a steam coal, 87·0 per cent. carbon; 4·5 per cent. hydrogen; assuming a mean specific heat for the flue gases of 0·24; 18·3 per cent. CO_2 in flue gases correspond with 11·6 lbs. of air theoretically required.

The earliest method of obtaining continuous readings of the amount of carbon dioxide was by the use of a suitable balance for estimating the density of the cooled gases. Owing to the high density of this gas as compared with air the density of the flue gas could be made a measure of its percentage, but so many reliable forms of recorder are now on the market that the balance method is obsolete. It is proposed to describe three typical forms of these instruments. The term "continuous" is not strictly correct; with one exception these instruments make frequent intermittent tests of which a continuous record is kept; the rate may be varied, but it is preferable not to exceed 15 estimations per hour.

The "Sarco" CO_2 Recorder.—A general view of the instrument is shown in Fig. 69, and its operation will be followed from the diagram, Fig. 70.

The gas is obtained through a $\frac{3}{4}$-inch pipe, which taps the side flue or last combustion chamber of the boiler or furnace, and is connected to the instrument at 3 (Fig. 70); in order that the gas samples may be secured rapidly and continuously the circuit is completed by another pipe of the same diameter. This is connected at 7, and carried to the base of the chimney, or to a convenient point in the main flue.

The power required to draw in the gas and operate the instrument is derived from a fine stream of water at a head of about 2 ft.; 3–5 galls. are required per hour. It enters the instrument through the small glass injector 9. By the use of injectors having apertures of various sizes the speed of the machine may be adjusted.

The water now flows through tube 74 into the power vessel 82; here it compresses the air above the water level, and this pressure is transmitted to vessel 87 through tube 78. The pressure thus brought to bear on the surface of the liquid, with which vessel 87 is filled to mark 95, sends this upwards through tubes 91 and 93. Thence it passes into vessels 77, 66, 67 and 68, and into tubes 51, 52 and 49, rising until it reaches the zero mark 71, which will be found on the narrow neck of the vessel 67.

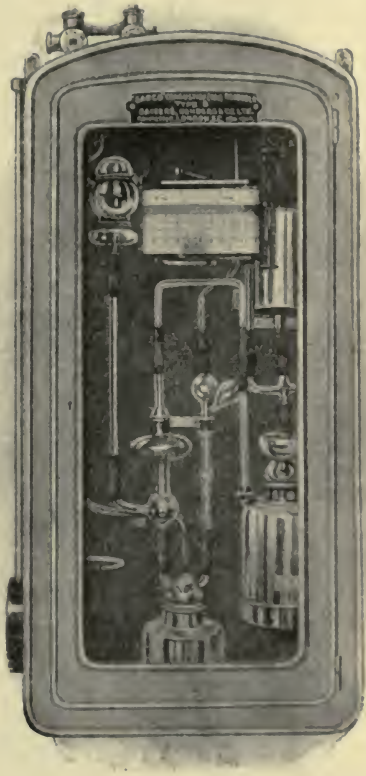

Fig. 69.—Sarco CO_2 recorder—general view.

At the moment it reaches this mark the power water, which, simultaneously with rising in vessel 74, has also travelled upwards in siphon 72, will have reached the top of this siphon, which then commences to operate. Through this siphon 72 a much larger quantity of water is disposed of than flows in through injector 9, so

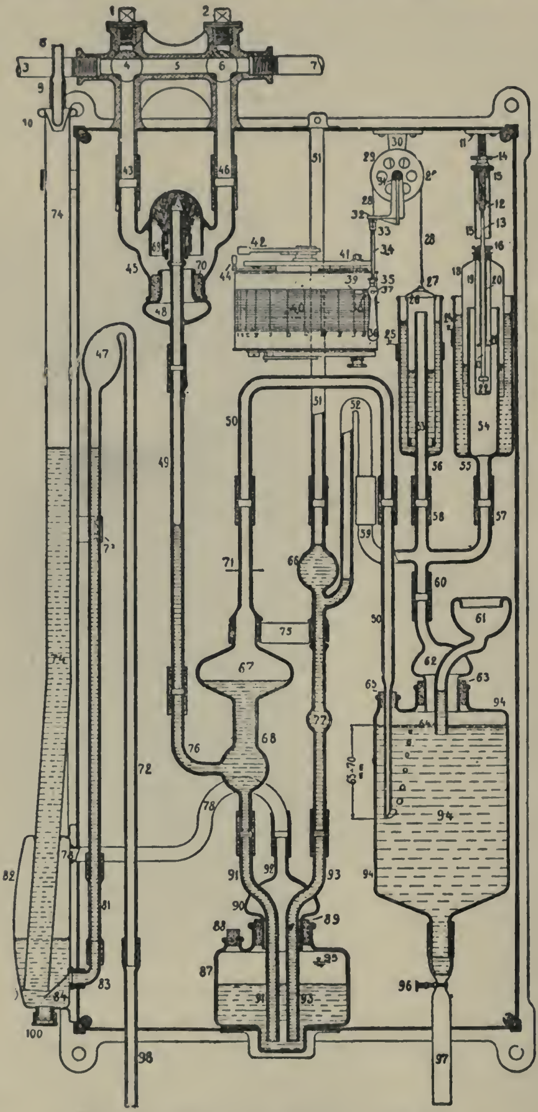

FIG. 70.—Sarco CO_2 recorder—diagram.

that the power vessels 74 and 82 are emptied again rapidly. The moment the pressure on vessel 87 is thus released, the liquids return from their respective tubes into this vessel.

Assuming tube 49 to be in connection with a supply of flue gas, a sample of this is drawn in from the continuous stream which passes through 43, 45 and 46, as the liquid recedes in 49, by the partial vacuum which is created by the falling of the fluid, As soon as the liquid has dropped below point 76, which is the inlet of the flue gas into vessel 67, the gas rushes up into this vessel and its connections. When the flow in the siphon stops, vessel 82 begins to fill again, and the liquids in tubes 91 and 93 rise afresh. The gas in 67 and 68 is now forced up into tube 50, and caused to bubble right through a solution of caustic potash (sp. gr. 1·27), with which vessel 94 is filled to point 64 marked on the outside. In this process any carbon dioxide that may be contained in the gas is absorbed completely by the potash.

The remaining portion of the sample collects in 62, and passes up through 60 into tubes 57 and 58 (it cannot pass out at 59, as this outlet is sealed by the liquid in 52). The gas now passes under the two floats 18 and 26, whereof the former is constructed larger and lighter, and will therefore be raised first.

By turning the thumbscrews 14 and 15, the stroke of this float is adjusted until just 20 per cent. of the whole of the sample remains to raise float 26, when nothing is absorbed in 94, as would be the case if air is passed through the recorder. This float has attached to it pen 36, which is caused to travel downwards on the chart, when 26 rises.

If no carbon dioxide were contained in the gas, nothing would be absorbed by the potash in 94, and the whole of the 20 per cent. would reach float 26. Thus the pen would be caused to travel the whole depth of the chart from the 20 per cent. line at the top to the zero line at the bottom. Any carbon dioxide contained in the sample would be absorbed by the potash, a correspondingly less quantity would reach float 26, and pen 36 would not travel right down to the bottom of the chart, *i.e.*, the zero line. Thus any carbon dioxide absorbed will be indicated by the length of the lines on the chart.

On the return stroke of the liquid the gas is drawn out from under floats 18 and 26, through tubes 57 and 58, and into tubes 59 and 52. From here it passes out into the atmosphere at 66, and through tube 51, as soon as the liquid has fallen below the outlet of tube 52.

Simmance and Abady's Valveless CO_2 Recorder—The latest pattern of this instrument is illustrated in Fig 71. There are four vessels in this apparatus—the siphon tank B, extractor D, recorder F and potash vessel E for absorbing the carbon dioxide.

The siphon tank is furnished with a heavy float, C, which rises slowly as the water fills up the tank, and falls quickly as the tank is emptied by the action of the siphon. The extractor consists of a movable gas chamber, D, attached to the float by means of a chain, M, passing over two pulleys and working in an outer tank filled with water. The recorder consists of a small gasholder with internal standpipe and rising bell, F, suspended from a sensitive balance, S, moving over a divided scale, N. The caustic potash tank, E, consists of a steel tank, fitted with gas inlet nipple and outlets, and furnished with an overflow pipe, L, closed with a pinch cock for draining off excess.

A small water cistern, K, is fitted with a water connection and cock X with an injector nozzle immediately below for exhausting the gases, and a loose valve, J, for discharging the contents of the cistern quickly at the moment of siphoning; a waste water tank and outlet, Y, is also arranged in bottom of case to carry away the water after siphoning.

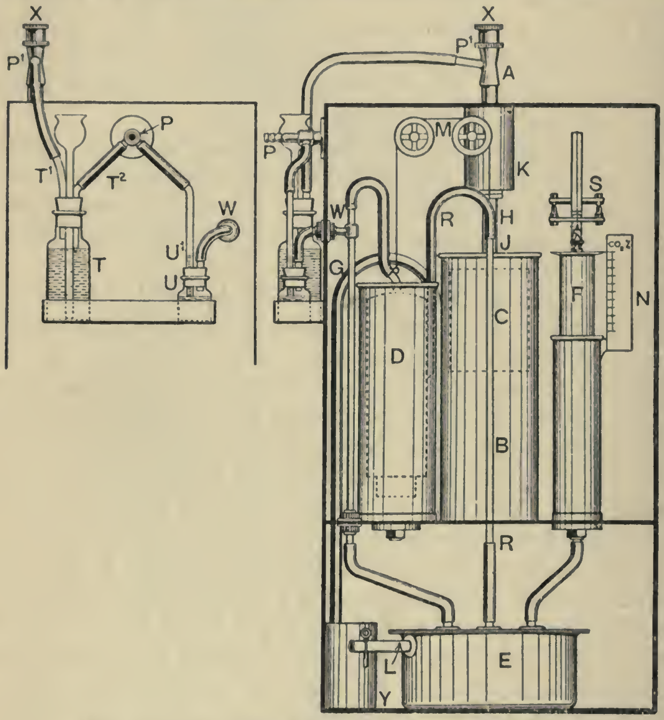

FIG. 71.—Simmance-Abady CO$_2$ recorder—diagram.

A non-return liquid seal, U, on the gas inlet, P, with a safety seal bubble bottle, T, on the injection connection, P′, are arranged on the side of the case, as shown in the small diagram.

Water is allowed to fall into the tank B, from the cistern K. Assuming that the former is nearly full, and the weighted float C therefore near the top, then, as the water still continues to flow, the float rises until it touches the end of the drip valve J, quickening the supply and starting the siphon, also actuating the pen. As the water siphons out the float drops and pulls up the extractor D, and a charge of gas is drawn in through W from the flue pipe through the non-return valve U. The siphoning being finished and the water still continuing to flow, the float again rises and the extractor falls until the gas is under sufficient pressure to force it through the potash solution and out through the vent pipe, R, until the end of the latter, which is fastened to the side of the extractor, is sealed in the water in the tank. On this point being reached, the remainder of the sample passes up into the recording bell as the extractor is lowered further into its tank.

The amount of gas trapped off in D by the sealing of the vent pipe, when transferred through the potash, is just sufficient to raise the recording bell, F, from 100 to 0 when the apparatus is working on air containing practically no carbon dioxide. When working on flue gas exactly the same quantity is passed from the extractor D, but on its passage the carbon dioxide is absorbed by the action of the potash; owing to such absorption the recorder bell F will not rise to its full height. At the maximum possible the pen marks on the chart its final position, and the percentage of carbon dioxide in the sample is automatically recorded. The pen is brought into operation by the last upward movement of the float, and the siphon again discharges, and the whole operation is repeated; the bell F being vented and the analyzed gas driven out through the vent pipe R, as the latter is drawn out of the water.

Each sample is measured off under the same conditions of pressure, irrespective of the vacuum or pressure at which the bulk of the gas may be, this instrument being constructed to work accurately up to 3 inches of vacuum.

The Bi-Meter CO_2 Recorder.—This instrument, originally designed by Mr. Otto Bayer, is shown in Fig. 72, and its operation will be followed from the diagram, Fig. 73. It possesses certain marked features in design; in the first place, liquid potassium hydroxide, which is employed in other recorders, is replaced by a solid absorber, slaked lime; the amount of carbon dioxide is recorded by two gas meters, which measure the gas before and after absorption of the carbon dioxide. Consequently the meters revolve at a different speed, and by means of suitable gearing operate the pen on the recording drum. There are no glass parts to get broken and no rubber tubing to perish.

As shown in the diagram, the gases are drawn first through a soot filter, which contains wood shavings and wood wool, the inverted bell standing in a water seal. From the filter the clean gases pass through a water-cooled system, the "temperature equalizer," and then on to the first meter. The carbon dioxide is absorbed in the large absorption chamber, in which are arranged layers of fine slaked lime, the layers being separated by alternate layers of wood shavings; the lime requires renewal about every third day.

FIG. 72.—Bi-meter CO_2 recorder—general view.

The heat of reaction renders the gas warm, so it passes through a second temperature equalizer, and then through the second meter, finally going through the aspirator and to waste.

Whilst the diagram shows very clearly the principle of working it does not indicate the compactness of the apparatus, which can be gathered from the general view. The temperature equalizers are arranged, of course, in one vessel, the long cylindrical vessel on the right-hand side of the case; from here the water passes to the aspirator, shown above No. 1 meter. The absorption chamber is the large vessel in the lower part of the case. The fluid in the meters is oil, and the level in each is so adjusted that with meter 2 running 4 per cent. slower than No. 1, both working on air, the line ruled by the pen just reaches the zero line on the chart. When carbon dioxide is being absorbed the speed of meter 2 is reduced further,

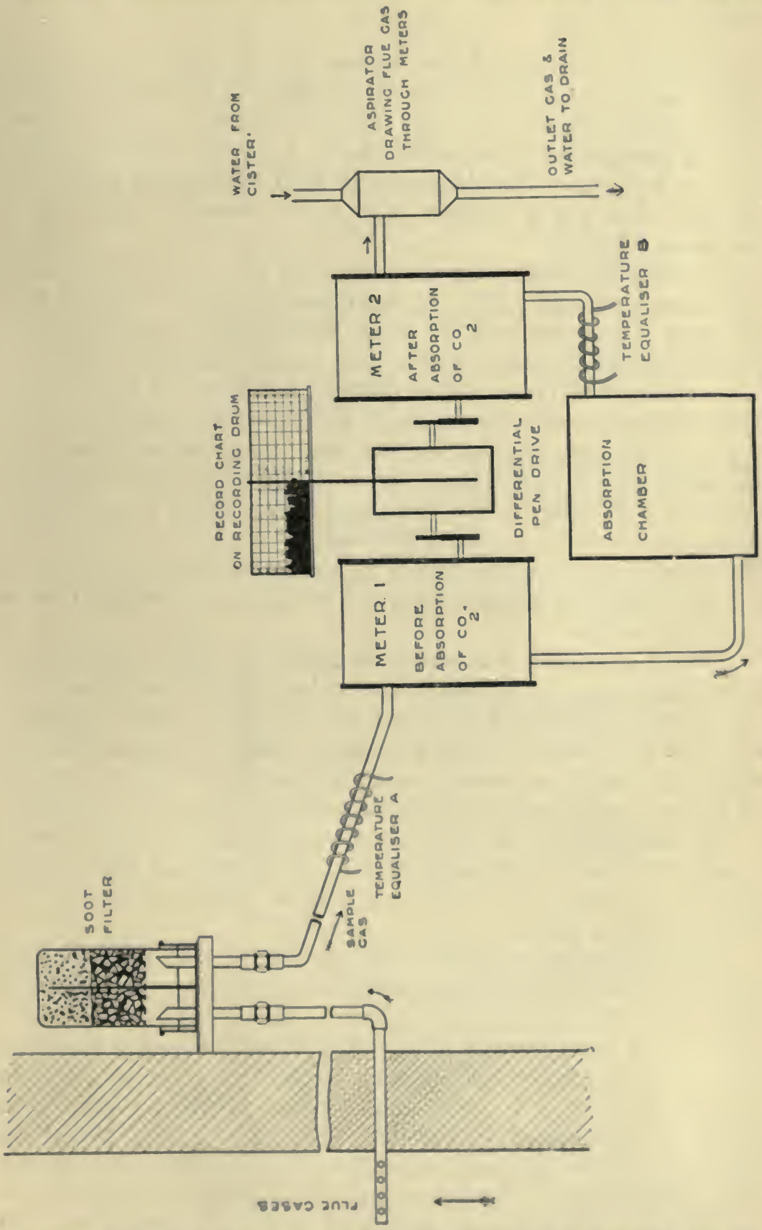

FIG. 73.—Bi-meter CO_2 recorder—diagram.

and the pen marks the corresponding percentage of carbon dioxide.

It must be emphasized that carbon dioxide alone furnishes the easiest and most applicable method of estimating excess air, but that carbon dioxide is only a measure of the heat losses due to this *when it is not accompanied by carbon monoxide.* A further small error is introduced by sulphur dioxide, produced from combustible sulphur in the fuel. This gas is absorbed also by the reagents which absorb carbon dioxide.

The saving of fuel when recorders have been installed generally has been very considerable. In many cases they have revealed that not more than 5 per cent. of carbon dioxide had been obtained in ordinary working before this check was introduced. With the instruments fitted in a suitable position, the record is at all times visible to the stokers, who are found usually to take a proper interest in maintaining the standard of the flue gases, and as a check to excessive firing at infrequent intervals during night shifts they have proved of great value. In power stations with widely varying load it is difficult to obtain proper adjustment of conditions for the best results without the employment of some such system, and as a means of detecting irregularity in the working of automatic stokers they are valuable.

A word of caution is necessary in reference to air leaks through boiler settings, etc. This would lead to low carbon dioxide, and the cause would be detected by failure of reduction of the air supply to the furnace to raise the carbon dioxide. There is, however, the risk that in attempting to do this, in the absence of knowledge as to an air intake, losses through incomplete combustion might be incurred.

In the operation of producer gas plants the automatic carbon dioxide recorders should prove of value in controlling the working conditions, as the carbon dioxide is a most useful indication of the reactions taking place.

Automatic recorders require daily attention if they are to be kept operating satisfactorily, but this attention, if regular, need occupy but little time. Particular attention must be directed to the cleansing of the gases by a suitable soot filter, which should be readily accessible for cleaning and renewal of material, and to arranging the gas pipes so that water does not condense and collect in bends: drain cocks should be provided at such points. The pipe system should be blown through at frequent intervals with compressed air or steam. With attention to the recorder as part of the daily routine of the boiler-house the instruments are capable of invaluable service, but with neglect for some days so much requires doing that it is never attempted.

APPENDIX

TABLE I.

Composition, Cubic Feet per Lb., Weight of 1 Cubic Foot and Calorific Value of Gases burnt at Constant Volume.

Gas.	Formula.	Weight per cub. ft.		Cub. ft. per lb.		Calorific value in B.Th.U. per cub. ft.			
						At 0° C. and 760 mm.		At 60° F. and 30 inches.	
		At 0° C.	At 60° F.	At 0° C.	At 60° F.	Gross.	Net.	Gross.	Net.
Oxygen	O_2	0·0894	0·0844	11·20	11·85	—	—	—	—
Nitrogen	N_2	0·0786	0·0742	12·73	13·50	—	—	—	—
Air	—	0·0807	0·0764	12·40	13·10	—	—	—	—
Carbon dioxide	CO_2	0·1234	0·1168	8·10	8·56	—	—	—	—
Hydrogen	H_2	0·0056	0·0053	178·50	188·70	342·8	289·0	325·2	274·2
Carbon monoxide	CO	0·0781	0·0739	12·80	13·50	341·8	341·8	323·5	323·5
Methane	CH_4	0·0447	0·0422	22·38	23·70	1063·0	954·4	1010·0	905·5
Ethane	C_2H_6	0·0837	0·0792	11·95	12·61	1852·0	1694·0	1762·0	1609·0
Ethylene	C_2H_4	0·0783	0·0740	12·77	13·50	1670·0	1564·0	1580·0	1480·0
Propylene	C_3H_6	0·1173	0·1111	8·52	9·00	2469·0	2306·0	2342·0	2188·0
Acetylene	C_2H_2	0·0727	0·0703	13·25	14·23	1556·0	1500·0	1475·0	1423·0
Benzene	C_6H_6	0·2235	0·2115	4·48	4·73	4018·0	3845·0	3803·0	3564·0

TABLE II.

WEIGHT AND VOLUME OF OXYGEN AND AIR FOR COMBUSTION, INCLUDING WEIGHT OF PRODUCTS AND COMPOSITION OF FLUE GASES.

Fuel.	Weight in lbs.		Volume in cub ft. per lb.				Volume in cub. ft. per cub. ft.		Products of combustion.					
	Per lb. fuel.		At 0° C. and 760 mm.		At 60° F. and 30 in.				Lbs. per lb. of fuel.				Composition by vol. (Water condensed).	
	Oxygen.	Air.	Oxygen.	Air.	Oxygen.	Air.	Oxygen.	Air.	Total.	CO_2.	H_2O.	N_2.	CO_2.	N_2.
Hydrogen . . .	8·00	34·80	89·4	425·4	94·2	448·7	0·5	2·38	35·8	—	9·00	26·80	—	100·0
Carbon (to CO_2) .	2·66	11·60	29·8	141·8	31·4	149·4	—	—	12·6	3·66	—	8·93	21·0	79·0
,, (to CO). .	1·33	5·79	14·9	70·9	15·7	74·7	—	—	6·8	2·33	—	4·46	34·7 (CO)	65·3
Carbon monoxide .	0·57	2·47	6·4	30·4	6·7	32·0	0·5	2·38	3·47	1·57	—	1·90	34·7	65·3
Methane	4·00	17·40	44·7	212·7	47·1	224·3	2·0	9·52	18·40	2·75	2·25	13·40	11·7	88·3
Ethylene . . .	3·43	14·93	38·3	182·3	40·4	192·2	3·0	14·28	15·94	3·14	1·30	11·50	15·0	85·0
Acetylene . . .	3·07	13·37	34·4	163·6	36·2	172·6	2·5	11·90	14·37	3·38	0·69	10·30	17·5	82·5
Benzene	3·07	13·37	34·4	163·6	36·2	172·6	7·5	35·70	14·37	3·38	0·69	10·30	17·5	82·5

TABLE III.

World's Output of Petroleum in Metric Tons.

Countries.	1910.	1911.	1912.	1913.	1914.	1915.
United States	27,940,806	29,373,252	29,615,096	33,126,164	35,435,005	37,480,547
Russia	9,378,210	9,066,259	9,317,700	8,124,731	8,936,070	9,353,077
Galicia	1,762,560	1,458,275	1,187,007	1,087,286	700,000	578,888
Dutch East Indies	1,495,715	1,670,668	1,478,132	1,534,223	1,634,403	1,710,445
Roumania	1,352,289	1,544,072	1,806,942	1,885,225	1,783,947	1,673,145
India	818,400	897,184	989,801	1,000,000	1,066,667	986,667
Mexico	444,374	1,873,552	2,207,762	3,426,172	2,825,124	4,388,068
Japan	257,421	221,187	222,854	258,934	365,117	415,785
Peru	177,347	186,405	233,486	247,647	255,707	331,633
Germany	145,168	140,000	140,000	132,769	140,000	140,000
Canada	42,119	38,813	32,612	30,410	28,641	28,729
Italy	5,895	10,000	12,000	7,000	5,500	5,500
Trinidad	—	—	—	—	85,804	100,000
Argentina	—	—	—	—	—	75,900
Egypt	—	—	—	—	103,605	29,569
Other countries	4,000	26,667	33,333	69,015	82,667	1,333
Totals	43,824,304	46,526,334	47,276,725	50,929,576	53,448,257	57,298,786

Returns for 1914–15 for countries affected by the war are necessarily approximate estimates.

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