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## ATMOSPHERIC POLLUTION

TO  
G. M. B. DOBSON, D.Sc., F.R.S.  
Chairman of the Atmospheric  
Pollution Committee  
1934-1950

# ATMOSPHERIC POLLUTION

ITS ORIGINS AND PREVENTION

by

A. R. MEETHAM, D.Sc.

2001



614.735

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LONDON  
PERGAMON PRESS LTD

1952

## ACKNOWLEDGEMENTS

This book is published with the permission of the Department of Scientific and Industrial Research, to whom the thanks of the author and publishers are due for making available so much published material. The author wishes to thank especially the Director and staff of the Fuel Research Station for all kinds of help, and in particular Mr. L. J. FLAWS for his help with Chapter V.

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2, 3 & 5 Studio Place, London S.W. 1

Printed by Universitätsdruckerei H. Stötz AG., Würzburg

Mehrotra's Book in Lib. 35-5

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## Chapter I

### INTRODUCTION

This book is meant to be of use to all who are professionally interested in atmospheric pollution—public health officers, smoke and sanitary inspectors, architects, engineers, meteorologists, city councillors, builders and legislators. It is also intended to encourage and help the many citizens who are aware of the degree of atmospheric pollution, and who by their writing, conversation, or example, are helping in the fight against it.

The term pollution is used to describe the admixture of any foreign substance which we dislike with something pleasant or desirable. Atmospheric pollution, therefore, is an undesirable substance mixed with the open air. Any objectionable gas in the air is atmospheric pollution, whether it is harmful or merely unpleasant, but this definition does not apply only to gases. The air frequently contains solid particles or tarry droplets, less than about one thousandth of an inch in diameter, which continue in suspension for a long time. Since any particulate matter is liable to cause trouble, these aerosols, as they are sometimes called, are all atmospheric pollution, irrespective of their chemical nature. Also, by general consent, the term atmospheric pollution is applied to larger particles, when these are lifted into the air by the wind or emitted from a chimney. Although the largest particles escape from the atmosphere relatively quickly by falling to the ground, they are capable of causing damage and intense irritation.

Some atmospheric pollution, notably that of natural origin, and the gaseous emissions from burning colliery spoilheaps, is produced in the open air. More commonly, the constituents are produced indoors under conditions which are more or less controlled, and are then discharged into the open as the most convenient way to get rid of them. Usually the

first thing we do when a room becomes stuffy is to open a door or window; fresh air enters and drives the bad air by some other exit into the open. If pollution is produced very rapidly within a room such natural ventilation may be inadequate, and we equip the room with ventilating hoods, fans, and flue pipes leading to the outside air. Many such installations are to be found in factories where fumes, dusts or gases are liable to be produced; but there is no need to look outside our own homes for an example, for every ordinary fireplace has a collecting-hood and every chimney is an exhaust flue.

There would seem to be little danger in discharging a small quantity of pollution into the open, where it is so much diluted that it quickly becomes harmless. In one square mile there are about 30 000 tons of air below roof level but, when it is realised that as little as one part per million, i.e. 0.03 ton of pollution in 30 000 tons of air, is sufficient to make the air unpleasant to breathe, a simple calculation will show how quickly such a quantity of air may be seriously polluted. In one square mile of a town, it is not uncommon for a ton of coal to be burnt every minute, and on an average each ton of coal produces about 0.05 ton of pollution, including solid particles and gases such as sulphur dioxide, but not counting carbon dioxide. If all this pollution is emitted into the atmosphere, as it usually is, it is enough to cause serious pollution in the air below roof level in 36 seconds. Usually, of course, much of the pollution spreads above roof level and cleaner air is continually being brought in from outside the town and above it; but if this natural ventilation were to fail, it can be calculated that we should be gasping for breath in half an hour, and dead in five to ten hours.

It has been estimated that over 8 million tons of atmospheric pollution are produced each year in Great Britain from the combustion of coal and its derived fuels. This causes far more damage than pollution from any other source, even from decaying vegetation, the evaporation of sea spray, or wind-blown dust. Pollution from fuel is thus the main subject of this book.

## INTRODUCTION

To complete the definition of atmospheric pollution it might seem necessary to enumerate the chemical compounds in it, but this would be an academic exercise of little real value, for pollution contains most of the 92 natural elements in one combination or another. The various polluting materials which escape from chimneys can be more conveniently divided according to their properties into three groups: (1) the reactive substances, (2) the finest particles, which remain suspended in the air for a long time, ultimately being deposited as dirt on walls, ceilings and other surfaces, and (3) the relatively coarse particles which quickly fall to the ground.

Each group is dominated, as it happens, by one constituent. (1) The reactive substances include sulphur dioxide, sulphur trioxide, carbon monoxide, ammonia, hydrochloric acid and compounds of fluorine, but sulphur dioxide is by far the most important in ordinary town air. (2) The finest particles are mostly the "smoke" which is produced when fuels are imperfectly burned. (3) The coarser particles are mostly mineral matter and grit from fuel; though smaller in size they are the same material as the ash which collects under a fire, together with particles of unburnt and partly burnt fuel. Much attention will be given to sulphur dioxide, smoke and ash, not only because they are most important but because they serve jointly as prototypes: any other form of pollution when released into the atmosphere will behave similarly to one or other of them.

*Growth of Pollution.* The amount of atmospheric pollution which we endure today is partly the consequence of our living in communities where all kinds of fuel may be burnt, and partly due to our voracious demand for goods manufactured with the help of heat and power which come mostly from coal. In London, coal was first used on a serious scale in the thirteenth century, when local reserves of firewood were nearing exhaustion. Smoke from this coal soon invoked complaints, and in 1273 Parliament passed an act which prohibited the burning of coal in London. In 1306 an artificer was tried, condemned and executed for this offence.

By Elizabeth's time the law had evidently been relaxed, for a deputation of women went to Westminster to see the Queen about "the filthy dangerous poisonous use of coal". Another fruitless effort to rid London of smoke was made by the philanthropist John Evelyn in the reign of Charles II. He proposed that the factories of brewers, dyers, lime-burners, salt and soap-boilers, and others of the same class, should be moved lower down the Thames; and that Central London, as we now know it, should be surrounded by a green belt thickly planted with trees and scented flowers.

In other countries also coal had a limited industrial use. The Italian craftsman Vannoccio Biringuccio wrote in 1540: "Besides trees, stones that occur in many places have the nature of true charcoal; with these the inhabitants of the district work iron and smelt other metals and prepare other stones for making lime for building. But now I do not wish to think of that far-away fuel, for we see that Nature provides things for our every need, and she always generates an abundance of trees."

In England as a whole, and not merely in London, the "abundance of trees" began to be inadequate in the eighteenth century. Before then, goods were manufactured, as the word implies, by hand, and the commonest source of power was the muscular effort of men and animals. There were also water wheels, windmills, and sailing ships, but no satisfactory way to convert the energy stored in fuel into mechanical energy had yet been developed. Furnaces were used in a number of industrial processes and, in particular, the iron workers were heavy consumers of fuel. They required higher temperatures than could be attained by burning raw wood, so they burnt wood charcoal, and though this was an excellent fuel for their purpose, it was obtained by a very wasteful process. The demands of the iron industry, in conjunction with equally wasteful domestic fires and ignorance of the arts of reafforestation, ultimately caused our national shortage of wood. More, the demands of the iron industry were a major cause of the industrial revolution, for men sought a substitute for charcoal, and they discovered

how to convert coal into coke which was suitable for metallurgical processes. The coke was mechanically stronger than charcoal, permitting the invention of the blast furnace. This led to an increased production of all forms of iron, and encouraged the invention of engines and machinery made of iron.

In the nineteenth century came the completely unforeseen developments of the industrial revolution. In one manufacture after another, hand-work was replaced by machine-work, and the output of goods increased enormously. Great new industries sprang up in hitherto obscure districts where the requisite raw materials, of which the chief was coal, were found.

New towns arose in a haphazard manner, never keeping pace with the needs of the rapidly increasing population. Life in England was largely changed, ultimately perhaps for the better, since few of us would willingly give up all the advantages that machinery has brought. However that may be, in some ways the change was for the worse, and we are still suffering from the damage undergone by society as a result of those decades of blind economic readjustment. In particular, problems of atmospheric pollution increase very much as a town grows in size or industrial activity, and for many years the air of most British towns must have rapidly deteriorated.

Our bad habit of polluting the air with waste products of combustion and other chemical processes was formed long ago, but since the beginning of the industrial revolution a minor irritation has become a great social evil. In towns and industrial districts rain water loses its purity; ash and other solids fall continuously to the ground; the air contains a suspension of fine particles which penetrate indoors, to be deposited on walls, ceilings, curtains and furniture; our clothing, our skins, and our lungs are contaminated; metals corrode, buildings decay, and textiles wear out; vegetation is stunted and blackened; sunlight is lost; germs multiply; our natural resistance to disease is lowered. In a hundred and one ways the miasma of atmospheric pollution is lowering our vitality and our enjoyment of life.

*Smoke Abatement.* Ceaselessly but in part unconsciously, the minds and bodies of city dwellers are at war with effects of atmospheric pollution. This war is largely one of defence, but the campaign to annihilate atmospheric pollution is building up into a major offensive. Most progress has been made, so far, against industrial smoke. Smoke is a sure sign that fuel is being wasted, and the manufacturer saves money if he eliminates it by burning his fuel more efficiently. There have been fewer successes against the ash, sulphur dioxide, and other incombustible waste products in industrial flue gases, because there is usually no immediate economic justification for removing them. What headway there has been against domestic pollution has until recently been the result of accident rather than design. We cherish our freedom to do as we please in our homes, but just as we no longer throw rubbish into the street, we shall eventually cease to discharge smoke into the air. Our satisfaction at the second reform will be at least as great as it has become with the first.

A long fight is ahead if smokeless air is to be achieved everywhere, but much has already been done to alleviate the pollution in a number of the world's cities. Some advances have been made by individuals and private firms, some by local authorities, and some by central governments. Engineers in Britain, Germany and America have greatly improved the science of combustion in its application to raw coal, and more efficient combustion has always caused a reduction of smoke. Scientists have developed processes for transforming coal into various smokeless fuels; they have also designed numerous devices for removing dust and sulphur dioxide from flue gases. Manufacturers have tried to keep abreast of advances in engineering and science; their success may be judged by the differences between recent plants and those built twenty to fifty years ago. Local authorities have fought against pollution with such weapons as they possess, and they have many successes to their credit. The part played by central governments has been to prepare these weapons, by making laws under which local authorities can effectively act, and by sponsoring industrial research.

*Scope of the Book.* Although atmospheric pollution can be reduced or eliminated in many different ways, each way involves questions of economics, the time factor, availability of materials, priority over other urgent reforms and, to be frank, of individual and social psychology. To provide a basis for consideration of this variety of questions, it is not enough for a book to give information about atmospheric pollution, its measurement, distribution, and effects. These matters are important, but there is need to go into the subjects of fuel, fuel-burning appliances, industrial processes, and domestic requirements, not, perhaps, with too technical an approach, but deeply enough to provide at least a foundation for more technical studies.

The next six chapters deal with fuels, furnaces, and fires; the treatment of such subjects has been kept as free as possible from technical jargon. It is necessarily brief, but the reader may find further help in the books listed at the end of each chapter. The five following chapters are given to a study of the properties of atmospheric pollution. Remedial measures are considered last. One chapter is a summary of recommendations, many of which have been mentioned earlier in the book. The last chapter is an account of the law in England with some notes on American law, in so far as it concerns atmospheric pollution.

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## Chapter II

### ORIGIN OF FUEL

Fuels are used for generating heat, light, and mechanical power. Strictly, a fuel is a substance which can be made to react with air with the emission of heat, but this definition would exclude electricity, radioactive materials, rocket propellants, and certain explosives which do not require the presence of air. It is more convenient to call by the name "fuel" any substance which can be used for making heat in appreciable quantities.

Many substances which would satisfy the above definition are never deliberately used as fuel, because they do not possess certain important secondary qualities. These vary with the purpose for which the fuel is needed, but in general it may be said that the best fuels are those (a) which are abundant and readily accessible, without being too valuable as food or for other essential purposes, (b) whose generation of heat is easy to control (it is particularly important that the fuel shall not burn until it is heated above ordinary temperatures), and (c) which produce the maximum heat with the minimum weight of fuel and equipment.

*Primeval Fuel.* The story of terrestrial fuel began 2-3 thousand million years ago when the earth was created either from the sun or, as some astronomers now believe, from the residue of a supernova which had been a companion star of the sun. The sun and the stars radiate, in the form of heat and light, energy derived from nuclear changes in the atoms within them—now called atomic energy. The earth was too small, and the atoms of which it was made were on the whole too stable, to maintain it at a high temperature by nuclear changes, and the earth cooled by the radiation of its heat into space. The present average temperature of the earth's crust is such that energy is radiated into space only a very little faster than it is received from the sun.

The most abundant elements, whether free or combined, in the sea, the atmosphere, and the earth to a depth of 10 miles, are given in Table 1 (from F. W. CLARKE and H. S. WASHINGTON, "The Composition of the Earth's Crust", U. S. Geological Survey, Professional Paper 127).

Table 1. *Constituents of the earth's crust: per cent by weight*

per cent	per cent	per cent
<b>Oxygen</b> . . . 49.52	Titanium . . . 0.58	Fluorine . . . 0.027
Silicon . . . 25.75	Chlorine . . . 0.188	Zirconium . . . 0.023
Aluminium . . . 7.51	Phosphorus . . . 0.120	Nickel . . . 0.018
Iron . . . . . 4.70	<b>Carbon</b> . . . 0.087	Strontium . . . 0.017
Calcium . . . 3.39	Manganese . . . 0.080	Vanadium . . . 0.016
Sodium . . . 2.64	Sulphur . . . 0.048	Cerium . . . 0.014
Potassium . . . 2.40	Barium . . . 0.047	Ytterbium . . . 0.014
Magnesium . . . 1.94	Chromium . . . 0.033	Copper . . . 0.010
<b>Hydrogen</b> . . . 0.88	Nitrogen . . . 0.030	Others . . . 0.032

Perhaps the most striking feature of this list is the low place of hydrogen, which is the predominant element in the sun. The late Sir JAMES JEANS and other astronomers have shown how in the period when the earth was still gaseous much of the hydrogen could have been lost because of its lightness and the relatively weak attraction of gravity. According to them, if the earth had been a little smaller it might have lost much more of its hydrogen; while if it had been larger there would have been more hydrogen, and so more water, leaving less oxygen, possibly none at all, in the atmosphere. Those who uphold the hypothesis of a companion star are in no difficulty since many stars have companions which are quite different in chemical composition.

In the study of fuels, oxygen, hydrogen, and carbon are the most important elements. Oxygen will combine with most other elements, and it is contained in nearly all the common materials around us. When the elements that now form the earth's crust first cooled below the temperatures at which they could combine with one another, there was sufficient oxygen to combine with all the elements for which it had a strong affinity, leaving enough over to form 23 per cent by weight of the atmosphere. The rest of the atmosphere

is mostly nitrogen, which does not readily combine with oxygen.

Carbon is the foundation of all living matter, and in suitable circumstances it forms an extremely large number of compounds. At first, most of the carbon must have combined with oxygen to form the gas carbon dioxide. Later, some of this combined with metallic oxides to produce solid carbonates, which are very plentiful among our minerals, but a little carbon dioxide remained. Before life began, the atmosphere probably contained about 0.2 per cent, by weight, of carbon dioxide, but now it contains only about 0.04 per cent, the rest of the carbon having been converted by plants and animals to coal and other carbonaceous minerals. Atmospheric carbon dioxide, together with the carbon dioxide dissolved in the sea, and not the far more plentiful mineral carbonates, provides the carbon of living matter.

Detailed discussion is difficult in the present state of astronomical knowledge, but one fact is clear about the primeval earth. Owing to the great excess of oxygen, there could have been little material left which would readily combine with oxygen; that is, little fuel according to the strict definition which was given in the previous section. There are some deposits of sulphur and iron sulphide in the earth's crust, and these can be made to burn and yield a little heat. There are also the radioactive elements, which spontaneously produce heat as they emit nuclear particles. It has been suggested that the interior of the earth is warm as a result of radioactivity. Recently it has been shown that, by controlled nuclear fission of radioactive elements, unprecedented amounts of heat in proportion to the mass of material used can be recovered. It is early yet to consider the use of nuclear energy in place of fuels, but the possibilities seem almost boundless. Although radioactive elements are rare—uranium, the commonest, makes up only 0.0001 per cent of the earth's crust—it is not impossible that non-radioactive elements will ultimately be used in liberating nuclear energy.

*Cellulose.* The next step in the evolution of the earth was a big one. Life began; and living matter, drawing energy

from solar radiation, made fuel from the unburnable compounds, carbon dioxide and water. Life has not been scientifically explained, but we know that by its agency some of the original materials of the earth have been raised from what might be called their state of lowest potential. They have been formed into numerous compounds, many of which cannot as yet be made by any purely chemical means. The more abundant of these organic compounds are combustible, and they include the entire class of true fuels. Human beings thus depend on lower animals and plants not only for their food and clothes, but for their fuel as well.

Life began in the sea about 600 million years ago, but the first land plants did not appear until 300 million years later. When they became established they grew profusely and to great heights; in some districts they were to form the coal fields which we are working today.

The solid framework of plants is made of cellulose, whose molecular formula is  $(C_6H_{10}O_5)_n$  where  $n$  is an unknown number, probably between 1000 and 5000; we do not know how many groups of  $C_6H_{10}O_5$  are joined in each individual molecule of cellulose. Plants produce their entire substance out of carbon dioxide and water, with the help of traces of compounds from the soil which contain nitrogen, phosphorus, potassium, and other elements.

It is important to observe that if six molecules of carbon dioxide ( $6 CO_2$ ) and five molecules of water ( $5 H_2O$ ) were simply joined together, the result would be  $C_6H_{10}O_{17}$ ; thus, in forming cellulose, plants reject twelve out of every seventeen oxygen atoms. To do this they require energy, and they get the necessary energy from solar radiation and from the warmth of the soil which is maintained by solar radiation. Conversely, cellulose may be burnt in air, when it takes up the twelve oxygen atoms, forming water and carbon dioxide, with the emission of heat. The other organic substances in plants are formed in a similar way to cellulose, and they too are combustible.

Plants are the most primitive form of life because they feed on carbon dioxide, which is a simple inorganic compound. Animals cannot feed on carbon dioxide; they assimilate their

carbon from the plants or other animals which they eat. So even the fuels which come from animals are the indirect consequence of vegetable life, and all the organic fuels, being ultimately derived from plants, owe their potential heat-energy to the light and radiant heat of the sun.

*Superior fuels.* Cellulose is a carbohydrate; that is, besides carbon, it contains atoms of hydrogen and oxygen in the proportion 2 to 1, the same as in water. When carbohydrates are burnt, they yield approximately the same quantity of heat as the carbon in them would produce by itself; their hydrogen is of little value as a fuel because it is neutralized, as it were, by oxygen. Evidently it is a disadvantage for a fuel to contain oxygen, and it is desirable to consider what other natural organic compounds exist which contain a lower proportion of oxygen than the carbohydrates.

The sugars and lignins found in plants and the proteins that constitute a large part of animal substance, are little or no better than cellulose as fuels; but in the metabolism of both plants and animals, some carbohydrate is converted into fats, which are stored as reserves of food within the living organism. Fats contain relatively little oxygen, and when burnt they generate about twice as much heat as an equal weight of carbohydrates. Until comparatively recently, beef and mutton tallow were commonly used as fuels, as well as oils extracted from fish and from the seeds of various plants.

Other high-class fuels are made by bacteria from the remains of dead plants and animals and from animal waste products. The richest natural fuel, marsh gas, is made in this way. It consists mainly of methane,  $\text{CH}_4$ , which has a double advantage as a fuel since it contains a high proportion of hydrogen but no oxygen. An even more familiar example is alcohol, and this is produced commercially by bacterial methods for use as a fuel.

To-day the most important fuels are coal and mineral oil, and these have been produced by slow geological processes. If dead vegetation undergoes prolonged heating or compression it loses oxygen, and though it also loses hydrogen, it changes into a better fuel. In some measure these changes

can be copied in the laboratory. By the action of heat only, wood is converted to charcoal which is nearly pure carbon; by the combined action of heat and pressure, wood or damp cellulose can be converted to a substance rather similar to coal. There is no doubt that coal was evolved in this way by the slow action of heat and pressure, with micro-organisms helping in the process. The origin of mineral oil is less well understood, but oil too must have been made from organic matter by either physical or biological processes, or both.

### QUANTITY OF FUEL

*Calorific Value.* It is evident that the usefulness of a fuel must be measured, not merely by the amount available, but by the quantity of heat it will yield. To determine the heat which may be obtained by burning a known weight of fuel, the weight must be multiplied by a factor, dependent on the nature of the fuel. This factor is called the calorific value, and it is simply the number of units of heat obtainable from unit weight of fuel.

The calorific value is measured in specially designed instruments called calorimeters, the details of which depend on whether the fuel is a solid, liquid, or gas. The general principle is the same, however, namely to transfer the heat generated to a relatively large weight of water and measure its rise in temperature. A unit of heat is such as will raise unit weight of water through one degree of temperature. If the unit weight of water is taken as 1 lb, and the unit of

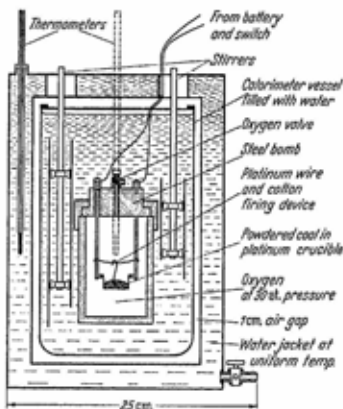


Fig. 1. Bomb calorimeter.

temperature as the degree Fahrenheit, the corresponding unit of heat is called the *British Thermal Unit* (B.Th.U). If the weight is 1 gramme, and the temperature rise is  $1^{\circ}\text{C}$ , the unit of heat is called the *calorie* (cal); 1000 calories equal 1 kilocalorie (kcal).

Fig. 1 is an illustration of a bomb calorimeter, for determining the calorific value of solid and liquid fuels. About 1 gramme of fuel is burnt in oxygen at a pressure of 25–30 atmospheres, and its heat is taken up by a large weight of water in a calorimeter vessel, the temperature rise being accurately measured. The heat taken up by the steel bomb and the calorimeter vessel is allowed for by finding in a separate experiment their water equivalent, i.e. the weight of water which has an equal capacity for heat. Allowance is also made for heat transferred into or out of the calorimeter

Table 2. *Determination of calorific value of a solid fuel*  
Bomb Calorimeter; Tynamwr Coal.

(f)	Weight of coal taken (grammes)		1.0017 g
	Water equivalent of calorimeter, and bomb, etc. . . . .	520 g	
	Weight of water used . . . . .	1980 g	
(w)	Total weight of water . . . . .		2500 g
(T)	Thermometer rise, corrected for cooling of water during test .		3.402° C
(wT)	Heat liberated ( $2500 \times 3.402$ ) .	8505 cal	
	Correction for heat from burning thread, used in igniting charge	-- 36 cal	
	Correction for heat from burning nitrogen from fuel . . . . .	-- 12 cal	
	Correction for heat from oxidation of sulphur dioxide and water to sulphuric acid . . .	-- 25 cal	
(wT, corrected)	. . . . .		8432 cal
(wT/f)	Calorific value, calories per gramme . . . . .		8418 cal/g
	$\times 1.8 =$ calorific value, B.Th.U/lb		15150 B.Th.U/lb

Note: Because in the bomb calorimeter the fuel is burnt in oxygen under pressure, reactions take place with nitrogen and sulphur in the fuel which do not occur when the fuel is burnt in the ordinary way. The amounts of the products, nitric acid and sulphuric acid, are determined chemically and corrections made for the heat generated by the abnormal reactions. In practice, the correction for sulphuric acid is applied after dividing by *f*.

during the test. Other small corrections are made, as will be seen from Table 2 opposite, which gives a specimen determination, somewhat simplified.

It will be seen that calorific values in calories per gramme are converted to B.Th.U/lb on multiplying by 1.8. This factor is the ratio of the degree centigrade to the degree Fahrenheit. The weights  $w$  and  $f$  in the expression  $wT/f$ , for calorific value, occur in the numerator and denominator, so it is immaterial what unit of weight is used, provided it is the same for both. The calorific value of a fuel could be defined without mentioning any unit of weight, as the rise in temperature ( $^{\circ}\text{F}$  or  $^{\circ}\text{C}$ ) when any weight of fuel is burnt and the heat used to warm up an equal weight of water.

Most fuels, however, would turn their own weight of water to very hot steam, so a more practical definition would be, say, 1000 times the rise in temperature ( $^{\circ}\text{F}$  or  $^{\circ}\text{C}$ ) of a quantity of water weighing 1000 times as much as the fuel burnt.

Fig. 2 is a drawing of a Boys' Continuous Flow Calorimeter for measuring the calorific value of gaseous fuels. The gas is burnt at a steady rate, and water flows at a constant speed through the copper heat-exchanger coil and out through the heavy brass equalizing chamber, leaving the calorimeter at

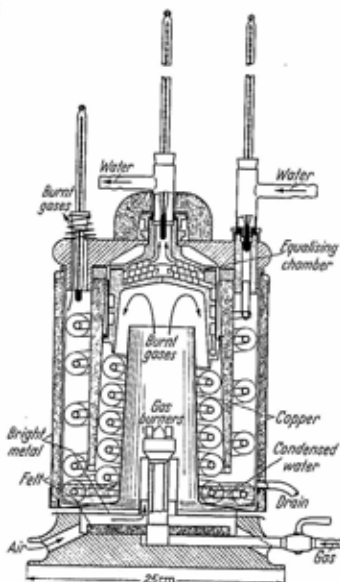


Fig. 2. Boys (Courtesy of Griffin and Tatlock Ltd., London) continuous flow calorimeter.



a higher temperature than when it entered. After a steady state has been reached, the test is carried out, three primary measurements being made over a definite interval of time: the volume of gas burnt ( $v$ ), the weight of water passed through the calorimeter ( $w$ ), and the rise in temperature of the water ( $T$ ). Table 3 is an example of a determination.

Table 3. *Determination of calorific value of a gas*  
Boys Calorimeter; Chamber-oven Gas.

	Volume of gas burnt, measured at temperature 58.0° F and pressure 30.43 inches of mercury (cubic feet) . . . . .	0.400 ft <sup>3</sup>
( $v$ )	Volume, corrected to what it would have been at 60° F and 30 inches of mercury . . . . .	0.408 ft <sup>3</sup>
( $w$ )	Weight of water (kilogrammes) . . . . .	3.054 kg
( $T$ )	Rise in temperature of water . . . . .	20.45° C
( $wT$ )	Heat liberated (kilocalories) . . . . .	62.45 kcal
( $wT \times 3.992$ )	Heat liberated (B.Th.U) . . . . .	249.4 B.Th.U
( $\frac{wT}{v} \times 3.992$ )	Calorific value . . . . .	611.3 B.Th.U/ft <sup>3</sup>
	Correction because effluent gases were 0.5° F warmer than the air with which the gas was burnt . . . . .	+ 0.2
	Corrected calorific value . . . . .	<u>612 B.Th.U/ft<sup>3</sup></u>

Although the mixture of British and international units is awkward, the calculation is simpler than for the bomb calorimeter in Table 2. The only corrections are to determine the volume of gas as it would have been measured at a statutory standard pressure and temperature, and to allow for any heat (or cold) brought into the calorimeter by the air needed for combustion. The answer is usually given to three figures, as the accuracy of the method does not justify a fourth.

*Gross and Net Calorific Value.* When a fuel is burnt which contains either free or combined hydrogen, one of the products of combustion is water vapour, and before the full calorific value can be extracted from the fuel, this water vapour must be allowed to cool and condense as liquid water. If the water vapour escapes, the loss of heat is appreciable, because of the very high latent heat of steam. In calorimetry,

there is little difficulty in retaining the water of combustion and allowing it to condense and cool to the end temperature of the calorimeter, and determining the so-called *gross* calorific value. In furnace practice, however, the water of combustion nearly always escapes before condensing; so it is of practical importance to know how much heat can be extracted from a fuel when the water of combustion escapes as steam. This is called the *net* calorific value; it is determined by weighing the water produced during combustion, and subtracting its heat of vaporization from the total heat liberated in the calorimeter. In the example quoted in Table 2 0.046 gramme of water was formed in the bomb, and the net calorific value was 14680 B.Th.U/lb. In the case of Table 3, 11.38 gramme of water of combustion was collected, and the net calorific value was found to be 546 B.Th.U/ft<sup>3</sup>.

The gross and net calorific values of typical specimens of representative fuels are given in round figures in Table 4.

Table 4. *Calorific values of some fuels—B.Th.U/lb*

	Gross	Net
Hydrogen . . . . .	62000	52920
Methane . . . . .	23715	21355
Natural gas, approx. . . . .	21500	19800
Crude mineral oil, approx. . . . .	19500	19200
Vegetable oils, animal oils, and fats . . . . .	17500	17000
Fuel alcohol, approx. . . . .	14000	13000
Coal, approx. . . . .	14500	14000
Carbon . . . . .	14600	14600
Coke, approx. . . . .	13200	13100
Lignite, approx. . . . .	13000	10000
Peat, air dried, approx. . . . .	10000	8000
Wood, air dried, approx. . . . .	9000	7000
Sulphur, when burnt to sulphur dioxide . . . . .	4000	4000
Pyrites . . . . .	3000	3000

It will be seen in the above table that for fuels which contain no hydrogen there is no difference between gross and net calorific value. The large differences for lignite and air-dried peat and wood are due partly to the moisture in the fuel, and partly to water of combustion.

*World Reserves and Annual Output.* Of all the plants and animals which have existed in the last six hundred million years, only a tiny fraction can have helped to form the so-called mineral fuels, yet there are available large reserves of coal and mineral oil. When great quantities of rich fuels began to be needed 150 years ago we began to consume the coal reserves at an alarming rate. Petroleum has been consumed at a rapidly increasing rate since 1900. The following table of world reserves and annual output gives some idea of the various natural fuels now in use.

Table 5. *Approximate world resources of fuel and energy*

	Reserves		Annual output	
	Tons	B.Th.U	Tons	B.Th.U
Coal . . . . .	$5 \times 10^{12}$	$2 \times 10^{10}$	$12 \times 10^8$	$4 \times 10^{10}$
Petroleum . . . . .	$10^{10}$	$4 \times 10^{17}$	$4 \times 10^8$	$17 \times 10^{10}$
Shale oil . . . . .	$2 \times 10^{10}$	$10^{10}$	$4 \times 10^8$	$2 \times 10^{12}$
Petroleum-well gas . . . .	$4 \times 10^9$	$2 \times 10^{17}$	$10^8$	$5 \times 10^{10}$
Lignite . . . . .	$10^{12}$	$2 \times 10^{10}$	$2 \times 10^8$	$4 \times 10^{10}$
Peat . . . . .	$10^{11}$	$2 \times 10^{10}$	$2 \times 10^7$	$3 \times 10^{14}$
Wood . . . . .	—	—	$7 \times 10^8$	$10^{10}$
Non-tidal water power . .	$2 \times 10^{16}$	B.Th.U./yr	—	$10^{10}$

*Note.* The reserves of coals and lignites are probably greater than the estimates given; and the reserves of peat, petroleum, natural gas and oil shale are probably much greater than the estimates. It is certain that it will be possible economically to win and utilize only a portion of the true reserves. Approximate conversions: 1 ton = 1 metric ton, 1 B.Th.U. = 0.25 kcal.

The table (with footnote) has been assembled from Table 13 and other data given in the 36th Thomas Hawksley Lecture to the Institution of Mechanical Engineers, 1949, by A. PARKER, D.Sc. The numerical values are nearly all expressed to one significant figure only, multiplied by a power of 10. In the first column, for instance,  $5 \times 10^{12}$  could be written as 5 followed by twelve 0's, and  $10^{10}$  as 1 followed by ten 0's. Dividing the reserves by the annual output gives an estimate of the time for which supplies will last: e.g. coal, 4000 years and petroleum, 25 years; but no one knows whether the rate of consumption will remain as it is, or whether technical development in ways of winning the fuel will keep pace with

the inevitable decrease of its accessibility, or whether further reserves will be discovered. The table shows that non-tidal water power might provide 20 times as much electricity as it does at present. If tidal power is included the figure rises to 50 times as much, and nearly equals our total fuel requirements, but the capital costs render such a hydroelectric project unthinkable at the present epoch. No reliable information about reserves of radio-active materials is available.

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### Chapter III

## NATURAL FUELS

*Wood.* The stems and branches of trees are not homogeneous; they vary considerably in chemical composition and even greater differences exist between different species of tree. The exact composition of wood is therefore quite important when it is used as a source of chemicals such as turpentine or cellulose, and it is important even in considering wood as a fuel. The approximate composition of a typical wood, after being allowed to dry under cover, is given in Table 6.

Table 6. *Composition of typical air-dried wood*

	Total %	Oxygen %	Hydrogen %	Carbon %	Others %
Mineral matter . . . . .	0.5	0.2	0	0	0.3
Water . . . . .	13	11.5	1.5	0	0
Resin and wax . . . . .	2.5	0.3	0.2	2	0
Lignin . . . . .	20	7	1	12	0
Hemi-cellulose . . . . .	18	9	1	8	0
Cellulose . . . . .	46	23	3	20	0
Total	100	51	6.7	42	0.3

The value of wood as fire-kindling material depends strongly on its resin and wax. Among different varieties of tree, there are important variations in the percentage of resin and wax: this ranges from 0.7 in beech, for example, to 3.2 in pine.

The table shows that, of the combustible constituents of wood, cellulose and hemi-cellulose contain a high proportion of oxygen, lignin rather less, resin and wax very little; their fuel value increases as their oxygen content diminishes. When wood is burnt the hydrogen, oxygen, and carbon are converted by the action of atmospheric oxygen to water vapour, carbon dioxide, and small proportions of carbon monoxide and smoke, all of which escape into the air. Part of the ash escapes into the air as well, and all the natural moisture of the wood is

driven off. As was shown in Table 4 at the end of the last chapter, the heating power of wood is normally about 7000 B.Th.U per lb, its net calorific value, instead of the much higher gross calorific value of 9000.

Wood fires require a lot of attention, but they are pleasant in the home, and cause less atmospheric pollution than coal. There are few manufacturing purposes, if any, for which wood is the ideal fuel.

*Wood Charcoal.* Air-dried wood is shown in Table 6 to contain oxygen about 51 per cent by weight, carbon about 42 per cent, hydrogen about 7 per cent, and a little mineral matter. The simplest way to improve its fuel value is by the application of heat in such a manner as to drive off most of the oxygen, when the hydrogen will also be liberated, leaving a residue which we call charcoal. This is more or less pure carbon, according to the thoroughness of the distillation, except that it contains most of the original mineral matter of the wood. Since before 3000 B.C. charcoal was made by piling wood in a heap, nearly covering it with earth, and setting it on fire at the bottom. Some of the wood burnt, providing the heat whereby the rest was converted to charcoal. Though simple, this process was inefficient, for only 30 per cent or less of the original heat of the wood remained in the charcoal.

Modern methods of wood distillation, in retorts heated usually by oil burners, are much more efficient. The gases that are driven off are allowed to condense, yielding turpentine and oils which are more valuable than the residue of charcoal. The best turpentine and oils are produced when the temperature of the retorts is lower than for complete carbonization, but wood has also been carbonized at higher temperatures, to yield purer charcoal and a combustible gas similar to coal gas.

As would be expected, charcoal is a smokeless fuel. It can be burnt safely indoors in braziers provided that all carbon monoxide is burnt at the periphery of the zone of combustion; but in most well-populated countries it costs more than other fuels. In times of petroleum shortage it can be used as the fuel in road vehicles driven by producer

gas. It is still useful, also, in certain metallurgical work where a very pure fuel is required. Its chief uses, however, are connected with its remarkable property of adsorbing organic compounds after it has been "activated" or out-gassed by blowing steam through it at  $900^{\circ}\text{C}$  ( $1650^{\circ}\text{F}$ ). Activated charcoal, made from specially chosen raw materials, is used in sugar refining, solvent recovery, and in respirators for protection against poison gas.

*Peat.* It is fortunate that the micro-organisms which attack dead vegetation do so mainly for the sugars and nitrogenous matter it contains. The result of these circumstances is that, on the whole, dead vegetation loses oxygen and hydrogen more rapidly than carbon, and so tends to higher fuel value the longer it remains.

Peat may be regarded as the lowest grade of naturally improved vegetable fuel. It is derived from the mosses and plants which grow in marshes, the lower parts of whose stems tend to die off while the upper parts go on growing. Because of the water with which both the living and dead growth is sodden, the bacterial decay is much more gradual than that going on in cultivated land or compost heaps, and the woody tissue and fats of the dead plants remain unchanged for a very long time. The time required to form peat beds can be estimated; some of them are as much as 30 feet thick, and their thickness is increasing by about a foot every hundred years.

There are large reserves of peat in Russia, Scandinavia, Germany, the British Isles, Canada and elsewhere in the same latitudes. It can be dug or cut, during summer, and allowed to dry in the wind. When first cut it contains over 90 per cent water, and after air-drying it still contains 20-30 per cent water. In consequence of this fact and of its bulky nature, hand-cut peat is seldom transported far from the peat bog. A modern way of preparing peat is to pump it from the bog and spread it in thin layers to dry. The powdered product may be compressed into briquettes twice as dense as cut peat and much easier to transport.

Peat can be distilled to give a kind of coke, as well as tar, ammonia, paraffin, and various oils, but at present its chief

use is in domestic fires. Like wood, it makes a noticeable amount of smoke, but this is not usually objectionable. As boiler fuel, both hand-cut peat and briquettes are satisfactory, and have been used at power stations in Northern Europe. Peat has also been used as a locomotive fuel, but in Ireland, where hand-cut peat was employed during the recent war in locomotives designed for coal burning, passengers found their journeys were taking them nearly twice as long.

### THE COAL SERIES

A consideration of Table 7 shows that the common natural solid fuels fall into a series, beginning with wood and ending with anthracite. In progression down the series the percentage of carbon steadily increases as the percentages of

Table 7. *The coal series*

	Air-dried fuel		Perfectly dry fuel		
	B.Th.U. per lb net	Volatile matter %	Hydro- gen %	Oxy- gen %	Carbon %
Wood . . . . .	7000		6.5	43	50
Peat . . . . .	8000	50	6.0	32	60
Lignite: brown . . . . .	10000	47	5.5	26	67
Lignite: black . . . . .	10200	41	5.4	19	74
Coal, bituminous: long flame, steam and house . . . . .	10700	35	5.0	16	77
Coal, bituminous: hard steam, house and manufacturing . . . . .	13900	34	5.0	8	84
Coal, bituminous: gas, and co- king . . . . .	14300	32	5.0	5.4	86
Coal, bituminous: Durham co- king . . . . .	14400	30	5.3	4.7	87
Coal, carbonaceous . . . . .	15000	11	4.0	2	92
Coal, anthracite . . . . .	15000	8	3.0	2	94

1 B.Th.U./lb = 0.556 Cal/g.

hydrogen and oxygen decrease. The oxygen decreases more rapidly than the hydrogen, and consequently the calorific value increases at every step from wood to carbonaceous coal. The percentage of volatile matter, driven off when the air-dried fuel is heated under standard conditions to 925° C, decreases from peat to anthracite.



It was thought for a long time that the coal series must be a clue to the past history of coal, and that the original vegetable matter passed through stages where it would have been described as peat and lignite before it became bituminous coal; though it was doubtful whether anthracite could have been formed in the same way because in South Wales the anthracites contain much *less* mineral matter than the adjoining bituminous coals. From geological evidence it is now generally agreed that there must have been fundamental differences in the parent material of the different constituents of the coal series, and also that the change to coal must have taken place relatively quickly. It is still uncertain, however whether the original vegetable matter accumulated where it grew, or whether it was transported by rivers into deltas and swamps until the land subsided and the deposition of sediment began.

*Lignite.* Large deposits occur in some areas of a fuel that evidently consists of decayed vegetation, because of its fibrous structure. It is called lignite, from the Latin *lignum*, wood. It may be either black or brown, but even black lignite is easily distinguishable from coal.

Lignite is found in Germany, Australia, New Zealand, Burma, North America, and other countries, including a little in Devon, England. It occurs near the surface in many districts, and can be quarried. It contains a considerable proportion of moisture, and tends to crumble into dust on drying, but it can be compressed into briquettes for transport. It can also be distilled, when it yields a high proportion of tar, but the "coke" is not easily utilized.

Great quantities of lignite briquettes are burnt in Germany, where it is known as "brown coal", in the large closed stoves which are the principal form of domestic heating on the Continent. The briquettes tend to disintegrate as they lose their last traces of moisture in the upper part of the stove above the combustion zone. The resulting powder is liable to choke the fuel bed, so the German housewives wrap the briquettes in newspaper before putting them in the stove. As may be expected from its yield of tar and other volatile

matter, lignite is far from smokeless. In the larger German towns, domestic flues used to be cleaned twice yearly by the local authority.

Industrially, lignite is used as boiler fuel, for making producer gas, and for making tar for hydrogenation.

*Bituminous Coal.* The word *bitumen* is derived from the Sanskrit for "pitch-producing". It is usually reserved for the natural pitch-like substances found in the Middle East, Trinidad, and elsewhere. The adjective *bituminous* is applied to coals containing over 20-25 per cent of volatile matter, because of the tarry substances they emit on heating.

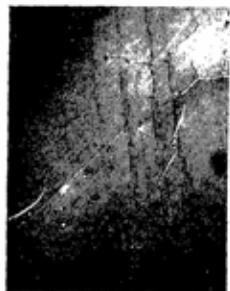


Fig. 3. Vitrain ( $\times 32$ ). This component of coal has been derived mainly from wood and bark of the original trees. At high magnification its cellular structure usually becomes apparent.

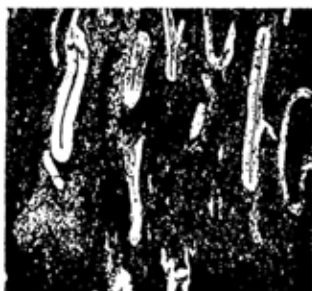


Fig. 4. Durain ( $\times 32$ ). Its origin is the finer debris of the original vegetation. The large flattened ovals are the exines of megaspores (the tough outer coatings of female spores).

More than half the known reserves of fuel of all kinds consist of bituminous coal. It is found in every continent, and in most large countries of the world. One of the most important problems, wherever coal is used, is to select from all the available varieties the best for each particular purpose. Enormous labour has been spent in the analysis, testing, and classification of coal, and only the merest outline of this subject can be given here.

If a large piece of coal is examined, it is seen to be divided into bands of different substances, which can be roughly

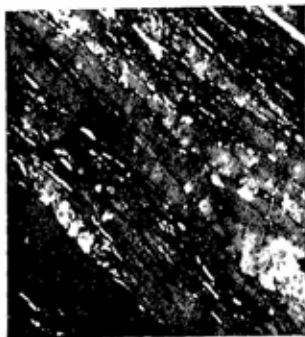


Fig. 5. Clarain ( $\times 32$ ). This is regarded as a mixture of vitrain and durain. Fragment of megaspore exines can be seen interposed between thin bands of vitrain.

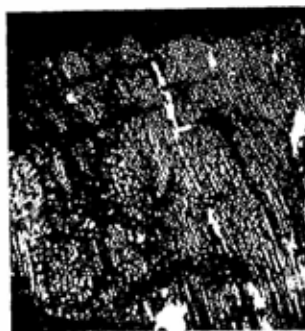


Fig. 6. Fusain ( $\times 32$ ). This has been formed from woody tissue which has undergone extensive decay before burial. In this example the cells are empty, but in many samples they are filled with mineral matter.

classified into four types. There are bright bands of pitch-like appearance which break with a conchoidal fracture: they

are *vitrain*. When the coal is put on an open fire this substance swells on heating, exuding tar, and it readily forms coke. There are also dull bands of hard material known as *durain* which, having been originally a sediment of fine particles, is liable to contain a high proportion of mineral matter. In addition there are bands of intermediate brightness known as *clarain*, which is in fact a mixture of vitrain and durain, though the constituents may be indistinguishable to the naked eye. From 0-10 per cent of the coal substance may consist of bands of *fusain*, which resembles charcoal; it is non-coking and low in volatile matter. Too much fusain is likely to impair seriously the coking property of a coal. There may also be bands of shale or mineral matter such as pyrites or compounds of calcium. Figs. 3-6 show the appearance of different constituents of coal, when thin sections are examined with a low-power microscope.

Another method of examining coal is by solvent extraction. Different fractions of coal are soluble in pyridine, chloroform, light petroleum, ethyl ether, and acetone; the undissolved residue is a brown powder. There seems to be no free carbon, and even when over 90 per cent of a coal is carbon, this is apparently all in molecular combination with hydrogen and oxygen. The compounds of which coal is composed are complicated and highly unstable, and their exact chemical formulae are still unknown.

Samples of every important kind of coal have been chemically analysed. The percentages of carbon, hydrogen, oxygen, nitrogen and sulphur have been found. The ash which is left after ignition in a crucible has also been examined, and the quantities in it of silicon, aluminium, iron, calcium, magnesium, manganese, phosphorus, boron, other common elements, and many rare elements such as beryllium, gallium, germanium and molybdenum have been measured. As a result of quite a simple examination of any given sample of coal, the expert can usually state its place of origin fairly accurately, provided that he has once properly examined other samples from the same place.

The important properties of coal, from various practical points of view, are (a) its ash and water content, (b) its

proportion of volatile matter, (c) its calorific value, (d) its softening or melting point, (e) its grindability, (f) its specific gravity, (g) its coherence, (h) its ignition point, (i) its tendency to spontaneous combustion, and (j) its suitability for conversion to coke. Although some of these properties can be estimated from a knowledge of the physical and chemical nature of the coal, all are best examined by direct experiment. Some indeed cannot be tested by any other way. For instance, the coking properties must generally be determined by direct tests; they cannot be inferred from a knowledge of the proportion of volatile matter, except that coal which contains either very much or very little volatile matter will not form good coke.

Bituminous coal may be burnt in all sizes below about six inches, in a great variety of fuel-burning appliances. The finest particles can be ground into pulverized fuel, and burnt almost like a gas; or they can be mixed with 7 to 8 per cent of pitch, or some other binder, and made into briquettes.

Whether or not bituminous coal is burnt smokelessly depends on the method of burning and the type of appliance. These subjects are discussed in Chapters V, VII and VIII. The smokeless fuels into which coal may be converted are discussed in Chapter IV.

*Anthracite* has been named from the Greek word, *anthrax*, meaning coal, but no coal should be classed as anthracite if it contains more than ten per cent of volatile matter. Anthracite is found in South Wales and Pennsylvania, but in few other places. It is hard, bright, and free-burning, its coke being friable and of little value. It is suitable for domestic stoves and boilers, particularly as it is virtually smokeless. Its other important uses are for central heating, steam raising, and drying malt and hops.

Types of coal which are intermediate between anthracite and the bituminous coals have been called carbonaceous or Welsh steam coal. They are excellent for all steam-raising purposes, and particularly for marine boilers, although the present tendency is for more and more ships to burn oil. They command a high price, nevertheless if present trends

continue they are likely to find increasing application in industrial and domestic fires.

*Cannel and Boghead* are the names given to varieties which are exceptionally rich in volatile matter and so do not fall within the series in Table 7. In some districts they occur as bands within ordinary coal seams. The deposits are relatively small, but may contain from 40 to 90 per cent of volatile matter; thus there may be more volatile matter than in peat or wood. The name "cannel" is supposed to have been given because splinters of it can be lit with a match like candles, and it burns with a long bright flame. Some varieties seem to have been derived from small water-weeds (algae); others appear to have originated from the spores of land plants of the fern family.

In the days when gas had to burn with a bright flame, before the invention of the incandescent gas-mantle, cannels and bogheads were much in demand by gas works, because they yield a gas of very high candle-power. In 1920 in Britain, gas became specifiable according to its calorific value instead of its candle-power, and the special properties of cannels and bogheads were no longer required.

#### ASH AND SULPHUR IN COAL

A small proportion of mineral matter in coal is welcome in specially hot fires, where the ash protects cast-iron fire bars from excessive heat and from corrosive fumes. The ash is also utilized in the chain-grate automatic stoker, where it accumulates at the back of the grate and prevents air from by-passing the combustion zone. In coal required for all other purposes mineral matter is merely a nuisance. It makes no heat, and yet it must be mined, graded, transported, and paid for at coal prices (unless coal is graded and priced according to ash content). It clogs the grate and flues, and if it contains certain substances it may cause frequent stoppages and seriously impair the efficient operation of modern boiler equipment. It lowers combustion efficiency by reducing calorific value, by causing extra opening of fire doors for raking, and by carrying with it, into the ash pit,

much useful fuel. If it melts on the fire grate, it becomes even more of a nuisance in the form of clinker. Particles of ash escape up the flues into the open air, and in some districts thousands of tons per year fall on each square mile of ground.

Ash is mainly aluminium silicate, the substance of clay, which softens above  $1600^{\circ}\text{C}$  ( $2900^{\circ}\text{F}$ ). If, however, other bases such as ferric oxide and calcium oxide are present, they form double silicates with the aluminium and the temperature of softening is lower. Ash which softens below  $1200^{\circ}\text{C}$  ( $2200^{\circ}\text{F}$ ) is particularly liable to form clinker.

Some mineral matter is inherent in coal, having been present in the original vegetation. The rest is derived from the soil which bore the carboniferous plants, and which has been compressed and modified to form rock or shale. At best, there is 1-2 per cent of mineral matter in coal; at worst, fuel containing about 50 per cent of ash can be successfully burnt.

Sulphur, too, is partly inherent in coal and partly extraneous, varying in amount from 0.5 to 4.0 per cent. The extraneous sulphur is mostly in the form of pyrites (iron sulphide) or mineral sulphates. When coal is burnt or distilled the sulphates mostly remain in the ash; but the pyrites and inherent organic sulphur give sulphur dioxide on combustion, or hydrogen sulphide on distillation.

The chief objections to sulphur in coal are (a) that it may attack the grate bars; (b) that its presence restricts the number of processes in which coal or its combustion product may be mixed with the material it is being used to heat; (c) that sulphur dioxide corrodes metal tubes in the flues; (d) that if the gases are allowed to cool below dew point in the flues, sulphuric acid is formed; (e) that hydrogen sulphide in the gaseous fuels derived from coal restricts their usefulness in several ways; and (f) that sulphur dioxide, when released into the air, causes damage and may affect health.

Coal also contains other substances which are potentially harmful. It contains 0.1 to 0.7 per cent of chlorine, up to 0.01 per cent of fluorine and small amounts of phosphorus, lead, and arsenic. The study of the effects of releasing these

substances into the atmosphere is often hampered by the much greater amounts of sulphur dioxide by which they are always accompanied.

*Washed Coal.* When coal is being graded at the colliery, large pieces of stone are picked out by hand, and the percentages of pyrites and other mineral matter are thereby reduced. A further reduction occurs if the coal is "washed", and the advantages are so great that about 50 per cent of British coal is now washed before leaving the colliery.

The specific gravity of coal is about 1.3, of shale about 2.5, and of pyrites over 4.0. If coal is thrown into a liquid of specific gravity about 1.5 to 2.0, e.g. a strong solution of calcium chloride or very muddy water, the pieces which are mainly coal will float, while the remainder sink. Or if water is kept in motion through or across a layer of dirty coal, the pieces which contain most coal will move furthest. Similar results can also be achieved by using jets of air in place of water. All these principles are in practical use at collieries.

Washed coal may contain as little as one per cent of ash and 0.5 per cent of sulphur, if all the extraneous matter is removed and only the inherent mineral matter and sulphur is left. Although these minimum concentrations are seldom reached by commercial washers, any increase in the proportional output of cleaned coal, or in the efficiency of cleaning, is desirable. It should be noted, however, that an important purpose of coal washeries is to reduce the labour underground of separating coal from minerals, by permitting dirtier coal to be dealt with economically above ground.

### COAL HAZARDS

Centuries of hard experience have taught us much general information about coal. As long ago as the early eighteenth century there were mine explosions in which hundreds of miners lost their lives. These explosions may occur if the air in mines contains a high proportion of marsh gas or of coal dust in suspension. With the help of the Davy lamp and other warning devices, and by using inert stone dust



as an inhibitor of explosions, the risks have been much reduced; but in spite of careful training, organization, and research colliery disasters have not been eliminated, though they have become less frequent. In Britain, most underground fatalities are caused by falls of ground or by haulage accidents. Recent years have shown a marked improvement, but the work of increasing safety in mines must go on unremittingly.

In storage, coal deteriorates, giving off hydrocarbon gases. The yield of gas from coal stored at gasworks diminishes in some cases by about 4 per cent in a fortnight, 8 per cent in six months, and 12 per cent in a year. While losing hydrocarbons, coal absorbs oxygen from the air and heat is generated. If the surface area of the coal in store is large in relation to the mass (i.e. if the coal is powdered), and if the heat of oxidation cannot readily escape, the temperature will rise until a faster rate of oxidation begins, and eventually the coal will ignite. As a result of this spontaneous ignition, many fires have broken out in coal heaps and many lives and ships have been lost through bunker fires.

The stagnant air trapped between the fragments of coal in a coal store is a necessary condition for spontaneous combustion to occur. If from the beginning the store is well ventilated by cold air, fire is avoided. Alternatively, water may be used to exclude all air, by storing the coal under water. It should be noted, however, that water in small quantities assists the chemical action, and that very large quantities are needed to put out a fire which has once taken hold of a coal store.

If coal is to be stored with air in the interstices, there are three precautions to be taken against spontaneous combustion. The first is to avoid accumulations of fine coal, such as would normally occur under loading hatches. The second is to provide for adequate ventilation by limiting the height of coal heaps to 2-3 metres (10-16 feet) according to the nature of the coal. The third is to insert iron pipes, closed at the ends, down to the danger points of the store, and take temperatures periodically by lowering in a maximum recording thermometer; increasing temperature is a danger signal, and if the temperature is between 50-80° C

(120-180° F) fire is inevitable unless preventive action is taken.

In some colliery districts the spoilbanks are often seen to be smoking or glowing, because of spontaneous combustion. These spoilbanks are dismal enough when they are quiescent, but when they burn they pollute the air and their smoke and sulphur dioxide can do harm to the pastures and crops, as well as to the health of people living nearby. The nuisance can be stopped by scattering the heap or by applying continuous fine water sprays.

The second remedy is not always permanently effective, as the heap is liable to catch fire again on drying. During the last war, many spoilbanks were kept continually drenched with water to prevent outbreaks of fire which might assist enemy night raiders. Afterwards the situation deteriorated for a time, and at the end of 1947 the Chief Inspector of Alkali etc. Works reported that there were 245 spoilbanks emitting no smoke or fume, 173 emitting slight smoke or fume, and 37 emitting much smoke or fume.

### MINERAL OILS AND RESINS

Since prehistoric times a large number of deposits of mineral oils and resins, all of either animal or vegetable origin, have been known to man. Most were practically disregarded, though *amber* has been in constant demand for ornaments, and *bitumen* (asphaltum) was for a long time valued as a natural cement.

In the nineteenth century their usefulness increased: bitumen was needed as a binder for road making, and some of the more easily recovered oils were used for burning and in preparing varnishes. Today, the main value of these minerals is as fuels. Those which are easily converted into the most valuable fuels are being exploited first, but it seems probable that sooner or later we shall be glad to produce fuels, and by-products, from all the richer deposits of mineral oils and resins. At the present time by far the most important of these minerals is petroleum, although a short reference to shale oil is also of interest.

Shale oil of high quality is produced in Britain and other countries, though it cannot usually compete with petroleum oils without some form of economic protection. Near Edinburgh it is distilled from certain shales which yield from 10 to 20 per cent of their weight of oil. It is then purified by further distillation. In spite of slight chemical differences, shale oil and petroleum have essentially the same uses.

The shale from which ordinary fletton building bricks are made contains a few per cent of oil, and this burns when the bricks are baked. The heat of combustion is nearly enough to bake the bricks. Thus there is a considerable saving of coal, and the cost of the bricks is appreciably reduced.

*Petroleum* gets its name from the Greek word for rock and the Latin for oil. It is found in many parts of the world, and the number of oil-producing countries is steadily increasing: recent additions are England, Hungary, Austria, and Holland.

Petroleum occurs in porous rock which happens to be surrounded at the top and sides by impervious rock. If, in a geological formation of this kind, the porous rock is saturated with water containing a small proportion of oil, in the course of time the oil globules will rise and collect in the covering dome. Less is known about the origin of petroleum than of coal, though recent investigations suggest that some of it may be derived from the dead bodies of a genus of sea animals, the ascidians.

Crude petroleum is almost entirely a mixture of hydrocarbons: a typical example might contain 84 per cent carbon, 12 per cent hydrogen, and four per cent oxygen, nitrogen and sulphur, of which sulphur seldom makes more than one per cent. It is subjected to distillation and other processes to obtain a wide range of products, whose proportions differ according to the type of crude oil. Some of the more volatile fractions are sold in steel bottles, under pressure, for domestic use as liquid petroleum gas. The next lightest fractions are used as petrol (gasoline) in internal combustion engines of the spark-ignition type. Less volatile fractions are used as

lamp oil, and for heating and cooking; others as gas oil for enriching water gas made at gas works; still others as Diesel oils in compression-ignition engines. Later fractions are used to manufacture lubricating oils, and as furnace fuel, while the residues of distillation include bitumen and paraffin wax. An important chemical industry based on petroleum is now developing, similar to that based on the distillation of coal.

Petroleum furnace fuels are easily handled and controlled. Before being admitted to the combustion chamber they can be atomized or vaporized, and then be intimately mixed with the correct proportion of air. Burnt in this way, they are efficient and entirely smokeless. Fuel oil is beginning to be used in appreciable amounts in British factories and business premises, and one of the new London power stations, Bankside, is oil burning. Oil has long been in service for firing ships' boilers; according to Lloyd's Register, the fraction of the world's tonnage of shipping in which oil was used for heating boilers increased from 30 per cent in 1939 to 56 per cent in 1949. The figures for oil in internal combustion engines were 24 per cent in 1939 and 21 per cent in 1949; and for coal, 45 per cent in 1939 and 22 per cent in 1949. About one per cent of tonnage used no fuel.

If oil is burnt with a drastically reduced air supply, it produces a dense smoke. This consists of oil droplets which have evaporated and recondensed, together with some products of disintegration. Oil has therefore been used for making smoke screens in warfare.

Where oil is cheap, its advantages for domestic heating and hot-water heating are great, and in parts of the U.S.A. it is an important domestic fuel. It is burnt in boilers which start up automatically when the water temperature falls below a selected value.

*Natural Gas.* This name is given to the combustible gases which, in some districts, may be recovered from underground. It is in great demand in North America for domestic and general industrial purposes, and its rate of production doubled between 1936 and 1944. Where natural gas is recovered from oil wells, petrol and other readily liquefiable hydrocarbons

are usually removed, leaving a gas which is mainly methane ( $\text{CH}_4$ ). Some of this is used for heat and power at the oilfield, and the remainder is distributed through pipes to general consumers. Natural gas is also obtained from "dry" wells which yield no petroleum. The total consumption in the United States and Canada is now about 10 000 million cubic feet per day.

Natural gas is difficult to store, though it can be transported long distances through high-pressure mains; in remote districts it can only be used locally, e.g. for the manufacture of carbon black and in chemical processes. Very large quantities are wasted each year because of the lack of economic outlets. Considerable waste may also occur before the flow at the well is controlled, or because in the case of "wet" gas it is only the oil which is sought.

A natural gas rich in methane occurs in association with coal, and in theory, at any rate, appreciable quantities could be recovered in coal fields. Reliable estimates are not available, but it has been suggested that the total yield in Britain, from coal mines, oil wells, and gas fields, might be over 100 million cubic feet per day.

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## Chapter IV

### ARTIFICIAL FUELS

*History.* With one important exception, no attempt was made for thousands of years to modify or improve on the fuels of nature. The exception was charcoal (see Chapter III) which has been used since prehistoric times for the smelting of metals and other special purposes. Yet natural fuels, particularly coal, usually fall far short of the ideal. Coal is such a complex mixture that to burn it properly requires much skill and attention. In addition it is difficult to store and transport; its ash has to be disposed of; and its products of combustion have to be mixed with many times their

Table 8. *Artificial fuels*

3000 B.C. or earlier	Charcoal	
1587 A.D.	Earliest references to coke making for malting etc.	
1709 A.D.	Metallurgical coke . . . . .	ABRAHAM DARBY (Britain)
1780 A.D.	Water gas . . . . .	F. FONTANA (Italy)
1792 A.D.	Coal gas, with coke, tar, and other products	WILLIAM MURDOCH (Britain)
1830 A.D. (appr.)	Producer gas . . . . .	BISCHOF (Germany)
1833 A.D.	Commercial alcohol, from vegetable matter, used as illuminant	U.S.A., France, and Britain
1873 A.D.	Carburetted water Gas . . . . .	T. S. C. LOWE (U.S.A.)
1907 A.D.	Low-temperature coke . . . . .	T. PARKER (Britain)
1918 A.D.	Liquid fuels from hydrogenation of coal and tar	F. BERGIUS (Germany)
1920 A.D.	Sewage-sludge gas . . . . .	H. PRUSS (Germany)
1925 A.D.	Synthesis of methane and liquid fuels from carbon monoxide and hydrogen	F. FISCHER and H. TROPSCH (Germany)

volume of air before they are fit to breathe. Thus there is an incentive to transform it into fuels which can be burnt with little handling or other attention in simple appliances, and whose products of combustion are as nearly as possible innocuous.

There is also the possibility of starting completely afresh with industrial wastes or vegetable raw materials, and synthesizing fuels of the required properties. Coal continues to be used mainly because it is in general cheaper and more abundant than artificial fuels, and because very much labour and vast capital equipment would be needed to produce the requisite quantities of alternative fuels. Table 8 shows some of the more important artificial fuels, and it is worth noting how recently most of them have come into commercial use.

The above artificial fuels (except charcoal) are briefly discussed below in the order solids, liquids, gases.

### COKE

If any member of the coal series is strongly heated in a vessel from which air is excluded it gives off combustible gases and leaves a residue of which a high proportion is carbon. The process is called "carbonization". Wood and peat yield coherent residues which may be used as lump fuel. Lignite and the bituminous coals of high oxygen content leave residues which easily crumble into powder; so do anthracite and carbonaceous ("steam") coal.

A number of the bituminous coals of low oxygen content behave quite differently. On heating they first appear to melt; the bubbles of volatile matter escaping from the viscous, semi-molten mass cause it to swell, in some cases to several times its original volume; and on further heating the mass hardens and takes the familiar spongy appearance of coke, which it retains when it cools to a normal temperature. These are the "strongly caking" coals which are among the most useful for the manufacture of gas and coke; all sizes down to the finest can be used since the component lumps and particles fuse together. Coals of lower coking power are useful in at least one important kind of retort

(continuous vertical), and blends of two kinds of coal are also used. The only coals and blends chosen for carbonization are those yielding cokes which are strong enough to be easily handled and transported without breaking. For some metallurgical purposes very strong coke is required, capable



Fig. 7. Metallurgical coke.

of bearing a great weight without crushing. The three main kinds of coke are illustrated in Figs. 7, 8 and 9.

*Metallurgical Coke* of the highest quality is made from strongly caking coals of 20–30 per cent volatile matter; less strongly caking coals of 30–35 per cent volatile matter are also used. The coal is carbonized at  $1000^{\circ}\text{C}$  or more in coke ovens (see Chapter VII). In 1949 Great Britain produced about 15.5 million tons of metallurgical coke, and the U.S.A. in 1945 about 66 million tons.

The most important use of metallurgical coke is for smelting iron in the blast furnace. Besides being hard and strong, the coke should contain as little sulphur as possible and be



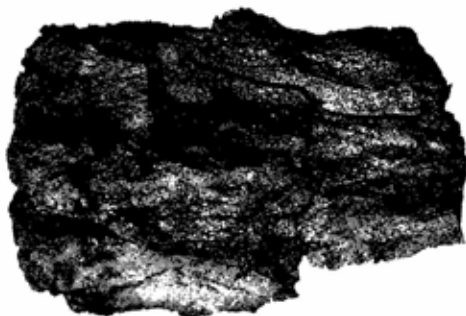


Fig. 8. Gas coke.



Fig. 9. Low-temperature coke.

relatively free from ash, since both must be removed in the slag, requiring extra lime as flux and additional heat for melting, and reducing the coke output of the furnace.

Coke for smelting was originally made in heaps similar to charcoal heaps; large coal was stacked round a central chimney, covered with small coal or coke breeze, and kept burning for about 10 days. Later, ovens were built of brick in the shape of beehives, and successive charges of coal were carbonized in them in periods of approximately 3 days; the heat for carbonization was still obtained by burning some of the coal in the charge. Some beehive ovens are still in use, but the modern method is to carbonize the coal in ovens lined with silica brick, heated externally, and to recover tar and ammonia as by-products. Some coke ovens are heated by burning the gases distilled from the coal and surplus gas is used about the works. In districts where coke is made from coal of 30–35 per cent volatile matter many of the ovens are heated by blast-furnace gas, and the richer coke-oven gas is purified and sold. In former years large quantities of coke-oven gas were wasted and even in 1947 1·4 per cent of the gas was bled or burnt to waste in Britain.

*Gas coke* is mostly made from coal of 30–40 per cent volatile matter. This is carbonized at 1000° C or more in coke ovens, or smaller retorts or chambers (see Chapter VII). A high proportion of the coke must be "saleable", though it is in a sense subordinate to the main product, "town's gas". Coal for gas making is selected to give a high yield of gas, and to have a low sulphur content because the hydrogen sulphide must be removed from town's gas; but it is also selected to give a strong uniform coke. In 1949 Great Britain produced about 11·5 million tons of gas coke, not including the coke used in gas works.

About one third of the gas coke made in Britain is used in the gas works and nearly one third is burnt in private houses. The rest is used industrially.

*Low-temperature Coke* is made usually from medium-caking or non-caking bituminous coal, in "nut" size or "smalls", carbonized at under 650° C (1080° F). It contains about 10 per cent volatile matter, and ignites and burns easily; it is suitable for domestic consumption. Considerable research on low-temperature coke was done at the Fuel Research

Station, Greenwich, England, in the nineteen twenties, and it was found to radiate more of its heat than coal when burnt in an open fire. In similar conditions it radiated 25 per cent of its heat, and coal radiated only 22 per cent. In 1930, 250000 tons were produced in Britain, and by 1937 the annual output had risen to 480000 tons.

All three kinds of coke are practically smokeless, however they are burnt. Contrary to a common belief, the proportion of sulphur in coke is no higher than in coal; the smell of sulphur dioxide is not particularly noticeable in the flue gases from a coal fire, because of the smoke with which it is mixed. Unavoidably, however, there is a higher proportion of inherent ash in coke than in coal—up to half as much again.

#### COAL TAR AND TAR OILS

In gas works, about 5 per cent of the original coal is recovered as crude tar, and smaller amounts in coke ovens. Tar can be used as a liquid fuel in furnaces, if its most volatile constituents are removed by distillation until its flash point rises above 150° F. Care is needed to prevent the original tar from containing much free carbon or water, either of which may choke the jets through which it is forced into the combustion chamber. However, tar is not commonly burnt in its nearly crude state, for some of the substances in it are too valuable to burn; in any case, tar is inferior as a liquid fuel to petroleum fuel oil.

Usually, nowadays, tar is carefully divided into fractions by distillation and the light oils driven off below 170° C (340° F) are redistilled to produce motor benzol. The residual tar is separated into solvent naphtha and heavy naphtha; anthracene oil; creosote (light for disinfectants—heavy for Diesel fuel, boiler fuel, or preservative of wood or iron); solid aromatic hydrocarbons; pitch; and road tar, which is pitch dissolved in the heavier oils of the original tar.

#### HYDROGENATION AND HYDROCARBON SYNTHESIS

One way of increasing the calorific value of a fuel, as we have seen, is to remove oxygen from it. A still more effective

way is to add hydrogen to it. At high temperatures, under pressure, hydrogen readily combines with carbon compounds, producing a complex mixture of hydrocarbons which can be separated by distillation. The proportion of the various hydrocarbons can be altered by varying the temperature and pressure in the reaction chamber, and by the choice of a suitable catalyst.

Fuel oils, and other products, are now being made by inducing hydrogen to combine with coal, creosote, tar, or carbon monoxide. The rapid strides of the hydrogenation and synthesis industry are due to the strategic need of countries with inadequate natural reserves of oil to have domestically produced supplies available in time of war. During World War II it was estimated that Germany was producing 5 million tons per year of liquid products by various methods, but these were costly in comparison with natural-oil products. As might be expected, the chemical techniques are too elaborate and highly specialized to be discussed in this book.

### ALCOHOL

*Alcohol* is a manufactured fuel which, mixed with gasoline, has been used in internal combustion engines of the ordinary motor-car type. From the viewpoint of world economy, alcohol is interesting because it can be derived from solar energy in a few months, compared with the millions of years required by all other fuels except wood and, perhaps, peat. It is made by fermentation of vegetable matter—often waste such as molasses, surplus grain, potatoes, or wood—but sometimes grown for the purpose. Alternatively it can be synthesized from ethylene or acetylene, which can be made with electric power from coal and limestone or similar raw materials.

The chemical formula of ethyl alcohol is  $C_2H_5OH$ ; its composition, by weight, is carbon 54 per cent, oxygen 32 per cent, hydrogen 12 per cent. Compared with petrol, alcohol has lower calorific value because of the oxygen it contains. Yet because it will tolerate a higher compression without re-ignition, it is in theory nearly as efficient as petrol in

internal combustion engines. In practice it presents difficulties because it absorbs water vapour from the air, and because it separates from the gasoline with which it has to be mixed. Its cost is at present much higher than of natural petrol, and it is likely to be of most value as a fuel in tropical countries where vegetation is profuse.

In 1938, about 30 000 tons, i.e. about 0.5 per cent of the motor spirit consumed in Great Britain was alcohol, in various blends with petrol. Since 1939 it has been *nil*.

### MANUFACTURED GASEOUS FUELS

*Coal Gas* began to be used in the early nineteenth century, not as a fuel proper, but as an illuminant; and it was not until the second half of the century that the advantages of gaseous fuels began to be generally realized. They are smokeless, ashless, and can be made sulphur-free; they have all the virtues of being "on tap"; and they can be used in very efficient appliances, internal combustion engines as well as furnaces. It is not surprising that, along with electricity, gas has revolutionized cooking methods, domestic hot-water supply, and supplementary domestic heating.

In America and Germany, gas manufactured for sale is obtained mainly from coke ovens. In England, coke-oven gas is distributed in the Yorkshire gas grid, and there are coke ovens for making "town gas", e.g. at Beckton and Greenwich, but in most other gas works the coal is carbonized in much smaller retorts and chambers (see Chap. VII, Fig. 27). About 25% of the calorific value of good gas coal is recovered in the form of gas, 50 per cent in the form of coke, and 7 per cent as tar and other by-products. From 5 to 10 per cent of the revenue of gas works arises from the sale of by-products other than coke but, quite apart from this, the carbonization of bituminous coal is an economical way of using its calorific value provided there is a satisfactory outlet for the coke.

Coal gas is a mixture of gases, and the products of different gas works are not necessarily the same. A typical coal gas of the present day would contain: hydrogen 50 per cent, methane and other paraffins 22 per cent, other hydrocarbons

2 per cent, carbon monoxide 14 per cent, nitrogen 8 per cent, carbon dioxide 3.4 per cent, oxygen 0.6 per cent. (All the above percentages are by volume; hydrogen, which is by far the lightest constituent, accounts for less than 10 per cent of the total weight.)

The calorific value of coal gas is about 16 500 B.Th.U per lb, or about 500 B.Th.U per cubic foot\*. Since gas is sold in Britain by the therm (which is 100 000 B.Th.U) and yet measured by the cubic foot, it is necessary for each gas works to specify the calorific value of its gas and to supply gas at no other than the specified value. Most gas works supply gas at declared calorific values between 450 and 520 B.Th.U per cubic foot. There is no technical difficulty in maintaining the right quality of gas in the gas holder.

Statutory determinations of calorific value are made at gas works with continuous-flow calorimeters such as that described in Chapter II. Recording calorimeters are also available which automatically record the calorific value on a moving chart. These are useful for quickly detecting any change in the calorific value of the gas, but they are not considered to be dependable enough to comply with the legal requirements, and frequent determinations must be made with a recognized design of non-recording calorimeter.

*Water Gas.* If steam is blown through red-hot coke at about  $1100^{\circ}\text{C}$  ( $2000^{\circ}\text{F}$ ), a simple chemical reaction occurs:



and two combustible gases, carbon monoxide and hydrogen, are formed. A small amount is also made of the non-combustible gas carbon dioxide:



The emerging mixture of gases is called water gas.

In both chemical reactions, heat is absorbed from the red-hot coke and stored in the hydrogen and carbon monoxide as part of their calorific value. To produce this heat, nearly half as much carbon must be burnt as is involved in the

\* 1 B.Th.U./ft<sup>3</sup> = 8.9 kcal/m<sup>3</sup>.

reactions, and the temperature of the coke can only be maintained by interrupting the steam blast and replacing it by air blasts in the intervals.

At gas works where continuous vertical retorts are used the red-hot coke as it nears the bottom of the retorts is

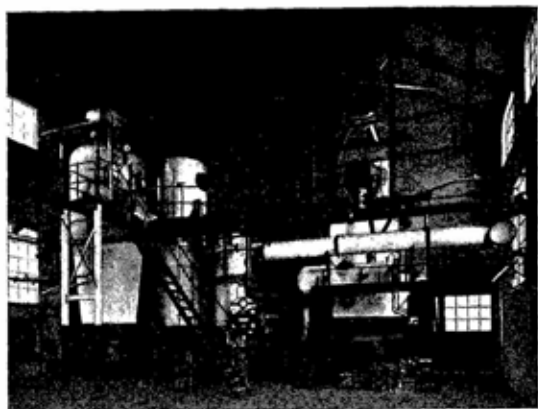


Fig. 10. Carburetted water-gas plant. On the right is the water-gas generator, followed by the carburettor, the superheater and the waste-heat boiler.  
(Courtesy of Humphreys & Glasgow Ltd.)

cooled by steam blown upwards through it; water gas is thus formed which mixes with the distillation gas.

Additional water gas can be made at most British gas works in separate water-gas plant and, on an average, one cubic foot of water gas is made for about every six cubic feet of true coal gas. The advantages of the separate water-gas plant are that extra gas can quickly be made to meet a sudden demand; that it adds to the demand for coke; and that it is economical in labour. Water gas is lower in calorific value than that which gas companies usually undertake to supply. This deficiency can fairly easily be made good by vaporizing and "cracking" oil from petroleum into the gas, forming

the mixture which is usually called carburetted water gas. Fig. 10 is a photograph of a water-gas plant at a gas works.

The output of gas in the United Kingdom in 1946 was  $64 \times 10^{10}$  cubic feet, or about  $77 \times 10^{12}$  kcal (roughly two thirds by gas supply undertakings). In the U.S.A. in 1944 it was  $126 \times 10^{10}$  cubic feet, or about  $250 \times 10^{12}$  kcal (roughly one sixth by gas supply undertakings); but about  $560 \times 10^{10}$  cubic feet of natural gas was produced in the same year.

In a modified form of water-gas plant, bituminous coal can be treated instead of coke, being completely turned into gas. Fewer by-products are recovered than from the distillation of coal, but the process is increasing in parts of the U.S.A. where coke and anthracite are expensive. In Britain it has been used on occasion at some gas works to prevent over-production of coke.

**Producer Gas.** If the right amount of air is blown through red-hot coke at about  $1000^{\circ}\text{C}$ , the effluent gases are chiefly carbon monoxide and nitrogen. This mixture is called producer gas, and the plant for making it is called a gas producer (Fig. 11).

In all large coke-burning producers a proportion of steam is introduced with the air which is blown through the red-hot coke. The products then contain a little hydrogen from the water-gas reaction, and there are considerable advantages in this system. The thermal efficiency of the process is raised; the calorific value of the gases is increased by the presence of hydrogen; and troubles due to the formation of clinker are reduced, because of the heat absorbed by the water-gas reaction.

Though its calorific value is relatively low (about 150 B.Th.U per cubic foot), producer gas has the great advantage over water gas that it is made by a continuous rather than

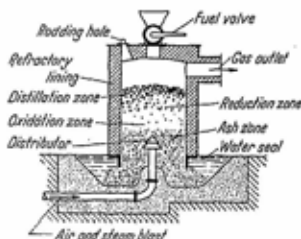


Fig. 11. Gas producer.  
(Courtesy of Industrial Newspapers Ltd.)



an intermittent process. It can be made from almost all solid fuels, from waste such as cotton seed, and even from colliery refuse containing 50 per cent of mineral matter. Producer gas which is free from nitrogen, and whose calorific value is 250 B.Th.U per cubic foot, can be made by blowing steam and oxygen instead of steam and air through the coke.

Industrial producer gas is often made from coal, in which case it is enriched by the coal distillates; but the tarry matter and ash which such gas contains must be removed before the gas is suitable for use in engines and other specialized equipment. Fig. 30, Chap. VII, shows a producer plant using coal, which includes a cooler for the separation of tar and water from the gas, and a scrubber for removing dust and the last trace of tar. If tarry producer gas from coal passes through cool pipes, tar condenses in the pipes and ultimately chokes them. The simplest way to remove this tar is by burning it in the pipes; but "tar burning" is most objectionable because dense clouds of smoke are produced.

The original use of producer gas was in metallurgical furnaces of the regenerative type, which were invented in 1861. Another major use is for heating the retorts, chambers, and coke ovens in gas works. It is also used in gas engines, and in emergencies for ships, motors, tractors, and road vehicles. Light, transportable gas producers have been devised for road vehicles. In France, charcoal can be spared for use in road producers, and their design is comparatively straightforward. In England, however, coke or anthracite has to be used, and it is then essential, if undue cylinder abrasion is to be avoided, to prevent ash from escaping with the producer gas into the machinery. Filters of reasonable, though not always perfect, efficiency have been devised, and a number of producer-driven vehicles have been seen on our roads in war time.

The research and inventiveness which have been devoted to producer gas are indications of its value and importance.

*Blast-furnace Gas* is the residual gas which passes out of the top of a blast furnace. In a blast furnace, the ore is reduced from oxide to metal by freshly made producer gas,

only a part of which is used in the chemical reaction. Blast-furnace gas is therefore similar in constitution to producer gas, but it contains a higher proportion of carbon dioxide. It retains about 60 per cent of the heat of the original coke, and its calorific value is 70–80 per cent of that of producer gas, so it should not be wasted, though in older plants most of the blast-furnace gas was either allowed to burn at the top of the furnaces or led through flues to the atmosphere.

It can be burnt to provide the supplementary heat and power required by the blast furnace, but less than half of it can be effectively used in this way. To provide power, it can be cleaned of solids and used in gas engines, or it can be burnt to raise steam. Blast-furnace gas can be used in regenerative furnaces, and it is finding increasing use in the heating of coke ovens.

*Sewage-sludge Gas.* At a number of modern sewage works, as the solid sediments are changed by bacterial action into an inoffensive form, the gases evolved are collected for use as fuel. The solids are kept at 27° C (80° F) for 3–4 weeks in sludge-digestion tanks equipped with gas holders. The gas, which is approximately 70 per cent methane, is burnt in internal combustion engines to generate electricity for use about the works. It is estimated that 40 million cubic feet per day would be available if all sewage in Britain could be so treated.

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## Chapter V

# INDUSTRIAL BOILERS

Before the problem of atmospheric pollution from fuel can be seen in perspective, it is important to understand where and how the fuel is burnt. This is particularly true in districts where atmospheric pollution is recognized to be a serious problem, and in such districts it would be interesting to make a summary of the fuel consumption by different classes of consumer. In south-west London, for instance, more fuel is burnt by power stations than by any other class, and domestic consumption is second; general industrial consumption is small, but the weight of coke burnt in gas works is very considerable. In Great Britain as a whole, the consumption of coal and coke for 1949 has been classified in Table 9.

The industries have been divided into (A) those which require fuel mainly for boilers, and (B) those which require fuel mainly for other types of furnaces. Group (C) contains domestic consumers; and other users of less than 100 tons per annum, obtained as a difference figure and therefore liable to be inaccurate. Non-industrial establishments with an annual consumption of 100 tons or more of solid fuel have been classified with Group (A), as many of them use the fuel in boilers.

Assuming that the fuel used for boilers by Group (B) cancels with the fuel not used for boilers by Group (A), it can be seen from Table 8 that about half the solid fuel was burnt in industrial boilers. One third of this was burnt at electricity works, and it is worth noting that the coal consumption by British power stations had doubled since about 1936.

Some of the more important industrial boilers will be discussed in this chapter. Other industrial furnaces will be considered in Chapter VII, and domestic uses of fuel in Chapter VIII. Chapter VI is allotted to a discussion of Power and Electricity, which seems to follow naturally after industrial boilers.

## INDUSTRIAL BOILERS

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Table 9. *Coal and coke burnt in Great Britain 1949*

	Million tons per year	
	Coal	Coke
<b>Group A (mainly industrial boilers)</b>		
Electricity works . . . . .	30.1	—
Water works . . . . .	0.4	—
Railways . . . . .	14.8	0.1
Collieries . . . . .	10.8	—
Engineering industry . . . . .	3.6	0.9
Food, drink and tobacco . . . . .	4.1	0.6
Chemical and allied trades . . . . .	5.3	1.1
Textiles, leather and clothing . . . . .	6.9	0.1
Paper, printing and stationery . . . . .	3.3	—
Mines, quarries, etc. . . . .	1.0	0.3
Other trades . . . . .	1.5?	0.1?
Non-industrial establishments . . . . .	3.7	1.9?
Coastwise bunkers . . . . .	0.9	—
Total:	86.4	5.1
<b>Group B (mainly other industrial furnaces)</b>		
Gas works . . . . .	—	3.8?
Coke ovens, estd. coal equivt. of gas burnt . . . . .	3.4?	—
Blast furnaces . . . . .	—	10.2
Other iron and steel works . . . . .	8.4	1.0
Bricks, tiles, fireclay, other building materials, and contracting . . . . .	3.3	0.2
China, earthenware and glass . . . . .	2.1	0.1
Cement . . . . .	2.7	—
Other trades . . . . .	0.7?	0.1?
Total:	20.6	15.4
<b>Group C (domestic and other users of less than 100 tons per annum)</b>		
Domestic house coal . . . . .	28.7	—
Domestic anthracite and boiler fuel . . . . .	2.2	3.4
Miners' coal . . . . .	4.9	—
Miscellaneous (this is a balancing item) . . . . .	5.7	2.8?
Total:	41.5	6.2

Notes: 1. The table is compiled from "Ministry of Fuel and Power Statistical Digest" 1948 and 1949. H. M. Stationery Office. 2. Where estimated figures have been inserted, which are not obtainable from the Digest, they are marked (?). 3. Group A contains the total solid fuel consumption by industries whose main use of fuel is in boilers. The remaining industries are in Group B. 4. Fuel used in industrial producers is considered to be burnt. 5. The items of the table account for about 85 per cent of the potential energy in the major fuels burnt in Great Britain in 1949. The remainder was made up of gas, 5 per cent, and liquid fuels, 10 per cent.

Table 10 provides information about some of the commoner types of industrial boiler now in use. The choice of a boiler depends on the amount, temperature and pressure of steam required; the variations in the steam demand, including opportunities for shutting down and cleaning; the space

Table 10. *Characteristics of Boilers*

Boiler and dimensions	Grate Area ft <sup>2</sup>	Easy Steaming Output lb/hr	Steam Pressure lb/in <sup>2</sup>	Lb steam produced per lb coal	Thermal Efficiency %
Vertical: 3 ft dia. by 9 ft high to 6 ft by 19 ft . . . . .	2 to 50	100 to 6000	80 to 150	5 to 8	40 to 65
Locomotive (stationary): 3½ ft dia. by 7½ ft long to 5½ ft by 10½ ft . . . . .	10 to 26	1000 to 6000	100 to 250	6 to 9	50 to 70
Lancashire: 6 ft dia. by 24 ft long to 10 ft by 30 ft . . . . .	22 to 50	3000 to 12000	100 to 250	6 to 9	50 to 70
Economic: 4½ ft dia. by 8 ft long to 13 ft by 20 ft . . . . .	10 to 150	750 to 30000	100 to 250	7 to 10	60 to 80
Water-tube: setting 4 ft wide by 4 ft long by 10 ft high to 25 ft by 35 ft by 90 ft. . . . .	6 to 1000	350 to 1000000	250 to 1400	7 to 11	60 to 90

Notes: The details of performance given in the four right-hand columns are approximate. Approximate conversions: 1 ft<sup>2</sup> = 0.1 m<sup>2</sup>, 1 lb = 0.45 kg, 1 lb/in<sup>2</sup> = 0.07 kg/cm<sup>2</sup>.

available; the alternative fuels; the quality of the water; and general economic considerations. An engineer making such a choice would calculate the size and type of boiler from information similar to that of Table 10, assuming conditions of easy steaming which have been assumed in the table. Under heavy steaming the output may be increased by thirty per cent or more for short periods according to the type of boiler. He would then review the characteristics of each boiler in greater detail.

*Vertical Boiler.* In the simple cross-tube boiler, the primary air for combustion is controlled by adjustable openings in the ash-pit door and enters under the fire grate which supports the burning fuel. The hot gases pass directly from the fire box into the uptake, the lower part of which, like the fire box, is encircled by the water space. Water also fills the cross tubes, one or more in number, which are slightly inclined to the horizontal to promote circulation. For the removal of scale resulting from the deposition of solids from the water each tube requires a separate cleaning door in the outer shell of the water space. The main advantages of these boilers are their requirement of small floor space and their general simplicity: they are often used as crane boilers.

For the maximum proportion of heat to be transferred from the fuel to the water, it is important that

(1) a large surface of the water space should be exposed to direct radiant heat from the burning fuel and (2) as much heat as possible should then be transferred from the flue gases to the water. The Cochran boiler, illustrated in Fig. 12, accomplishes the second purpose by the passage of the hot gases along fire tubes which cross the water space horizontally. By opening the front of the smoke box, the insides of the fire tubes are easily accessible for cleaning. The Cochran boiler is reasonably efficient and because of its robust design maintenance costs are usually low.

Any boiler in continuous service requires a feed-pump to force water into the boiler against the pressure of the steam.

*Locomotive Boiler.* Railway-engine boilers are designed to produce up to 20 000 lb of steam per hour, within the limited space prescribed by the width of tracks and the height of

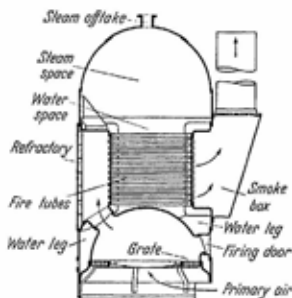


Fig. 12. Cochran boiler.

tunnels. A high rate of combustion up to 100 lb per square foot of grate area per hour is obtained by using exhaust steam from the engine as a flue-gas ejector, and circulation of the water is helped by vibrations. Although neither of these advantages is feasible under factory conditions, stationary locomotive boilers are used industrially, and an example is illustrated in Fig. 13.

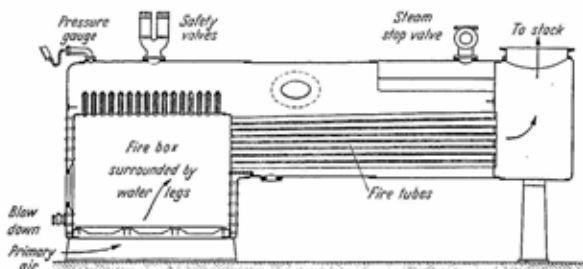


Fig. 13. Stationary locomotive boiler.

The fuel is burnt in an approximately cubical fire box which is placed at one end of the horizontal cylindrical shell, and the water space extends round all sides of the fire box. As with vertical boilers primary air is controlled by ash-pit dampers, and secondary air enters through the fire door. The hot gases are drawn through horizontal fire tubes in the main water space to the smoke box, and then into the chimney stack. The main advantages of the stationary locomotive boiler are that, for its weight, its output of steam is high; it requires no elaborate foundations or auxiliary structures; and it responds quickly to changes in demand. There is a tendency, however, for overheating to occur, with serious damage to the boiler, as a result of inadequate circulation of water round the sides of the fire box. The boiler feed-water should contain the minimum of dissolved solids, and the boiler must be washed out weekly or fortnightly. If possible the fire tubes should be swept clean every three days or so, as they are of small diameter, and quickly

accumulate an internal layer of soot which materially reduces the transfer of heat from the flue gases.

*Atmospheric Pollution from Small Boilers.* The burning of coal in small boilers nearly always produces smoke, especially after the fire is raked or refuelled, and whenever the boilers are worked beyond their rated output. In theory, but apparently not often in practice, smokeless combustion can be achieved if coal is added in small amounts at a time, and provision is made for extra secondary air to be admitted (for example through nozzles situated above the fuel bed, or through openings in the fire door). Generally, however, it is better to burn coke, low-volatile coal, or anthracite, large charges of which can be given at times when the demand for steam is not too great. In recent years, too, more and more use has been made of oil and gas as fuels for the small boiler.

Sulphur dioxide is produced in proportion to the amount of sulphur in the fuel. The amount of ash emitted to the atmosphere depends on the mineral content of the fuel and also on the draught, being greatest when the velocities of the chimney gases are highest. Small boilers are usually provided with relatively short chimneys, and the nuisance of their atmospheric pollution is then aggravated; smoke and sulphur dioxide enter nearby buildings and often descend to street level, particularly when the chimneys are little higher than the buildings which surround them.

*Lancashire Boiler.* In Great Britain this is the commonest form of industrial boiler, though it is quite uncommon in most foreign countries. It will tolerate unskilful handling, and burn most ordinary fuels, as well as sawdust and other wastes; and it may have a useful working life of over 40 years. Its chief disadvantage is its great size, which is increased by the setting and flues, with the superheater and economizers which are necessary if high thermal efficiency is to be attained.

The Lancashire boiler is of such dimensions that, during overhaul or cleaning, a man can reach any part. It has two independent furnace tubes, about 3 ft in diameter, placed side by side within a horizontal boiler shell, of average size



8 ft diameter by 28 ft long. As Fig. 14 shows, the first 6 ft of each furnace tube is divided by a horizontal grate into a combustion zone above and an ash pit below. At the inner end of the grate, the lower two-thirds of the furnace tube is filled by a firebrick wall, the "bridge". Normally the furnace door is kept closed and the entrance to the ash

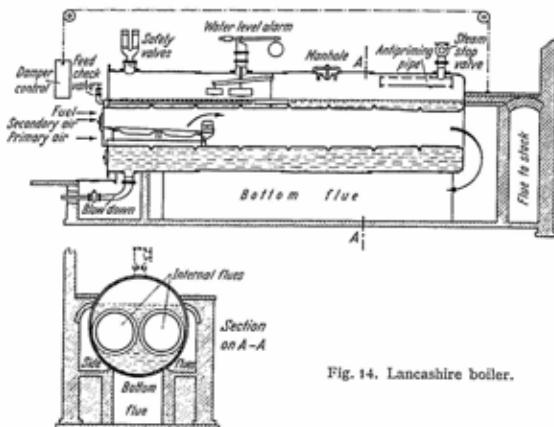


Fig. 14. Lancashire boiler.

pit open. The primary air supply is admitted through the ash pit, and its amount is controlled by dampers in the side flues or a single damper at the base of the chimney. Flames and hot gases pass along the furnace tubes, and the gases are made to return under the bottom and then along the sides of the boiler, to give up as much as possible of their heat before escaping up the chimney. If superheaters are fitted in these flues they also remove some of the heat from the gases. The flues and setting are of brickwork, and they must remain airtight in spite of the thermal expansion of the long boiler shell. The entry of air through leaks into the bottom- and side-flues is well known to be the greatest potential source of heat loss in a Lancashire boiler.

The gases escaping up the chimney are still hot, and a saving of fuel, often 5 per cent or more, is effected with economizers, which enable the flue gases to impart heat to the cold feed-water before it enters the boiler. Air pre-heaters also are sometimes used.

The draught which draws the air through the furnace and flues is provided by the difference in density between the warm gases inside the chimney and the cold air outside.

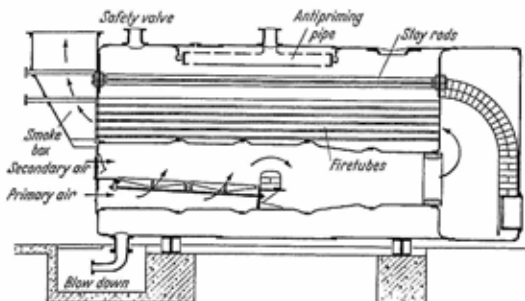


Fig. 15. Economic boiler.

This natural draught may be supplemented by (1) an induced-draught fan placed within the stack, (2) forced-draught fans supplying air to the closed ash pits, (3) a combination of (1) and (2) known as balanced draught, or by (4) steam jets injecting air into the ash pit.

The operation of industrial boilers, and methods of limiting the atmospheric pollution they produce, are discussed later in this chapter.

**Economic Boiler.** To use effectively the heat from the burning fuel, a Lancashire boiler must be long, and have an extensive setting with accommodation for economizers and, possibly, air pre-heaters. Consequently the complete boiler occupies a large total space. With the Economic boiler, illustrated in Fig. 15, the same thermal efficiencies are achieved without economizers or air pre-heaters, and with a great saving of space.

The fuel is burnt in one or more furnace tubes similar to those of the Lancashire boiler, immersed in the same way in a horizontal boiler shell, though this is only about 16 ft long. The hot gases finish burning in a combustion chamber, lined with refractory bricks, at one end of the boiler, and return along horizontal tubes through the boiler shell; they may also be passed through the boiler a second or even a third time, through other nests of tubes. Finally the gases enter a smoke box from which they escape up the chimney.

Apart from its combustion chamber of brick, the Economic boiler needs no brick setting, but it is less robust than the Lancashire boiler and has a smaller space for storage of steam. Soot is removed from the smoke tubes by brushing or by blowing steam through them (soot blowing). Like the Locomotive and other fire-tube boilers, Economic boilers need water as free as possible from dissolved solids and frequent cleaning of the water space.

*Water-tube Boilers.* The Lancashire, Economic, and other so-called "shell" boilers have a large reserve of water, which makes for steadiness of steam generation. This class of boiler is suitable for many heating and manufacturing purposes, particularly where steam is required at pressures of less than 200 lb per square inch; e.g. "process" steam which is used simply as a carrier of heat, or steam used to drive a reciprocating engine. The size of shell boiler is limited by the weight of the shell and the cost per unit of performance.

Water-tube boilers can be used, given reasonable attention, in the place of shell boilers. Although they are costly, their cost increases more slowly, with output, than that of shell boilers; and where very large outputs of steam are required, at all pressures over 300 lb per square inch, as in modern power stations, they are essential. They can be quite small or very large indeed, being assembled from bricks, tubes, drums, and other relatively small components, and they can be designed to burn almost any type of fuel. Both their water space and steam space are small, and as a result they can meet sudden fluctuations of up to 15 or 20 per cent in the demand for steam, but to achieve best results they

require either continuous attention or automatic control. Further points are that their brick settings are complicated and must be frequently inspected, their feed water must contain the minimum of dissolved solids, and they require highly skilled attention.

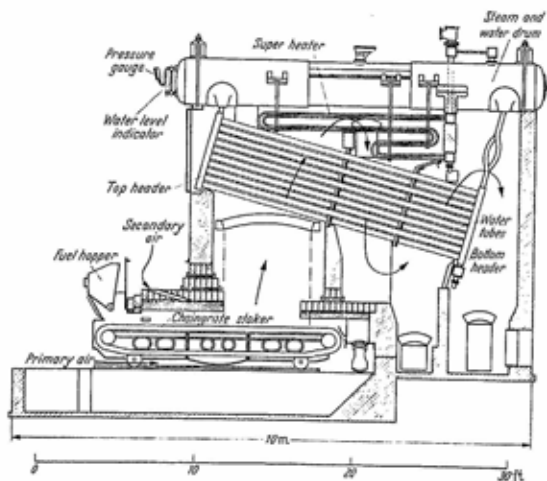


Fig. 16. Water-tube boiler (straight tubes with sectional headers) with chain-grate stoker.

Industrial water-tube boilers differ greatly in design, but there are two main classes: those with their water tubes expanded, as in Fig. 16, into sectional headers; or into three or more drums, as in Fig. 17. In the boiler of Fig. 16, water is pumped through the economizer into the saturated-steam and water drum, and circulates by convection through the bottom header, the tubes and the top header back to the drum, from which steam passes through the superheater to the steam line.

In the three-drum boiler illustrated in Fig. 17, feed-water from the economizer passes first through tubes embedded

in the walls of the combustion chamber to the two water drums, and then through water tubes across the combustion space to the saturated-steam drum. Forced circulation is employed, for the sake of a saving in water space and a

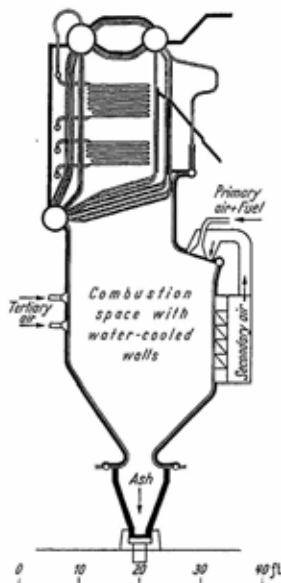


Fig. 17. P. F. multi-drum boiler, evaporating 300 000 lb. per hr. (Courtesy of the Institute of Fuel.)

quicker response. Steam from the saturated-steam drum is driven through the superheater to the turbines. For highest thermal efficiency, it is now recognized that the maximum radiant heat must be transferred from the fuel to the water, and in large boilers the walls of the combustion chamber are water cooled both for the sake of efficiency and to prevent overheating.

The methods of firing, too, are various. The sectional-header boiler in Fig. 16 is shown with a chain-grate stoker; the grate moves slowly to the right, carrying coal from the hopper into the combustion zone, and tipping the residual ash over the far end into the ash pit. In the multi-drum boiler in Fig. 17 a mixture of pulverized coal and primary air is blown downwards into the top of the combustion chamber; secondary air is blown in through suitably

placed tuyères. The heavier unburnt particles, mostly mineral matter, fall into the ash pit, but the lighter particles are swept in an upward curve by the air stream, and combustion continues until the first bank of water tubes is reached. Either the sectional-header or the multi-drum type of boiler may be designed for pulverized fuel or for the chain-grate, the retort stoker, or any other form of automatic stoker.

## BOILER OPERATION

With a hand-fired boiler, it is the business of the fireman to provide as much steam as is required, using the minimum fuel. The efficient use of fuel can only be achieved after considerable experience and training; but it is made much easier when the boiler is adequately equipped with instruments. In the next three paragraphs the operation of a natural-draught boiler with the bare minimum of instruments is described. In later paragraphs a brief account is given of additional instruments and their value in helping to secure efficiency.

As precautions against a burst boiler, a *steam-pressure gauge* and a *safety valve* are required by law; also a *gauge glass* showing the water level, and a *low-water alarm*. If the pressure gauge shows that the pressure in the saturated-steam space is falling, the fireman knows that steam is being used more quickly than it is being generated, and he increases the rate of burning by opening the dampers and so admitting more air to the fuel. If the pressure of steam rises, he reduces the rate of burning by closing the dampers. If the pressure exceeds the limit of safety for the boiler, steam escapes through the safety valve.

Water must be admitted to the boiler at such a rate as to keep the water in it at the working level. All water, with the exception of that from condensed steam, contains solids in solution, but no solids escape with the steam, so periodically the "blow-down" valve at the bottom of the boiler is opened through which water with entrained solids escapes under the pressure of the steam above.

Every five or ten minutes, perhaps, the fireman adds fresh coal to the furnace; once in each period he levels the fuel bed with a rake and, less frequently, he slides a slice bar between the fuel and the fire-bars, to loosen clinker which has formed at the back of the grate. Clinker and ash are removed through the fire door when necessary, and ash from the ash pit underneath. These operations are all part of the task of bringing air uniformly, at the right rate, through the fire-bars to the unburnt coal. Other operations undertaken

at longer intervals are the stoppage of leaks in the brickwork setting of a Lancashire boiler; removal of scale from inside the boiler when it is shut down; and removal of ash from fire tubes, economizers, super-heaters, the base of the chimney and other places of accumulation in the flues.

It is quite possible to operate a boiler with no instruments apart from a steam-pressure gauge and a water gauge but, unless further measurements of one sort or another are made, it is difficult for the outsider either to obtain or even discuss fuel efficiency.

The *rate of inflow of water* and the *output of steam* are obviously important. If they are expressed in the same units, pounds per hour, and no steam is being wasted about the boiler, these measurements will be equal. One method of measuring the water fed to the boiler is by passing it through two open tanks, at different levels, separated by a V-shaped weir. The height to which the water rises above the bottom of the V is a measure of the rate of flow. If the angle of the V is  $90^\circ$ , and the height is  $h$  inches, it has been found that the flow, in pounds per hour, is approximately  $1100 h^{2.5}$ . More precise formulae are given in engineering books. A different principle for measuring boiler-feed water is illustrated in Fig. 18. A fraction of the water flowing in the main is diverted through a small turbine, whose revolutions are recorded on the counter.

The *output of steam* can conveniently be measured by the method of Fig. 18. An alternative way is to determine the drop in pressure when the steam passes through an orifice of, say, half the diameter of the steam pipe. A flanged joint is made in a straight part of the pipe well away from bends or other restrictions of flow, and an orifice plate is inserted. Small pressure-lead pipes are inserted into the steam pipe at positions, which should be determined by formula, on either side of the orifice. The pressure leads are connected to a manometer, which may be a dial-reading or recording instrument. The velocity of the steam through the orifice is approximately proportional to the square root of the pressure drop. Accurate formulae are given for calculating the flow of steam in pounds per hour, making corrections

for the temperature and moisture content of the steam. If the steam is not superheated, and contains liquid water, the

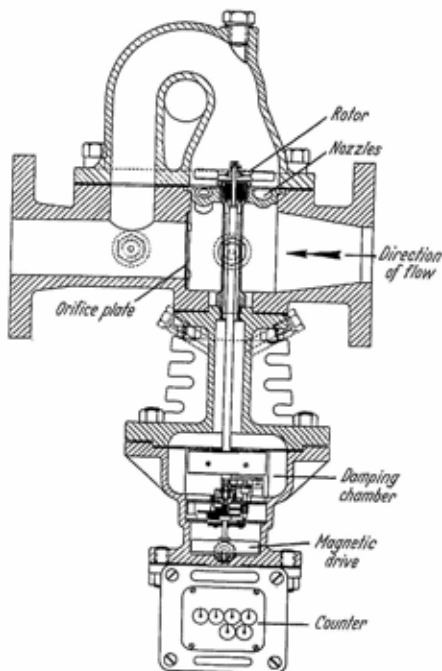


Fig. 18. Water or steam meter (Courtesy of George Kent Ltd., Luton).

moisture content may be determined from the fall in temperature when a small quantity of the steam is allowed to expand to a lower pressure.

Manometers are also used for measuring the *draught*, i.e. the pressure differences drawing air through the fuel bed and through the boiler. The total draught is the difference in



pressure between the air under the grate and the gases about to pass into the chimney. As this is usually less than one inch of water, it requires sensitive gauges such as that illustrated in Fig. 19, but it is a most useful index of the rate at which fuel is being burnt.

There are a number of places in boiler systems where useful information may be gained by measuring *temperature*. Thermometry is not an easy subject, and numerous precautions are necessary if the measurements are to be reliable.

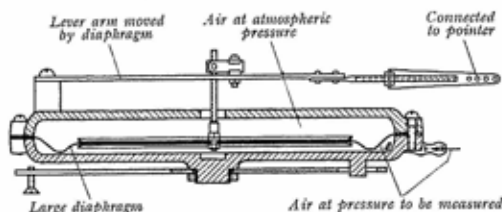


Fig. 19. Draught gauge (Courtesy of Drayton Regulator & Instrument Co.).

The following types of thermometer are used: for the temperatures of steam, water, and air, either mercury-in-glass or dial-reading mercury-in-steel thermometers, or thermocouples which operate dial-reading or recording milli-voltmeters; for the flue gases, thermocouples or mercury-in-steel thermometers; for the furnace itself, various forms of pyrometer for measuring the light or heat radiated from a convenient point in the furnace.

The *consumption of solid fuel* can only be found by the laborious method of weighing or, less accurately, by estimation from the volume used. The test of whether fuel is being used most efficiently is the "equivalent evaporation" in pounds of steam generated per pound of coal burnt (see Table 10). If the calorific value of the fuel is also known, it is quite a simple calculation to arrive at the *thermal efficiency* (see right-hand column of Table 10).

A *heat balance* (i.e. a statement of where the heat goes) can be drawn up when the following are known: (a) the thermal efficiency, (b) the heat in the flue gases escaping

up the chimney, (c) the potential heat in the unburnt combustible gases and (d) the potential heat from the carbon content of the clinker and ashes. For the measurement of (b), (c) and (d) different forms of *calorimeter* may be used, but as a rule chemical analyses are made and formulae applied. Table 11 is an example of a heat balance, from a hand-fired Lancashire boiler, under very good conditions of operation.

Table 11. *Example of a heat balance*

A hand-fired Lancashire boiler, with integral superheater, burning bituminous coal of 11 690 B.Th.U/lb (as fired), gave 6.58 lb of steam at 543° F and 142 lb/in<sup>2</sup> for each lb of coal. The water-feed temperature was 49° F.

A: Total heat in the 6.58 lb of steam =	8 450 B.Th.U	
B: Calorific value per lb of coal =	11 690 B.Th.U	Per cent of heat in fuel
Therefore Thermal Efficiency (100 A/B)		72 **
Heat lost in flue gases: Water vapour*	5 %	
Other gases	15 % **	
Total		20
Potential heat in unburnt gases		2 **
Potential heat of the carbon in ash and clinker		3
Radiation losses, etc., to make up 100 %		3
		100

Notes: \* Water vapour produced from the moisture in the fuel and from combustion of the hydrogen in the fuel.

\*\* These three items are the ones most likely to vary under different firing conditions. The figure for radiation losses depends very much on the design of the boiler, but should be constant within one or two per cent for any given boiler.

**Carbon Dioxide.** The composition of the flue gases is in itself an index of the efficiency of combustion. Combustion is inefficient either (a) if too little air enters the furnace, when the flue gases contain too much combustible matter (usually hydrogen, methane, carbon monoxide and smoke) or (b) if an unnecessary amount of excess air is entering, when the flue gases contain too much oxygen and nitrogen. The proportion of carbon dioxide is particularly informative, as it is a measure of the proportion of the air which has been used for burning carbon. Combustion is correct when the flue gases contain the highest proportion of carbon dioxide,



containing filters to exclude flue dust. The gas sample may be passed through an absorbent which removes carbon dioxide, and the reduction in volume may then be measured (see Fig. 20). Alternatively, the density or the thermal conductivity of the sample may be measured, in comparison with the density or the thermal conductivity of air. Carbon

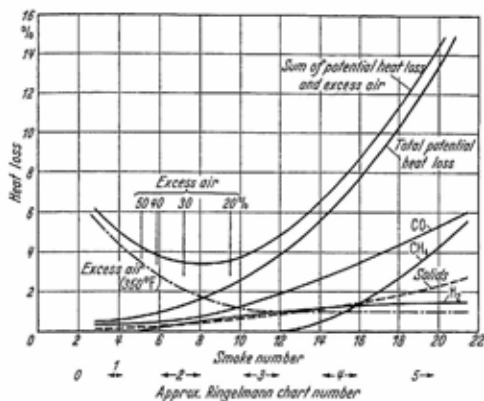


Fig. 21. Heat losses—full load.

dioxide is denser than oxygen or nitrogen, and it has a lower power of conducting heat; either of these properties therefore serves to determine approximately the proportion of carbon dioxide in a mixture of gases which is mostly oxygen, nitrogen and carbon dioxide. In most commercial instruments, the proportion of carbon dioxide is indicated directly on a dial or recorded on a chart.

*Smoke as an Index of Efficiency.* Where coal is burnt, the efficiency of combustion may be judged from the smoke. The upper curve of Fig. 21 represents the total heat loss in a particular furnace; i.e. the heat wasted in warming any excess air, added to the heat which could be produced by burning all the combustible matter in the flue gas. This

curve never reaches the zero line, because in a limited time it is impossible to make every ounce of fuel combine with oxygen unless a very large excess of air is supplied. The curve reaches a minimum when the air supplied is between 20 and 40 per cent above the theoretical requirement of the coal. As can be seen from the horizontal scales of Fig. 21, the flue gases will then contain an appreciable amount of smoke. The two horizontal scales are two different ways of measuring smoke, but the appearance of the smoke at the chimney top, when 20 per cent of excess air is used, is usually described as a light haze. If there is any more smoke than this, insufficient excess air is being used and efficiency is being lost. If there is a little less smoke, the efficiency is still very near the maximum. If there is no smoke, either all the coal in the furnace has turned to coke, or some special anti-smoke device is being used, or too much air is being admitted into the furnace.

The fireman is not always willing, even if he is able, to walk outside at frequent intervals to a position from which he can see the chimney top; but there are simple ways of showing him how much smoke is being made. One way (see Fig. 22) is to make two holes at opposite sides of the chimney stack, and cover them with glass windows which may be kept clean by currents of clean air or by heating them electrically. The light from an electric lamp shines across the stack into a photoelectric cell outside the opposite window. The current from the photoelectric cell is indicated by a galvanometer and recorded on a chart; it drops nearly to zero when smoke is emitted. An even simpler arrangement is possible if there is a convenient place in the stack where a window may be put which can be seen directly by the fireman, for there is then no need to use a photoelectric cell. The window is made of opal glass and placed at an angle so that the fireman can see for himself how much light is passing across the stack from an electric lamp at the other side.

*Smoke Elimination from Boilers of Medium Size.* Atmospheric pollution from boilers includes sulphur dioxide and particles

of ash and grit, whose emission to the atmosphere depends on the nature of the fuel, and the design of furnace and chimney; these may be reduced or eliminated in various ways, which will be discussed in Chapter XIV. But smoke and other

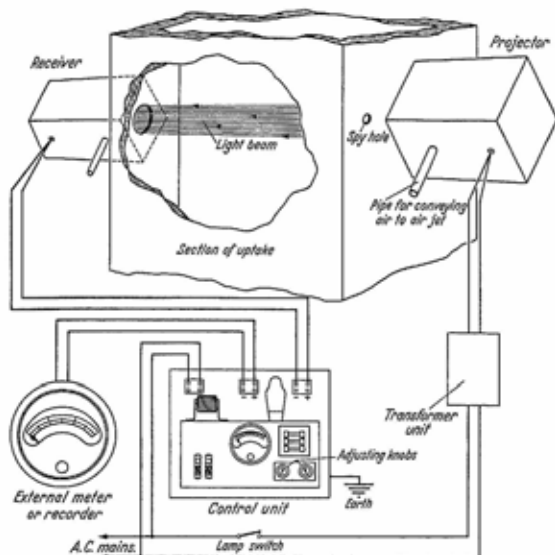


Fig. 22. Smoke indicator (Courtesy of Radiovisor Patent Ltd).

unburnt combustible material is mainly the responsibility of the fireman, and will therefore be discussed here.

Where boilers are fired by hand with bituminous coal, there is the ever-present risk that dense smoke will be produced and emitted to the atmosphere. As was pointed out above, any smoke denser than a light haze is a sign that fuel is being wasted. Smoke itself is unburnt fuel, and it carries with it from three to five times its own weight of invisible fuel, in the form of hydrogen, carbon monoxide,

methane and other hydrocarbons. Moreover, when a clear fire is burning, a very considerable amount of heat is radiated to the boiler walls, but this is reduced if smoke is present.

The worst emission of smoke usually occurs immediately after firing, when bituminous coal is thrown on the fire. Volatile matter equal to about one eighth of the coal is distilled off within two minutes, and will escape unburnt, unless its temperature is raised above  $750^{\circ}\text{C}$  ( $1200^{\circ}\text{F}$ ) and sufficient air is admitted, with adequate mixing, to burn it. Very many boilers are so designed, unfortunately, that sufficient air cannot be admitted in a suitable way to burn the volatile matter. The best their firemen can do is to throw coal along one side of the grate at a time, so that the smoke is quickly heated by radiation from the other side; this is called "side-firing". During the first three or four minutes after firing, the adjustable grids in the furnace door must be wide open, to admit as much air as possible above the grate, where it can mix with the smoke. Even with these precautions, smoke is emitted from boilers fitted with the usual design of furnace door, because the grids are not wide enough to admit as much secondary air as is required by a half charge of coal.

The principles governing the combustion of bituminous coal have been known a long time, but have not always been properly applied. In 1940 it was found that the heavy clouds of smoke from the funnels of coal-burning ships allowed enemy submarines and aircraft to spot and shadow convoys without themselves being detected. At the request of the Admiralty, the possibility of reducing smoke from ships was examined at the Fuel Research Station, by providing simple equipment to introduce sufficient air over the fuel bed for a short period immediately after firing each charge of coal. Two types of "smoke eliminator" were designed, one of which could quickly be fitted to existing forced-draught marine boilers, and the other to natural-draught boilers. They were soon fitted to most of the British and Allied ocean-going ships burning coal, and were found to be capable of preventing smoke entirely. Later it was shown that smoke eliminators saved over five per cent of

the fuel when operated by the ordinary personnel of a typical merchant ship. With an experimental marine boiler on land the saving had been higher still.

Similar improvements were then designed for natural-draught Lancashire boilers, and work has started on vertical boilers and forced-draught boilers. To convert an existing natural-draught Lancashire boiler, the furnace door is replaced by a new one which has very large openings instead of the usual grids. Whenever the door is opened and subsequently shut the openings are automatically uncovered by a simple flap valve, and enough air enters over the fuel bed to consume all smoke. If the door is opened without coal being added or the fuel bed disturbed, the flap valve should be shut immediately. If fresh coal is added, the fireman should shut the flap valve later, when

he judges that the first volatile matter has been burnt. The chimney or the smoke indicator will tell him if he is too soon.

Fig. 23 shows the smoke-eliminator door for Lancashire boilers. Fig. 24 shows (curved line) the rate at which combustible gases are given off after a fresh charge of coal is

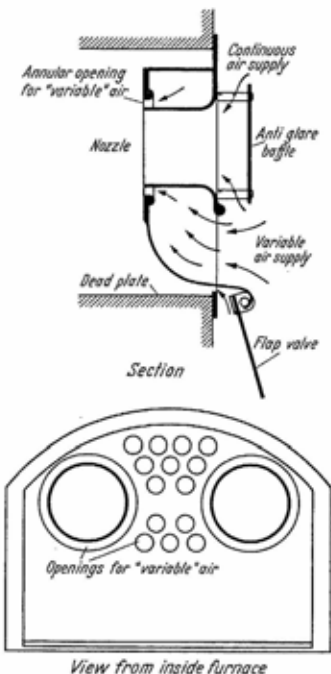


Fig. 23. F.R.S. smoke-eliminator door for natural draught Lancashire boiler (diagrammatic).



added at time  $O$ . The area  $Y$  shows the amount of gases burnt when the ordinary door is used. The area  $X$  is the extra amount burnt when the special door is used, admitting extra air during the first few minutes after firing. The area  $Z$  represents the unnecessary air which would be used if the flap valve were open all the time.

In recent years more attention has been paid to the job of firemen, many of whom now attend short courses of

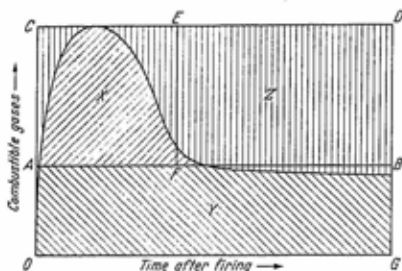


Fig. 24. Rate of evolution of combustible gases and secondary air required.

training. These courses are an advantage to employers and firemen alike, for they save both fuel and unnecessary labour. When the smoke-eliminator door becomes more generally known, there will be no difficulty in training firemen in its use, thereby still further increasing fuel efficiency. Smoke from hand-fired industrial boilers is already being reduced by this simple means, and there is no reason why it should not be almost eliminated.

*Alternatives to Hand Firing.* In a large proportion of water-tube boilers, and quite a number of shell boilers, the human stoker shovelling fuel is replaced by mechanical devices. One method popular in big power stations, but useful also in quite small installations such as Lancashire boilers, is the technique of burning pulverized fuel. Coal is first ground in mills to particles of 25-50 microns (0.001-0.002 inch) in diameter. This powder is easily lifted in an air stream and transported along pipes to the furnace, where it is burnt

like a gas, with the aid of secondary and tertiary air admitted to the combustion chamber at suitable points (see Fig. 17). There is no smoke from pulverized fuel if the combustion conditions are correct, but the ash is in a finely powdered state, and much would escape into the atmosphere if it were not caught with special equipment (electrostatic precipitators are now considered necessary, see Chapter XIV).

Where fuel oil or creosote is burnt in boilers, the flames are similar to those from pulverized fuel. The oil is preheated and forced into the combustion chamber through atomizers, air being admitted through separate ports. There is no smoke from oil-fired boilers when they are correctly managed, but smoke will be produced if (a) the oil droplets are too large because of inadequate preheating or a faulty burner top, (b) too much oil is being fed into a cold furnace just being lighted, or (c) insufficient air is entering the combustion chamber because the air ports are too small or the draught is inadequate.

For burning lump coal in boilers, various forms of automatic stoker are used. A well-known form is the sprinkler stoker, in which coal from a hopper is spread on the fire by revolving blades; the charges are quite small, and the volatile matter is burnt fairly completely as it passes over the red-hot parts of the fuel bed. Another type is the coking stoker, which first pushes the coal into a hot region where the volatile matter distils off to pass over the fuel bed where it is burnt completely; the coked coal is gradually moved onward along the grate and the residual ash falls over the far end.

Underfeed stokers employ devices for pushing the coal from below into the fuel bed; the volatile matter is released and has to pass through the fuel bed where it becomes hot enough to burn completely on encountering the secondary air. There are also varieties of overfeed stokers (known as retort stokers) in which the coal is pushed down a slope of inclined steps, between which primary air enters. A thick fuel bed is formed, and although in theory this might seem likely to give rise to excessive quantities of combustible

gases, inadequately mixed with air, satisfactory combustion can be achieved in practice.

The chain-grate stoker may be regarded as a development of the coking stoker, and is used at many power stations. The grate is an endless belt of steel links which draws coal from a hopper adjacent to the furnace, and slowly moves the fuel forward. The volatile matter is given off near the entrance, the coke burns over the larger part of the grate area, and the ash falls over the far end in sufficient quantities to bar the entry of air past the far end into the combustion space (see Fig. 16).

All automatic stokers have the advantage that the fuel enters the fire continuously or nearly so; therefore the supply of air needs little alteration once it has been correctly adjusted in relation to the rate at which fuel is being admitted. Except from some sprinkler stokers, smoke is eliminated, but all boiler flue gases contain dust and sulphur dioxide. At power stations it has become the accepted practice for stoker-fired boilers to be furnished with efficient grit arrestors of the cyclone or electrostatic type. The use of high chimneys is also a safeguard against heavy depositions of grit and dust, and against high concentrations of sulphur dioxide near the ground. At present the removal of sulphur dioxide from flue gases is taking place at only very few stations.

*Boiler Availability.* Water-tube boilers are designed to use the greatest possible amount of heat from the fuel. In a modern power-station boiler the flue gases usually pass between banks of boiler tubes, superheaters, economizers, and air preheaters. If the gases contain condensable vapours or solid particles in suspension, these may accumulate on the tubes and (1) seriously impair the transfer of heat from the gases to the water, steam or air within the tubes, or (2) so choke the passages between the tubes that they cease to function properly. Power-station boilers should be able to remain on load for 6-12 months without being shut down for cleaning, but there have been cases of boilers shutting down within a few weeks because of (2) above. The effect has been to increase the number of power stations or, at any

rate, the number of boilers necessary to satisfy the demand for electricity.

In Britain the investigations of the Boiler Availability Committee have revealed how boiler deposits are formed and how they may be kept within bounds. On tubes which may be reached by the flame, deposits known as "bird-nesting" occur as a result of the accumulations of coal ash, solidifying from the molten state. On tubes and other surfaces more removed from the flame, "bonded deposits" occur, which are particles of ash and grit immersed in a bonding medium of the sulphates or acid sulphates (mainly pyro-sulphates) of sodium and potassium. These salts are formed from the sulphur, sodium, and potassium present in coal; they have relatively low melting points, and form sticky deposits on the cooler surfaces, to which particles of ash and grit will readily adhere.

"Phosphatic" deposits are similar in appearance to bonded deposits, but they are caused by the presence of phosphorus compounds distilled from certain coals; fly-ash particles are chemically attacked by phosphorus or its compounds and hard masses of phosphates are formed. Since the susceptibility of a boiler to bonded or phosphatic deposits depends very much on its design, and since there are coals containing very different proportions of sodium, potassium, and phosphorus, the deposits can be reduced by the allocation of coal suitable to each boiler.

Deposits on economizers are due to fly ash in the presence of sulphur and phosphorus compounds. Air heaters suffer serious deposits if the heating surfaces are so cool that liquid from the flue gases collects on them, and it should be noted that the presence of small quantities of sulphuric acid may raise the dew point to 300° F or more. Evidently coals containing a high proportion of sulphur are to be avoided if possible where air-heater trouble is prevalent.

Pulverized-fuel installations are most likely to suffer from re-fusion deposits (birdnesting) on the boiler tubes and super-heaters, because of the quantity of fly ash in the gaseous products of combustion; the trouble can be reduced by designing the combustion chamber to have the maximum

amount of cooling by water tubes embedded in the walls. Apart from the accumulation of dust in the economizers and air heaters, pulverized fuel installations are almost immune from all other forms of deposit. Boilers with mechanical stokers and retort stokers do not suffer seriously from refusion deposits unless very fine coal is burnt, but they are susceptible to the other forms of deposit unless suitable precautions are taken. The high temperatures in the fuel beds of some retort-stoker boilers make them particularly liable to trouble if the coal contains much phosphorus.

*Soot Blowing.* The efficiency of both large and small water-tube boilers is improved if the heating surfaces can be kept free from deposits while the boiler is on load. This ideal can be to some degree realized by the intermittent spraying of the surfaces with jets of steam or water. Large boilers usually have steam jets built into positions where they are likely to be most useful, and steam is blown through them at regular intervals of about 8 hours. The operation of soot blowing may cause the emission of particles to the atmosphere together with some smoke, since the deposits usually contain a proportion of combustible matter. When there are suitable grit arrestors in the system, however, the emission may be quite negligible.

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## Chapter VI

### POWER AND ELECTRICITY

Before considering industrial furnaces for heating substances other than water, it is important to give some attention to the generation of mechanical power, and of electricity which may readily be transformed into power. Progress has been rapid since the invention and initial development of the steam engine in the latter half of the eighteenth century. Before then, our only sources of power were men, animals, water, and wind, and the most powerful machines generated no more than a few horsepower. A modest total of 10 million tons of coal was burnt each year in Britain, entirely for domestic and industrial heat. By 1910 the annual total exceeded 260 million tons, of which 180 million tons were used for generating steam power. Since then the total consumption of coal has dropped appreciably, but owing to improved efficiency the output of power has risen.

The development of various types of prime mover (i.e. machines for converting the heat from fuel, or any natural source of power, into controlled mechanical energy) may be studied from Board of Trade reports of the Census of Production. The first full post-war report is likely to be published at about the same time as this book. According to the Fourth Census of Production, the total capacity of prime movers (not including engines for any type of transport) was nearly 18 million horsepower in 1930. Reciprocating steam engines accounted for 6 million, and steam turbines for 10 million, but whereas steam-turbine power had nearly doubled since 1924, reciprocating steam-engine power had diminished. The total horsepower of road vehicles must be of the order of 100 million, but many road vehicles are used very intermittently compared with the running of industrial machinery.

The machines in Great Britain now easily outstrip the animal power: Sir ALFRED EGERTON has estimated that the useful external work performed by our working population

and our 900 000 horses is equivalent to less than a million horsepower. The energy from fuel used in the service of man has been simply described by Dr. A. PARKER. In the United States, on an average, each individual has energy equivalent to 27 servants working for him; the corresponding number in Great Britain, which comes next in the utilization of fuel and energy, is 13-14 servants for each individual.

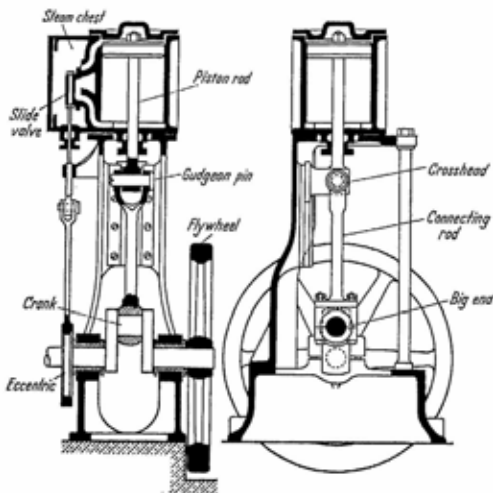


Fig. 25. A simple vertical reciprocating steam engine. (Figs. 25 and 26 are reproduced by permission from *Engines* by E. N. da C. ANDRADE, Bell 1932.)

*The Reciprocating Steam Engine* (see Fig. 25) is a cylinder in which a piston, connected by a rod to a crankshaft on which is mounted a wheel or flywheel, can move backwards and forwards. Steam under pressure from a boiler is admitted to the back of the cylinder and the piston is pushed forwards, rotating the flywheel about one third of a revolution. The steam is then shut off by a valve and the piston continues to be pushed forwards by the expansion of the steam in the

cylinder. As it expands, this steam cools and begins to condense into droplets of water. At the beginning of the backward stroke a second valve opens to admit steam to the front of the cylinder, and the piston is pushed backwards. The condensing steam at the back of the cylinder escapes into a "condenser" where it is completely converted to water, the vacuum created helping to draw back the piston. The condensed water is pumped into the boiler against the pressure of the steam by the boiler feed-pump. The valve mechanism is very robust, a single slide performing the operations of connecting each end of the cylinder alternately to the steam pipe and the condenser with suitable intervals for the expansion of the steam in the cylinder.

The steam engine is a "heat engine", deriving its energy from the difference in heat content between hot steam and boiling water. When the temperature difference is  $100^{\circ}\text{C}$  ( $180^{\circ}\text{F}$ ) a maximum of about 30 per cent of the heat given to the steam is recoverable as power. The fraction of the fuel's energy which can be recovered from a reciprocating steam engine is seldom more than 15 per cent, and efficiencies of 3-12 per cent are the most usual. There is no room in locomotive engines for condensers, and their over-all thermal efficiencies are consequently low, 3-6 per cent. In most steam engines about 25 per cent of the energy is lost in the boiler, and the rest in the engine.

Reciprocating steam engines are most useful where up to a few hundred horsepower are required, but they have to compete in this range with internal-combustion engines and electric motors.

*The Turbine* is a more efficient machine for using steam, where 100 to 100 000 horsepower are required. It is able to convert into useful work the energy in the steam as it expands right down to the pressure in the condenser. The turbine is more compact than the ordinary steam engine, and rotates more smoothly.

In operation, jets of steam are directed between curved blades on the rim of the rotor. The steam is made to change its direction of motion and also to expand, doing work on the rotor. A two-pole 50-cycle turbo-alternator rotates at



3000 revolutions per minute, a four-pole alternator at 1500; in America where 60-cycle machines are common, the corresponding speeds are 3600 and 1800 revolutions per minute. The largest, fastest turbines will recover up to 30 per cent of the fuel's energy as mechanical work, but the usual efficiencies are from 12-18 per cent. Steam turbines provide about 60 per cent of the total horsepower in Britain, mostly at electric power stations.

*The Gas Turbine* is still in its infancy, although the principles controlling it have been known for nearly 200 years. Liquid fuels are used at present, and they are burnt in compressed air in such a way that the gaseous products of combustion become very hot. If these were retained in the combustion chamber the pressure would increase very much more, but the gases are made to escape between turbine blades, expanding and cooling as they do so. The gas turbine is relatively light, because combustion takes place near the rotors. It is efficient only if the gases are allowed to reach very high temperatures, between 600 and 850° C, and materials have not been available until recently for making a rotor which will operate satisfactorily within this range of temperatures. A 5400 horsepower gas turbine was built in 1939 in Switzerland for use as a stand-by electric generator. It is fired by oil and has a thermal efficiency of 18 per cent. The British Electricity Authority by 1948 had three oil-burning gas turbines of 10 000-15 000 horsepower, for supplying electricity at times of peak load.

Since 1944 there have been great developments in small gas turbines for aircraft, naval vessels and other uses. These engines can generate great power in proportion to their size and are particularly suited to "jet" propulsion. They burn paraffin, which is both cheaper and safer than petrol.

*Internal-combustion Engine.* The gas turbine is an internal combustion engine, since the fuel is burnt within the turbine space, but the phrase is generally restricted to piston engines in which the fuel is burnt inside the cylinder. Any gaseous fuel, such as town's gas, producer gas, sewage-sludge gas, or the vapour of petrol or oil, can be made to burn very

rapidly, in fact explosively. This is done by mixing fuel and air in the right proportion, raising the temperature above a minimum which depends on the fuel, and by applying a flame or spark if the temperature is insufficient for spontaneous ignition. The same is true for liquid and solid fuels when these are broken up into droplets or particles less than about 25 microns ( $1/1000$  inch) in diameter.

As a result of such rapid combustion it is possible to make effective reciprocating engines in which the gaseous products of combustion are the working substance instead of steam, combustion taking place inside the cylinder instead of under a separate boiler. Internal-combustion engines are classified according to the method of igniting each charge of air and fuel mixture (spark ignition or compression ignition) and according to the cycle of operations undergone by the mechanism (four stroke or two stroke).

The four-stroke engine works with the help of two valves to each cylinder. On the charging stroke, the piston acts as a pump, sucking the mixture of air and fuel into the cylinder through the inlet valve. On the return stroke it compresses and adiabatically warms the mixture, which is then ignited. A rapid rise in temperature and pressure results and the working stroke begins, during which the mixture of gases expands and partly cools. On the return from this stroke the exhaust valve is opened, and the piston drives out the spent gases. The exhaust valve closes and the cycle is repeated.

In the two-stroke engine (see Fig. 26) the under side of the piston is used to compress the mixture of air and fuel during the down stroke. Towards the end of the down stroke the piston uncovers ports in the cylinder wall, and the fresh mixture enters the cylinder head, driving out the spent gases. A proportion of spent gases inevitably remains, but though the explosions are less powerful they occur twice as often as in the four-stroke engine, and the final efficiency is about the same.

The commonest fuels are petrol and light oil; but by appropriate modification in the design of the engine, many fuels can be used, though powdered fuel and some liquid

fuels present difficult technical problems, connected with the damage done to the piston and cylinder by the residues after combustion. In some situations, town's gas, producer gas and blast-furnace gas are most convenient for use in stationary internal combustion engines, but the latter two

have to be freed of the particles of ash which may be suspended in them.

Gas engines are rather less wasteful of fuel than steam engines. Their efficiency is 25–30 per cent, though this should be multiplied by the thermal efficiency of making gas, which may be 0.75–0.85 (75–85 per cent). Small motors driven by petrol or oil are about as efficient as gas engines, their efficiency being 18–25 per cent. Larger engines of the compression-ignition (Diesel) type have efficiencies ranging from 25–33 per cent. They are at present the most efficient machines for converting the

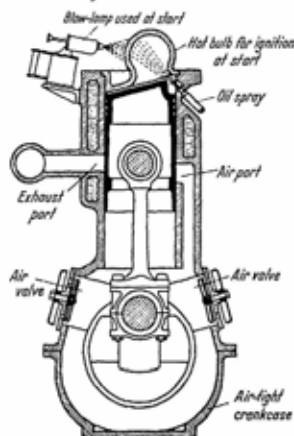


Fig. 26. A simple internal combustion engine. Two stroke; compression ignition.

energy of fuel to mechanical energy, though they are not always the most suitable because of fuel and upkeep costs. Very large Diesel engines can be made, and in 1934 there was one of 22 500 horsepower. Their main use is for marine propulsion, and they are also used to generate electricity.

### ATMOSPHERIC POLLUTION FROM ENGINES

It is evident that large engines of all types are usually more efficient than small ones. As a matter of world and national fuel economy, therefore, it is important to develop large power plants. This is also a good policy when atmospheric pollution is considered, because in a large plant it is worth while to take very strict precautions against emitting pollu-

tion. There are still a great many small power plants in this country, most of which burn raw coal, but these are tending to be replaced by electric motors, and the problems of combustion and atmospheric pollution are becoming more centralized in the big electric generating stations.

Except for local effects from cooling towers which are discussed below, the problem of pollution from steam engines is no different from the problem of pollution from boilers. It has been referred to in the last chapter, and will be discussed again in Chapter XIV. Perhaps the nuisance is proportionately greatest from railway engines, in which about 14 million tons out of a total of about 190 million tons of coal are burnt each year in Britain. It is difficult to estimate the total weight of smoke emitted from this 14 million tons of coal but probably the answer is about 0.4 million tons. The emission of sulphur dioxide is normal, but considerable quantities of ash are likely to be emitted since forced draught is used in railway engines. The nuisance of all three types of pollution is aggravated by the unavoidable shortness of the smoke stack, though it is true that much of the emission occurs in engine sheds or in open country.

Atmospheric pollution from internal-combustion engines occurs partly because of the limited time in which the fuel can burn. As a result petrol exhaust gases contain unburnt fuel, and a high proportion, perhaps 7 per cent, of carbon monoxide. The "smoke" which is particularly noticeable for a time after a cold engine has been started, consists of droplets of fuel and lubricating oil. When the exhaust gases can be emitted through a chimney, their contribution to the general atmospheric pollution is not usually large, and the carbon monoxide ultimately oxidizes to form the harmless carbon dioxide. When they are emitted near street level, or in garages or tunnels, exhaust gases can be dangerous. Concentrations of one per cent of carbon monoxide in air are rapidly fatal, and accidental deaths from poisoning by carbon monoxide have been frequent. Fatal concentrations are likely to occur only in confined spaces, and can be prevented by adequate ventilation. All forms of pollution from street traffic can best be reduced by preventing

undue concentration of vehicles, and especially avoiding traffic jams.

*Cooling Towers.* For thermodynamic efficiency, all steam engines require condensers, where exhaust steam is quickly changed to water, thus creating a vacuum which helps the motion of the piston or turbine. It is also an advantage to re-use the condenser water in the boiler for making steam, since this is "distilled" water that is free from dissolved solids. The condensers are kept cool by an independent water supply circulating through numerous small tubes across the space in which the steam is condensing. This condenser water need not be pure, and it is drawn from town mains, rivers, or canals; but it is wanted in large quantities, about 600 tons for each ton of coal burnt in the boilers. Where town-mains water is used or where the natural supply is limited, the condenser water is circulated through cooling towers, where it is cooled by air and its own latent heat of evaporation, so that it can be used again. Cooling towers, particularly the large ones used by power stations, tend to produce a fine mist which may fall outside the precincts. In accordance with the definition at the beginning of Chapter I, this is atmospheric pollution, and therefore calls for some further consideration.

Although forced-draught cooling towers are common in the U.S.A., natural draught is generally employed in Britain. Near the base of the tower, the incoming water is distributed by sprays or other devices on to a wooden packing over whose many surfaces it flows down to a sump, from which it is pumped for recirculation through the condensers. At the packing heat is transferred from the water to the air, and the warmed air rises, drawing fresh air through the inlets at the base of the tower. A natural draught is thus produced by the difference in density between the cold air outside and the warm air within the whole height of the tower; the air moves up the tower with velocities usually of 1-3 m/sec (2.5-10 ft/sec). The temperature rise of the air and the fall in water temperature are quite small, perhaps 15 to 20° C, but the volumes of air and water are so great that a very large quantity of heat is dissipated.

The air becomes saturated with water vapour as it rises through the packing, and water droplets also are entrained in the air stream. In a typical modern cooling tower, perhaps a hundredth of the water circulated is lost by evaporation, and a thousandth by entrainment. Some of the entrained water drops fall back at once to the packing, but the smaller ones are lifted right out of the tower. In the open these may at first grow in size by condensation from the saturated air around them, now beginning to cool, but they soon fall out of the saturated air, with velocities comparable with the air velocity in the tower. If the normal atmosphere is unsaturated the droplets will partly evaporate before reaching the ground.

The nuisance from cooling towers is now thought to be due almost entirely to the entrained droplets, and hardly at all to the water vapour in the warm air of the tower. If there were no droplets already present, some of the water vapour would condense on reaching the open, but the droplets then formed would be extremely fine, and would have time to mix with fresh unsaturated air and evaporate before they could reach the ground.

The mist from cooling towers is usually worst in cold weather for three reasons: (1) the air flow in the towers tends to increase when the incoming air is cold, (2) the demand for electricity is high and (3) the evaporating power of ordinary air, even if the relative humidity is low, is much reduced in cold weather. It is questionable, however, whether for efficient generation of electricity the cooling-tower water needs to be cooled by the same amount in cold as in warm weather, and one way of reducing the mist in cold weather might be to throttle the air flow into the base of the tower, or lead a proportion of the water through a by-pass instead of through the tower.

The most obvious way of eliminating the nuisance is to reduce the load on each tower by providing extra towers, but less costly methods are preferable. Assuming that the trouble is due to entrainment rather than evaporation it may be attacked in at least three other ways: (1) by ensuring that the air flows uniformly through all parts of the packing

and that there are no places where the flow is excessively fast, (2) by distributing the water over the packing without splashing, and (3) by trapping entrained water with wooden baffles or other "eliminators". The third method has already been found effective in America. As a result of research now in hand by the British Electricity Authority and other bodies there is a good hope not only that mist from cooling towers will be prevented but that their general efficiency will be improved.

### ELECTRICITY

Since the earliest days of engines one of the main problems has been to bring their power to the place where it is wanted. The locomotive, the crane, the lathe, and the riveting machine, for example, call for widely differing methods of transmitting power. In a factory where many machines are liable to be in use it is often an advantage to make a single engine drive a number of machines. This was generally done by using the engine to drive a line of "shafting", which by the use of fixed and loose pulleys could be geared independently to each machine.

Although there are many processes and situations where such methods are still the best available, recently there has been a strong tendency for mechanical to be superseded by electrical transmission of power. Electric power can be transmitted long distances along wires. Electric motors are relatively cheap and their efficiency is high, from about 70 per cent for a  $\frac{1}{4}$  H.P. motor to 90 per cent for a 100 H.P. motor. It is often economical, instead of using a line of shafting, to drive each machine with a separate electric motor. Also a greater variety of machine tools is possible, and their layout in the factory is more flexible.

Many of the electrical properties of matter were known in early times, but it was not until Faraday studied the relation between electricity and magnetism that the possibility of making dynamos and motors was realized. Electricity then began to come into its own as a highly convenient method of transmitting rotary power. At the "power station" a dynamo is rotated by any suitable means. Two,

three, or four wires connect the dynamo to a number of electric motors and each of these rotates, when required, on the closing of a switch.

Dynamos are rotated by many sorts of engine, including each of the major types described earlier in this chapter. By far the biggest output of electric power, however, is from dynamos driven by steam turbines; in Great Britain they provide about 95 per cent of the total output, as may be seen from Table 12 (derived from annual reports of the Electricity Commission).

Table 12. *Total capacity of British plant for generating electricity*

	1933/34 kilowatts	1937/38 kilowatts	1946/47 kilowatts
Steam turbine plant . . . . .	7 513 000	8 483 000	12 100 000
Water power plant . . . . .	159 000	296 000	342 000
Reciprocating steam plant . . . . .	71 000	42 000	22 000
Oil engine plant . . . . .	82 000	87 000	78 000
Gas engine plant . . . . .	11 000	7 000	4 000
Total (kilowatts) . . . . .	7 836 000	8 915 000	12 546 000
Total (horse-power) . . . . .	5 850 000	6 650 000	9 300 000

*Hydroelectricity.* In Great Britain in 1946 there were hydroelectric generators in the Grampians, Galloway, and North Wales, with a total available power of 342 000 kilowatts; this provided only 2.7 per cent of the country's electric power, but the proportion of hydroelectric plant will soon be doubled. The corresponding figure for 16 Western-European countries in 1946 was 40 per cent; and for the U.S.A. was 35.2 per cent. So far, the greatest advances have been made in such countries as Norway, Sweden, Switzerland and Italy, where the mountains and rainfall provide enough water power to satisfy the entire demand for electricity, and in the U.S.A. where 20 million kilowatts was available in 1946.

Unlike steam, water does not contract appreciably under pressure, and it is more liable than steam to flow with a turbulent motion and thus to dissipate its energy. For these and similar reasons, water turbines are different in detail from steam turbines, though they are similar in general principle. The capital costs of hydroelectric stations are



2 to 3 times those of thermal stations, but their operating costs and rate of depreciation are remarkably low. Because of the great ease with which water turbines can be started and stopped, the tendency is for hydroelectric stations to be used for peak load, instead of being kept running day and night (base load) like some of the most efficient thermal stations.

Like practically every other source of power except the tides and radioactivity, water power comes from the radiation of the sun. Contrary to popular belief, however, it is not derived from the heat which evaporates water from the sea and the ground. It is derived from the turbulent circulation of air, which is due chiefly to the different temperatures of different parts of the earth's surface. According to D. BRUNT in "Physical and Dynamical Meteorology", turbulence in the atmosphere dissipates about 2 per cent of the solar energy which the earth receives. What happens is that water from the sea and the ground is evaporated, taking the necessary heat of vaporization from the sea, the ground and the surface layers of air, this heat having originally come from the sun. The newly formed water vapour is distributed by turbulence to heights up to about 10.5 km (35000 ft). In regions of different temperature and pressure there is often more than enough water vapour to saturate the air, so some vapour condenses and clouds are formed. The heat of vaporization is given up to the air when this vapour condenses, but the potential energy acquired by the water-substance on being raised by turbulence to these heights remains in the clouds until the rain falls. If the rain falls in the sea or on land near sea level, all its potential energy is lost, being ultimately converted into heat which is not recoverable; but if the rain falls in the mountains, it still has some residual potential energy which is normally spent in streams and rivers flowing down to the sea. The hydro-engineer taps some of this residual potential energy by diverting water down pipes. At the lower end of the pipes, water turbines slow down the water, and some of its momentum is transformed into electrical energy instead of slightly warming the river.

In Table 5 the world's present output of hydroelectric power is given as less than 1/200th of the output of coal

energy, but if this had been made from coal it would have required the destruction of 5-10 times as much coal energy. Hence from 2.5 to 5 per cent of the world's coal consumption is already being saved by hydroelectricity.

*Tidal Power.* The practicability of converting some of the potential energy of tides into electricity has been debated for many years, and there is a scheme for a tidal generator on the Severn. There are two major difficulties. The immediate one is the high capital outlay required to provide dams and to tap the power of large volumes of water falling small distances. When this is overcome, the energy of dammed tidal water will only be available intermittently, at times when the water levels are sufficiently different on either side of the dam; there will be some difficulty in making economic use of the electricity generated when the period of greatest production occurs during the early hours of the morning. Electrical energy cannot easily be stored in quantity; the most practical method of storage seems to be by using it to pump water into a mountain reservoir which serves a separate hydroelectric station. Another way of smoothing the output would involve supplementary tidal generators on the Humber and other places where low tide occurs at the times of high tide in the Severn.

When tidal generators are built they will use energy which cannot be traced ultimately to solar heat. The tides rise and fall according to the gravitational pull of the moon, supplemented by that of the sun. In mid-ocean the difference between high and low water is only a few inches, but round the shores of the continents the difference is much greater, and in estuaries there may be changes in water level of 60 ft or more. As a result, and especially because of the tidal rush of water through the Bering Straits, the earth's rotation is being slowed down by frictional forces; though it is estimated that five thousand million years will elapse before our day lengthens to twice its present duration. The energy of rotation is being gradually turned into heat by the impact of tidal waters on the shore. Tidal hydroelectric stations would put some of this energy to profitable use, instead of allowing it to degenerate into heat.

*Uses of electricity.* The only form of power which can conveniently be distributed, over long distances if necessary, to houses and factories is electricity; and once it has been "laid on" it can be obtained when required with the minimum of effort. The supply in many countries, however, is at present unequal to the demand, and care is needed in assigning it to the uses for which it is best suited.

It is all-important when mechanical power is needed, and for radio and other electronic purposes. It is efficient and convenient for lighting, by filament lamps, arcs, or discharge tubes. Even as a provider of mere heat it can be used with great effect in specialized equipment such as cookers, grillers, toasters and irons.

It has great industrial uses in furnaces where high temperatures are needed, or where the product to be heated must not be contaminated. Electric furnaces are capable of temperatures as high as  $4100^{\circ}\text{C}$  without contamination of products; combustion furnaces seldom exceed  $1500^{\circ}\text{C}$ . The heaviest users of electricity for furnace heating are the steel industry (for casting steel, and for producing ferrosilicon, ferro-chromium, and other compounds used in making high-grade steels), and the chemical industries for producing phosphorus, calcium carbide, carbon bisulphide, and other materials. Even greater quantities of electricity are used for electrolysis, i.e. the decomposition of compounds by passing a current through them in fused or dissolved state. Electrolytic methods are used for making soda ash, caustic soda, chlorine, sodium hypochlorite, aluminium and magnesium, and for purifying copper and zinc.

As an ordinary heating agent, electricity has the advantage that it can be used intermittently, but it usually costs more than solid, liquid, or gaseous fuels per unit generated (see Chapter VIII). This is because the unavoidable losses of a heat engine make it difficult to produce electric power from coal or other fuels without wasting 70 to 75 per cent of the calorific value of the fuel. In gas manufacture, for comparison, only about 18 per cent of the calorific value of coal is lost beyond recovery. An ordinary electric radiator, consuming electricity made from coal with an over-all

efficiency of 25 per cent is as wasteful of coal as a coal fire of 20-25 per cent efficiency or a gas fire of 30 per cent efficiency. Recently there has been some development of the electric heat pump. This is a heat engine in reverse which extracts heat from an already cold substance such as out-door air or river water, and adds it to any heat produced directly from the electricity; experience has shown that over 35 per cent of the original heat of the coal used in generating electricity can be recovered in this way.

It is scarcely possible to assess the value of electricity to civilization. The value of a commodity is not simply proportional to its total cost; it is better measured by the cost of the next alternative. The importance of electricity would then be estimated by considering the alternatives to the electric light, the accumulator, or the electrolytic preparation of aluminium and magnesium. In the latter case the alternatives are so costly that it would be a question, not of other ways of making aluminium or magnesium, so much as of finding substitutes.

In Britain about half the electricity generated is used industrially, and about a quarter domestically. The rest is used at generating stations, in transmission and distribution, in shops, offices and public buildings, for transport and for public lighting. The amount supplied is increasing by about 10 per cent (compound interest) each year, and still is not catching up with the demand; this is true also in other countries. For the present, evidently, the less essential uses of electricity, chief of which is house heating, must be limited at times of greatest load. In addition, means must be used of "spreading the load" so that the minimum amount of generating plant lies idle for part of each day, held in reserve for periods of peak load.

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## Chapter VII

## INDUSTRIAL FURNACES

In Chapter V consideration was given to the design and operation of boilers, which consume nearly three quarters of the solid fuel burnt in British industries. The remaining quarter is burnt in furnaces of many different kinds. Some data about the furnaces and fuels used are collected in Table 13. The information in the two right-hand columns is approximate; it was compiled as far as possible from Table 9 (in Chapter V), the Ministry of Fuel and Power

Table 13. *Fuel burnt in different types of furnace*

Substance heated	Furnace	Fuel	Annual amount (coal equivalent) million tons	Cost ratio Fuel/Product (%)
Water . . . .	boiler	coal	86	
		coke	5	
		oil	2	
Coal . . . . .	retort	producer gas	4	3.5
	coke oven	blast-furnace gas	0.3	3.5
		coke-oven gas	3.1	
Petroleum . . .	refinery	oil	0.6	10
Heavy clays . .	continuous kiln	coal, producer gas	3.5	15
Glass . . . . .	regenerative	gas, oil		7
Pottery . . . .	intermittent	coal		10
	continuous kiln	producer gas	2.4	
Lime, cement .	lime kiln, rotary kiln	coal, pulverized	2.7	19
Iron ore . . . .	blast furnace	coke	10.2	
Iron and steel (melting)	regen. hearth, shaft, crucible, arc, induction	gas		
		coke, gas, oil	8.4	
		electricity	1.0	
(heat treat- ment)	intermittent, continuous	all fuels		
		gas, p.f., oil	2	
Non-ferrous ores and metals	smelter, crucible	coal		
		coke		
Aluminium and magnesium	electrolytic, induction	electricity		

Statistical Digest, and "Chemical Process Industries" by R. N. SHREVE.

Although the various furnaces of Table 13 have all evolved from a few common ancestors, the number of types of furnace now in use is too large for a separate discussion of each. Some kind of grouping is necessary, and a convenient criterion for this purpose is whether the substance to be heated is in contact with the fuel or the products of combustion. Three main groups of furnaces then emerge.

(1) *Substance separated from fuel and gases.* Examples: boilers, coke ovens, gas retorts, crucible furnaces, muffle furnaces, electric furnaces.

(2) *Substance and fuel in contact.* Examples: blast furnaces, shafts, charcoal heaps and beehive coke ovens.

(3) *Substance in contact with flames or gaseous products of combustion.* Examples: hearth furnaces, reheating furnaces, pottery kilns, brick kilns, lime and cement kilns.

#### GROUP (1) FURNACES

Some typical examples of furnaces which are likely to be of general interest will now be considered. In group (1), apart from boilers, coke ovens and retorts are the most important consumers of fuel.

Fig. 27 shows how the fuel is burnt in the carbonizing plant of a gas works. Coke breeze from the hopper is fed into the gas producer. Producer gas passes immediately into the combustion space round the coal chambers. After combustion the waste gases pass through the waste-heat boiler into the chimney stack. (The waste-heat boiler is a gas-tube boiler similar to the economic boiler illustrated in Chapter V, though without the main furnace tube. The steam is used to provide mechanical power or to generate electricity for use within the gas works.)

Fig. 27 may be taken as representative of many carbonizing plants, though there are important variations in design and operation, some of which are discussed below.

*Horizontal Retorts.* The horizontal retort used in gas works is a tube of silica brick or fire-clay about 20 ft long, 24 in.

wide, and 16 in. high. From six to ten are arranged in one "setting". These are heated by producer gas from a single, coke-using producer, which is built as part of the

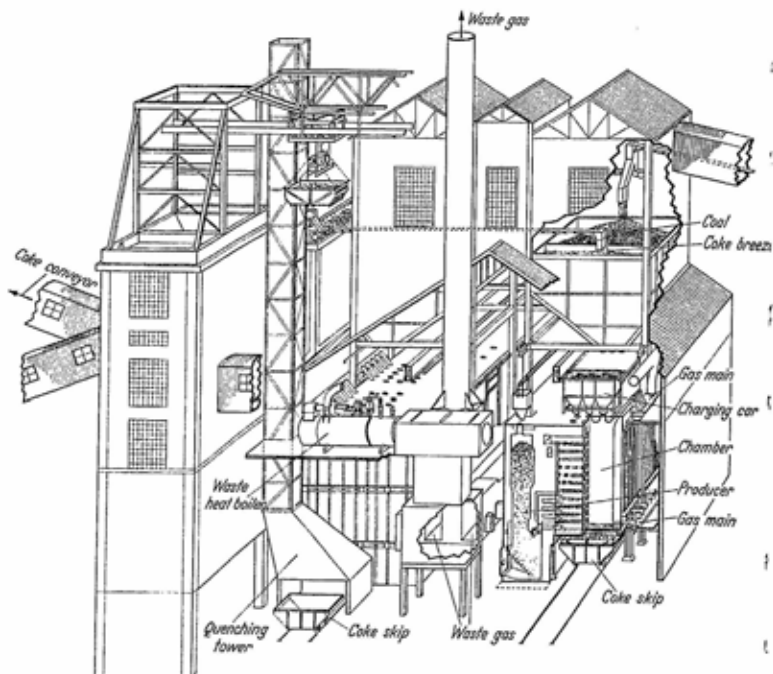


Fig. 27. Carbonizing plant of a gasworks (Courtesy of North Thames Gas Board).

setting. The producer gas and air for its combustion are admitted in the correct proportions, each through about 12 openings, to the combustion chamber which envelops all the retorts in the setting. The air is pre-heated in *recuperators* where heat is transferred to it from the waste flue gases

through three-inch dividing walls of fireclay. Less than half the heat of the flue gases is recovered in this way, but up to three-quarters of the remainder can be used for raising steam in waste-heat boilers.

The retorts are charged about five-sixths full with coal of sizes up to about one inch. This is heated to about  $1000^{\circ}\text{C}$  for about 12 hours. The products of carbonization pass from the ends of the retorts usually into ascension pipes from which they pass down dip pipes into hydraulic mains placed along the top of the retort setting, and here the processes of tar and liquor separation and gas purification commence. The coke is discharged by pushers into cars where it is cooled by water. In two British works the coke is dry-cooled by inert gases, from which heat is recovered by waste-heat boilers.

*Coke Ovens.* The width of a horizontal retort is limited by the need for all the coal within it to be heated equally. There is no restriction on its height, provided the sides can be adequately heated. Coke ovens are very high retorts, a common size being 18 in. wide, 14 ft high, and 38 ft long. Though they are used at very big gas works, coke ovens in Britain are mostly employed in the manufacture of metallurgical coke, i.e. under conditions where sudden fluctuations in demand do not occur.

Coke ovens are built in batteries of 25 to 60, and each charge of 15 to 25 tons of coal per oven is heated for 12 to 22 hours, its final temperature being about  $1000^{\circ}\text{C}$ . This temperature can be reached using coke-oven gas, producer gas, or even blast-furnace gas, by the employment of *regenerators* instead of recuperators. The regenerators are chambers containing fire-bricks in the form of a three-dimensional chequerwork, and four regenerators are used with each setting of ovens. The hot flue gases are used to warm two of the regenerators, while the incoming gas and air are brought to the furnace through the other two. At intervals of about half an hour four flap valves are reset, and the functions of the two pairs of regenerators are transposed. (If coke-oven gas is the fuel it is not preheated as it is liable to decompose, forming carbon; only two regenerators are



used, and only the air is preheated.) Although regenerators are a highly efficient way of preheating the gas and air, the flue gases still retain about half their heat, and can be used in waste-heat boilers before escaping to the atmosphere.

Coke ovens supply all but about one per cent of the coke manufactured in the U.S.A., and over half the total coke made in Britain. They are increasing in importance for the British gas industry. Two large gas works in London are now using coke ovens, and in steel-producing areas more and more coke-oven gas, of calorific value over 500 B.Th.U per cubic foot, is being sold to gas undertakings for distribution. If there are blast furnaces adjoining, the coke ovens may be heated by the blast-furnace gas which might otherwise be wasted.

The coke from most coke ovens is still quenched by water, requiring about 3 tons of water per ton of coke. In one British plant dry-cooling by inert gases is used. It is claimed that dry-cooling, though complicating the plant, improves the quality of the coke, and saves heat equivalent to about three per cent of the original coal.

*Vertical Retorts.* Horizontal retorts and coke ovens are intermittent in operation, because production from each retort or oven must stop during charging and discharging. There are also intermittent vertical retorts or chambers (illustrated in Fig. 27), in which each batch of coke can be steamed, if desired, with the production of water gas. The vertical retort which operates continuously is much more common in Britain, as can be seen from the attached table. This is

	per cent of total gas made (1945)
Continuous vertical retorts . . . . .	42
Horizontal retorts . . . . .	32
Intermittent vertical chambers . . . . .	6
Coke ovens . . . . .	2
Water-gas plant . . . . .	18
	<hr/> 100

taken from a paper by T.C. FINLAYSON, "Gas Production in Perspective", Publication No. 334 of the Institute of Gas Engineers, 1948. It divides the total gas made in 1945 by

British gas undertakings among the five main types of plant. After 1949 there was an increase in the production from coke ovens and static vertical retorts (see below).

There are several designs of vertical-retort settings, but typical dimensions for an individual retort are 25 ft high, 80 in. by 10 in. in section at the top, increasing to 80 in. by 18 in. at the bottom to allow for expansion of the coal during carbonization and to reduce its tendency to stick to the sides and form arches across the retort. The setting may contain 2 or 4 retorts, and single retorts are also used.

The retort is heated by producer gas burnt at the sides, air for combustion being admitted at suitable levels to distribute the heat. The incoming air is partly heated by passing it round the outside of the combustion chamber, and the flue gases are used in waste-heat boilers.

The coal for carbonization is admitted through a gas-tight hopper at the top, and the coal gas is withdrawn from near the top. The coke is discharged at the bottom by a mechanical extractor, after being cooled by steam, which is blown through jets into the extractor box. The steam combines with some of the coke to make water gas (see Chapter IV) and this passes up the retort and mixes with the coal distillates. The effect of the steam is that heat which would otherwise be dissipated on cooling the coke is converted into therms of gas.

The advantages of continuous vertical over horizontal retorts are (1) continuous operation, which implies uniformity of treatment of all coal passing through, and uniformity in output and quality of gas, (2) smaller ground space of plant, (3) dryness and ignitability of the coke, and (4) avoidance of smoke during charging and discharging operations. The possible disadvantages are (1) elaborateness of the mechanism of the coke extractor, (2) limitation of size, and (3) tendency to stick when coal is used having different caking properties from those the retort was designed for.

*Static Vertical Retorts.* A recent development in the design of retorts seems likely to combine effectively the advantages of earlier types of intermittent vertical chambers and continuous

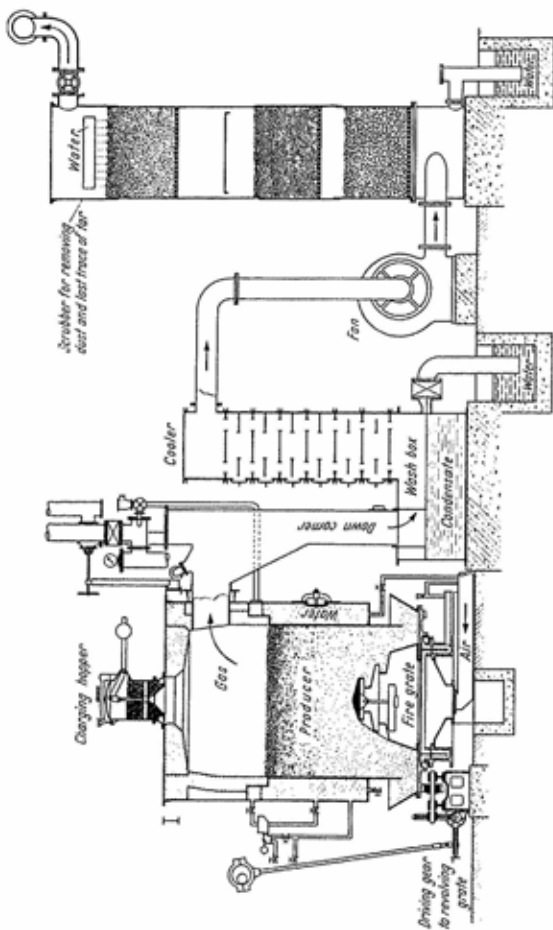


Fig. 30. Producer gas plant with equipment for removing tar and dust.

an air blast is used. Cupolas are mostly operated intermittently, although they can be used continuously, like blast furnaces. If the scrap iron is contaminated with oil, tar or other volatile matter, heavy emissions of smoke may occur.

### ATMOSPHERIC POLLUTION FROM FURNACES IN GROUPS (1) AND (2)

All the furnaces so far discussed in this chapter should employ smokeless fuel, though cupolas are usually lighted each day with coal. There are also unavoidable emissions of smoke during charging and discharging where coal is carbonized in horizontal or intermittent retorts or coke ovens. The amount of smoke produced depends on the time the retorts or ovens are open for charging and levelling, usually 5-6 minutes in each coking period of 12-22 hours; when ovens were charged by hand the time was 15 minutes or more, and the emission of smoke was proportionately greater. Any other emissions of smoke at these plants are due to leakages or intermittent technical difficulties.

At the majority of coke ovens and many gas works the hot coke is quenched with water, and this is a serious cause of pollution by grit and hydrogen sulphide. Apart from sulphur dioxide which is discussed below, the chief smells associated with gas works are from tar and ammonia-liquor wells, from spent oxide being revived, and from purifier boxes being emptied. If tar is distilled and ammonium sulphate is prepared at the works, there will also be the smells of hot pitch, phenols, and pyridine.

From furnaces where coke is burnt, the principal forms of pollution are sulphur dioxide and particles of grit and ash. The sulphur dioxide generated may be taken as about 3 per cent by weight, on an average, of the coke burnt; not quite all of this reaches the atmosphere because a little is absorbed within the flue system. At gas works about 15 tons of coke are burnt for every 100 tons of coal carbonized; the emission of sulphur dioxide is about 2.7 per cent of the coke burnt or about 0.4 per cent of the coal carbonized. Since as much as a million tons of coal per year may be carbonized at a large gas or coke-oven works, and since the stacks are often a bare

100 ft high and near to buildings of similar heights, the concentration of sulphur dioxide in the immediate neighbourhood may be considerable.

Metallurgical coke is frequently made from coal which is low in sulphur content, and when it is burnt as little as 2.0 per cent of its weight may be emitted as sulphur dioxide.

It is hard to give a generalized estimate of the weight of grit and ash emitted from the various coke-burning furnaces which have been described. Only a small proportion of the particles can settle out in regenerators, recuperators, or other parts of the flue system, and particles may be emitted up to three or four per cent of the weight of coke burnt. A more usual proportion would be about 0.5 per cent. Grit from built-in producers causes blockage of flues and serious abrasion of the expensive brickwork of retorts and coke ovens; and some large gas works now use external producers, because the grit can be removed, and because greater control and efficiency in the producer is then possible. Fig. 30 shows a grit remover for producer gas. From such plant, and from blast furnaces whose gas is purified, there should be no ash or grit emitted to the atmosphere.

In all works the particles falling from the chimney stacks tend to be augmented by dust raised during the handling of large quantities of coal, coke, and other material; the amount of dust raised is very variable, depending upon such factors as the quantities handled, the proportion of fine particles, the dryness, and the strength of wind.

### GROUP (3) FURNACES

*Open-hearth Furnaces* are an example of this group, in which the substance is in contact with the gaseous products of combustion (see Fig. 31). They are used for melting steel, purifying it, and alloying other substances with it. The fuel burnt is sometimes oil, but usually producer gas from coal, a long, luminous flame being required above the bath of molten metal. Both producer gas and air for combustion are preheated in regenerators similar to those used with coke ovens. Atmospheric pollution is similar to that from coke

ovens, with the addition of smoke if insufficient air is used in proportion to the producer gas.

*Reheating furnaces* are used for the heating of steel and other metals for cogging, rolling, forging, pressing, and other

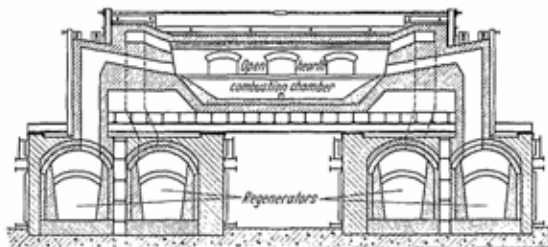


Fig. 31. Open-hearth furnace (Note: the regenerators and their reversing gear occupy a considerably larger floor area than that below the combustion chamber.)

methods of working them. The fuel used may be coal, pulverized coal, gas, oil, or electricity, and the furnace may be intermittent or continuous. In the intermittent furnace a batch of material is heated to the required temperature, when its place is taken by a second batch. In the continuous furnace the material is moved from the coolest to the hottest zone at a suitable rate; cold material is continuously being put in at one end and hot material taken from the other. All types of steel reheating furnaces are in group (3). The one illustrated in Fig 32 is a coal-fired batch furnace, suitable for a small rolling mill.

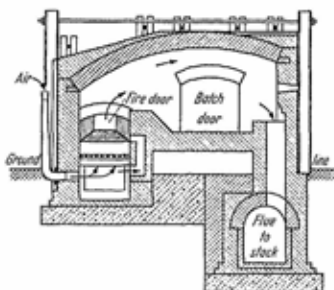


Fig. 32. Coal-fired batch re-heating furnace.

*Smoke in the Steel Industry.* It is usually necessary to keep the metals in a reducing atmosphere to prevent damage by oxidation and, since this atmosphere is produced entirely

by the gaseous products of combustion, it is necessary that the fuel should be incompletely burned. When the fuel is coal, it follows that a great deal of smoke is liable to be produced, especially if the stoking is by hand, the fire grate is unenclosed, and there is no provision of controlled secondary air. The production of smoke tends to be greatest when the furnace or the charge is cold, but much can be done to reduce smoke by skilful stoking designed to keep the flame conditions steady within the combustion chamber.

It has frequently been claimed that the presence of smoke in the combustion chamber is an advantage. Perhaps this is because smoke serves as a convenient indicator that no oxidation is taking place; the conditions of temperature and oxygen supply at which steel oxidizes are probably about the same as those at which smoke burns. But it is quite fallacious to state that the only reducing atmosphere is a smoky one. In the blast furnace the atmosphere is strongly reducing, yet a smokeless fuel is used. Intermittent and continuous reheating furnaces are already in use in which the fuel is oil or producer gas, and heat is conserved in regenerators. The place of smoke as an indicator of reducing conditions is taken by instruments which record the volumes of fuel and air entering the furnace.

*Tar Burning.* Where producer gas is made from bituminous coal and passed through mains in which the gas is allowed to cool, tar is deposited in the mains. This can be got rid of by occasionally shutting off the gas, opening up the mains to the atmosphere, and allowing the tar to burn away. In steel works this practice is usually carried out on Friday or Saturday, and when several works are tar burning at the same time a very thick smoke pall can be produced.

For the sake of those who live near, tar burning should be abolished by never permitting tar to be deposited in the mains. This can be achieved in any of three ways: (a) by making producer gas from coke or anthracite instead of bituminous coal, (b) by cleaning the gases of tar before they enter the mains, or (c) by keeping the mains short and hot.

*Clay Industries.* Numerous examples of furnaces in group (3) are provided by the clay industries, which make (a) refractory

bricks of fireclay, silica, and other materials for industrial use, (b) building bricks, tiles, and pipes, and (c) china, earthenware, glazed tiles, porcelain, and many similar articles. The method is much the same in every case. Wet clay is moulded to the required shape, and heated, gradually at first to about  $120^{\circ}\text{C}$  to evaporate the free water, then more strongly to  $900^{\circ}\text{C}$  to drive water out of the molecules of clay, and finally to the baking temperature between  $1200$  and  $1450^{\circ}\text{C}$ .

Hand-made bricks were at one time fired exclusively in clamps, such as are still in use in Belgium and south-east England; great skill is required both in setting and burning the bricks by this method.

The simplest brick kiln, with a permanent structure, is the up-draught or Scotch kiln, of four upright walls forming a rectangular chamber usually about 26 ft long by 16 ft wide and 12 ft high. The two end walls are removable to facilitate filling and emptying. Along each side are fire holes about 16 in. wide and 2 to 3 ft high, lined with firebricks.

The down-draught kiln, whether circular or rectangular, is the most efficient and satisfactory of intermittent kilns for firing all kinds of clay products. It is in fairly general use for brick making, and in the pottery industry where, however, the old bottle-shaped up-draught kiln has not been entirely superseded. Fig. 33 illustrates a typical circular down-draught kiln, of 20–25 ft diameter. Coal fires are lighted in the 10 or 12 grates, not much bigger than domestic grates though taller in shape, round the outside. Smoke and gases from the fires pass up over a wall towards the crown of the kiln and down through the ware into bottom flues, beneath the floor of the kiln, then through an underground main flue to the chimney stack, usually separated from the kiln and about 30 ft high.

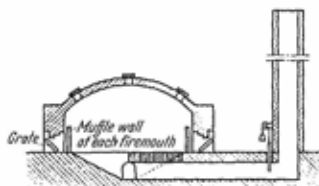


Fig. 33. Down-draught kiln.



The entire kiln is cold to begin with, and when the fires are made of bituminous coal much of the volatile matter in the coal escapes as smoke from the chimney. Smoke emission during the "water-smoking" period (up to 120° C) can be eliminated by using low-temperature coke, gas coke, or anthracite. If these fuels are not available in quantity, smoke can be reduced by using steam coal, or a mixture of coal and coke. Other precautions are (a) to shorten the time required by starting with the ware as dry as possible, (b) to charge the fuel in small quantities, alternate fires at a time, and to put the fresh coal at the front of the fires or, better, to use mechanical stokers, (c) to admit secondary air, preheated to about 500° C, over the fuel bed, (d) to remove ash and clinker from one fire at a time and (e) to keep the kiln and flue structures in good repair.

During the later stages of firing, when the kiln is very hot, it is generally necessary to use long-flame bituminous coal to ensure that no part of the ware is overheated. Correct use of the fire doors and of secondary air controls will ensure smokeless combustion. Insufficient air will cause heavy smoke, but too much air may spoil part of the ware by overheating.

For the very highest temperatures to be reached and maintained, excess air must be avoided and smoke is usually emitted, especially while refuelling is in progress. Another difficulty during the later stages is that some ware has to be heated in a reducing atmosphere, to convert ferric oxide to ferrous oxide and produce a blue colour rather than red. For a long time there appeared to be little hope of reducing the emission of smoke in these circumstances, but smoke can now be avoided by using tertiary air. This is drawn through special flues under the kiln where it is heated; it then mixes with the waste gases and the smoke is burnt within the flues before it can pass up the chimney. The heat of combustion of the smoke is not entirely wasted, since it helps to raise the temperature of the bottom of the kiln.

Intermittent kilns, such as those which have just been described, are still considered the best for producing silica goods, salt-glazed pipes, large fireclay blocks, some kinds of

tiles, and materials of which the required output is small. For all other products continuous kilns are preferable, and they can provide all the necessary conditions for the elimination of smoke and most of the fly ash. They have been used in the brick industry since 1858. There are many types of continuous kiln, in all of which the flue gases are used for heating the cold goods, and the heat of the finished goods, during their cooling, is used for preheating the air. All stages of drying, heating and cooling go on concurrently in the kiln, different units of the ware going through each stage in succession. The thermal efficiency of continuous kilns is high; partly for this reason the number using town's gas, producer gas, and electricity is steadily increasing. Fig. 34 illustrates a Dressler continuous car-tunnel kiln.

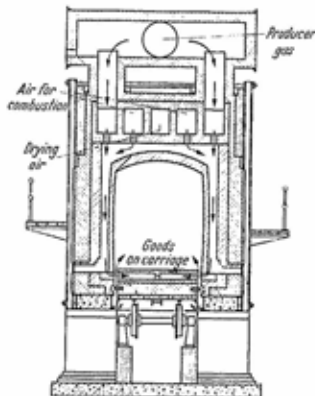


Fig. 34. Continuous kiln (car tunnel).

#### *Lime and Cement Kilns.*

Unlike pottery, lime and cement are products whose cost is greatly affected by the fuel economy of their manufacture. Much attention has therefore been paid to the fuel efficiency of the kilns in which they are made.

Lime, i.e. calcium oxide, is made by heating limestone, i.e. calcium carbonate, to temperatures of 1000–1100° C. The reaction is



Lump limestone is "burnt" in continuous vertical kilns, heated either by coal or producer gas. Each lump of limestone is in the kiln for about six hours, gradually falling towards the hot zone as the finished product is withdrawn from the bottom of the kiln. Lime is also manufactured from powdered

limestone in rotary kilns similar to those which will now be described in connection with the manufacture of cement.

Portland cement is made by heating a mixture of lime and clay to about  $1300^{\circ}\text{C}$ , forming complex calcium silicates and aluminates which fuse and produce clinker on cooling. The clinker is ground to the familiar grey powder.

The rotary cement kiln illustrated in Fig. 35 is a steel tube, lined with alumina bricks, about 10 ft in diameter and

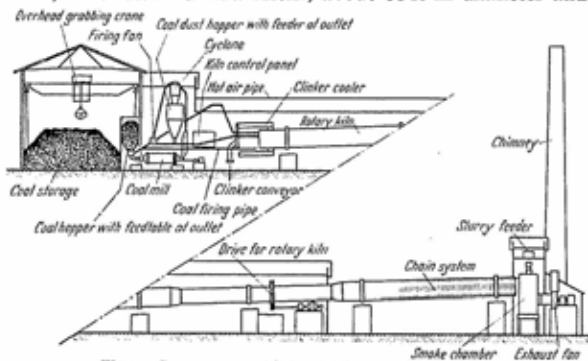


Fig. 35. Rotary cement kiln fired by pulverized coal.

100–400 ft long. It is steadily rotated at about one revolution per minute. The kiln is slightly inclined so that materials fed in at the upper end travel slowly to the lower end in two to three hours. Pulverized coal and air are admitted at the lower end, and the products of combustion travel up the kiln and on into a chimney stack.

At the top of the kiln the mixture of lime and clay enters as a wet slurry. The inside of the kiln carries numerous slack chains which fall across as it rotates and bring the maximum quantity of slurry into contact with the flue gases. Great care must be taken to ensure that the slurry does not become dry too near the top of the kiln. If this happens, much of it crumbles to a powder and is carried away by the flue gases. This is both wasteful and a cause of serious nuisance in the form of deposited atmospheric pollution.

The flue gases are normally passed through cyclone grit-arrestors, which recover much of the escaping powder and reduce the pollution, but they are quite inadequate to prevent the emission of grit when the kiln is operating near the maximum efficiency. Electrostatic precipitators are better, but they need to be kept in really good order. Unfortunately the need for fuel economy makes it important to remove as much heat as possible from the flue gases before they escape, and the risk of drying the slurry too soon is tending therefore to increase, rather than diminish, with improvements in technique. More efficient grit arrestors such as multi-cyclones and electrostatic precipitators are being installed in many cement works. These are described in Chapter XIV.

#### ATMOSPHERIC POLLUTION FROM FURNACES IN GROUP (3)

Mention has already been made of smoke from the steel and clay industries, and dust from lime and cement works. In addition, sulphur dioxide is produced in proportion to the amount of sulphur in the fuel. Most of this is emitted to the atmosphere, except in the clay industries where it comes in contact with alkaline materials and is removed. Probably the best ways practicable at present to reduce sulphur dioxide are to remove as much sulphur as possible by washing the fuel, and to aim at greater efficiency in using the fuel.

The amount of grit and ash emitted depends on the fuel and conditions of draught, tending to be particularly large from some of the metallurgical reheating furnaces. In heavy-industrial districts these particles mix with the smoke, of which there is usually plenty, to produce an oppressive general pall. Unless there are large particles, for example those emitted where pulverized coal is burnt without efficient grit arrestors, the complaint will usually be of "smoke". There is much to be said, however, for distinguishing carefully between the different forms of particles. In every district whose atmosphere is already badly polluted there is a noticeable tendency for new and perhaps unnecessary pollution to appear. This tendency will be checked if each new emission

can be traced to its source; this is a matter for some skill, the first step being to avoid confusion by regarding all forms of pollution as "smoke".

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## Chapter VIII

### DOMESTIC FIRES

From the Dark Ages until Tudor times, most of our ancestors lived in one-roomed huts or cottages. They were heated in winter by a central fire of sticks or logs, under a hole in the roof; so were even the baronial castles and Norman manors. This arrangement made good use of the heat obtained from the fuel, but whenever fresh logs were added, the room must have been filled with smoke. There is no doubt that the first smoke problem which faced the world was that of removing smoke from inside a dwelling; charcoal was the only smokeless fuel available in those days, and it must have been in considerable demand.

The problem of indoor smoke was solved by the Romans with a form of central heating. They built villas on raised floors of concrete and tiles, and made the fire underneath the floor. In this way they could burn even coal without discomfort. Their technique was forgotten in the Dark Ages, and it was not until the 19th century that modern central heating methods were introduced.

There was another internally smokeless form of house heating which was used in pre-Christian Europe. The fire was made in an earthenware brazier outside the dwelling, and brought indoors when the smoke subsided. There was also a type of closed stove for baking and cooking, but the heating stove, built within a room and having a flue pipe built into the wall, did not appear until the 8th century. The early closed stoves were made of bricks and decorated with tiles; iron stoves were first produced much later, in the 16th century.

The open fireplace, with its flue forming part of the outer wall, is a much more recent invention than either the stove or central heating (Roman fashion). It first appeared in Britain in the 12th century, and it was not common until the 16th century.

As a general rule, the most efficient forms of domestic heating have been developed in districts where the winters are severe, or where fuel is scarce. The stove was in general use, in the 19th century, throughout Russia, Scandinavia, Germany, and the northern states of America and China. In these countries the open fireplace was a luxury possessed by the few, and used only for supplementary heating on special occasions. In the southern states of Europe and of North America, any form of house heating was a luxury because the number of cold days in a year hardly justified the expense of building fireplaces in living rooms; here the open fireplace was favoured by those who could afford it.

Winter in the British Isles is as long as in the temperate continental regions, but although sunshine is less frequent, the air is warmer and more humid. Perhaps in the circumstances it is natural that open fires are popular. Their cheerful blaze and radiant heat are a fair substitute for the sun. They do not make a whole room habitable during cold spells, but they serve fairly well during most of the winter and there is always a hot zone round them in which a comfortable position can be found.

Table 14. *Annual domestic fuel consumption*

(From "Heating and Ventilation of Dwellings", H. M. Stationery Office, 1945)

	Britain 1938	U.S.A. 1936	Germany 1936
Number of households . . . . .	12½ million	32 million	18 million
Population . . . . .	46 million	129 million	66 million
Fuel, in B.Th.U:			
Coal, gas*, coke*, anthracite . . . . .	$1740 \times 10^{12}$	$4045 \times 10^{12}$	$1267 \times 10^{12}$
Natural gas . . . . .	—	$346 \times 10^{12}$	—
Wood . . . . .	small	$640 \times 10^{12}$	$254 \times 10^{12}$
Electricity* . . . . .	$101 \times 10^{12}$	$265 \times 10^{12}$	$65 \times 10^{12}$
Fuel oil and paraffin . . . . .	$15 \times 10^{12}$	$185 \times 10^{12}$	small
B.Th.U per house . . . . .	$149 \times 10^6$	$171 \times 10^6$	$88 \times 10^6$
B.Th.U per person . . . . .	$40 \times 10^6$	$43 \times 10^6$	$24 \times 10^6$

\* Figures refer to raw coal used in the production of gas, coke, and electricity.

\*\* In the United States 40 per cent, and in Germany about 20 per cent, of the total energy was generated from water power; for the sake of comparison, this has been regarded as having all been made from coal.

It is probably not generally realized, even now, how extravagant is the use of open fires. Table 14 shows the amounts and proportions of fuel used for domestic heating in Britain and two other countries. The simple assumption can be made that fires are wanted when the daily average outdoor temperature falls below 55° F. In Germany, where the average winter temperature is over twice as much below 55° F as in Great Britain, only about half as much fuel was used per person before 1939. In the United States where most of the population experience lower winter temperatures than in Great Britain, what is generally acknowledged as a far higher standard of heating was maintained with the same amount of fuel per person.

Recently the British have begun to realize the existence of reasonable alternatives to the open fire. Improved standards of hygiene and growing difficulties in obtaining fuel and domestic servants, have made them wonder whether open fires are really worth while. In answer to a house-to-house enquiry in 1942 by the Wartime Social Survey, 75 per cent of housewives of all classes admitted that they would like to have a house with central heating in all rooms and constant hot water in bathroom and kitchen. Forty per cent said they would still like central heating even if no open fireplace was provided.

#### CHOOSING A HEATING APPLIANCE

Few people have an absolutely free choice either in buying their house or in selecting the heating system for it, but it is interesting to consider some of the heating appliances available and some of their main features. One very importance feature is the amount of fuel they burn for a given standard of heating, but this is not known accurately. It depends on the size and shape of the room, the materials of which the walls, floor, and ceiling are made, the temperatures of adjoining rooms, and so on. If variations due to these and similar causes are avoided by confining attention to a particular room, it still depends on the skill of the householder in managing the appliance, the wastage of fuel during periods when the room is overheated, and the time



needed for the appliance and the room to warm up. With these difficulties in mind, observations are being made at the Building Research Station of the quantities of fuel used by ordinary householders in different appliances, and measurements are in progress at the Fuel Research Station which will determine the efficiencies of a number of appliances under rigidly reproducible conditions.

Estimates of efficiency have been made in the past, but these differ widely from one another, because great care and elaborate apparatus are essential for an objective comparison even of two fairly similar heating appliances. The figures for efficiency given in the following paragraphs are based mainly on the report "Heating and Ventilation of Dwellings", Post-war Building Study No. 19, published in 1945 by the Stationery Office. An attempt is made to allow for the difference between ideal and normal conditions of use and for wastage during periods of overheating, since these items are not the same for different appliances. The figures should be used as a rough guide only, and for information about the wide variations to be expected in actual performance of each type of appliance, the reader should refer to the report mentioned above.

By the efficiency of an appliance, in the following paragraphs, will be meant the fraction of the potential heat in the fuel effectively used; i.e. not wasted by overheating of rooms, by other imperfections of average management, or as heat and combustible materials escaping up the chimney.

Other important features to be considered when choosing an appliance are its appearance, the amount of cleaning it will require, the method of removing ash and clinker, and the possibility that moving parts will break, wear out, jam, or get out of adjustment. The cost of the appliance and of installing it, as well as its probable life, should be taken into consideration together with the cost of the fuel it will consume. Many of these points differ among different makes of the same kind of appliance, but only the main features of each type of appliance will be considered here.

*The Open Fire* heats mainly by radiation. The kindling sticks and the coal, as it begins to burn, make bright flames which

radiate a little heat. As the coal changes into red-hot coke, it radiates more heat. During this transformation the fire-brick forming the back and sides of the fireplace has been warming up, and this, too, radiates heat into the room. Finally the chimney breast, the walls of the room, the carpets and furniture become warm, and they convectively transfer a little heat to the air of the room. The air never becomes

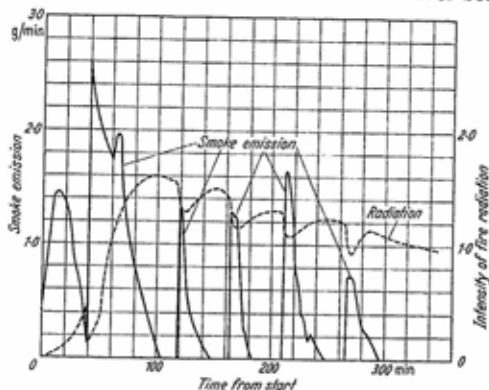


Fig. 36. Smoke cycle from open fire.

very warm, because the open fire quickly draws it up the chimney, and it is replaced by cold air from outside. Thus, even when doors and windows are all shut, the open fire is a very effective means of ventilating a room, though it often produces a draught.

The degree of comfort produced by an open fire cannot be measured by an ordinary thermometer which measures air temperature rather than radiation. Provided the air is nearly saturated with water vapour, its temperature may be well below  $65^{\circ}\text{F}$  without causing discomfort. If the air is dry it will feel cold as a result of the evaporation of moisture from the skin.

The open fire emits most smoke when newly lit, nearly as much when fresh coal is added, but considerably less when a clear fire is burning (see Fig. 36). The smoke arises

from the volatile matter of the coal; it is brown and tarry if the volatile matter is unburnt, or black and carbonaceous if it is partly burnt. The ignition and complete combustion of the volatile matter may be expedited in various ways when once the fireplace is hot, but there seems to be no simple way of consuming the smoke emitted from a newly lit fire.

Until 1920 the design of fireplaces adhered very closely to tradition, although the physicist Count Rumford pointed out a number of valuable improvements in 1796, and although more efficient designs were demonstrated at the Smoke Abatement Exhibitions in London and Manchester in 1882. The Victorian fireplace, with its register and vertical fireback, had an efficiency of less than 15 per cent. After 1920 there was a change in design, and the fireback was made to slope forward in order to reflect into the room heat which would otherwise have been radiated up the chimney. There was another big improvement after World War II and Fig. 37 illustrates a simple open fire of modern design. Its better performance is due to the front brick, and to the tightly fitting ashpit front with fine control of primary air; the gas burner for lighting the fire is an advantage. Other installations are available in which the boiler is omitted.

In a discussion of improvements that might be made to the typical pre-war fireplace, the following recommendations have been put forward:

Primary air, i.e. air entering beneath the grate, should be controllable and capable of being completely cut out. Secondary air, i.e. air entering above the grate, should be controllable by an adjustable canopy above the fire. Both primary and secondary air should be supplied through a duct in the outer wall.

Flues should be inside the house, not in an outer wall. A large, well fitting ashbox should fill the whole space below the fire.

The dimensions of the fireplace should be carefully proportioned, and the spacing of the bars in the grate should be calculated according to the type of fuel to be burned. Either air from the room should circulate round the sides and back of the fire, or the firebrick should be insulated

with slag wool; this is a much better heat insulator than the more common solid filling, and less heat is conducted into the brickwork behind the fireplace.

If bituminous coal is to be burned, the firebrick back and sides should join together to form a hollow dome above the fuel bed; this promotes smokeless combustion.

Some of the above suggested improvements, such as the use of slag-wool insulation or the enlargement of the ash box' are extremely simple; others might at first lead to difficulties. Little would be gained, for example, by having controllable air supplies if the controls were not properly used; and though it would reduce the rate of accumulation of soot in the chimney, a combustion chamber in the form of a hollow dome might interfere with chimney sweeping. In view of the numerous possibilities, however, the few developments in the open fire before 1945 seem very unenterprising.

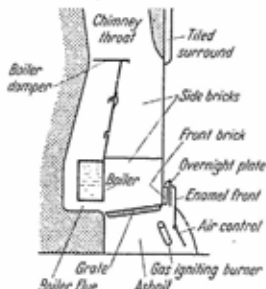


Fig. 37. Fulham grate. An open fire of modern design  
(Courtesy of Radiation Ltd., Birmingham).

The fuel chiefly used in open fires is bituminous coal, but there are several advantages in burning coke or carbonaceous (low-volatile) coal. Coke is of course smokeless, and it is more efficient than coal, because it becomes red hot more quickly and because it burns at a higher temperature, enabling a greater proportion of its heat to be converted to radiant energy. The gain in efficiency has been estimated at 2 to 3 per cent of the total heat of the fuel, saving 10 to 15 per cent of the fuel needed. Low-temperature coke is as easy to kindle and burn as coal, but gas coke is difficult to kindle by the paper-and-stick method. The simplest way of burning gas coke with a gas-fired lighting device is in a special grate with the bars at the best distance apart, a tightly fitting ashpit door, and an extra firebrick lining at the front of the fire (see Fig. 37). This arrangement is an economical and laboursaving form of open fire.

Both forms of coke have the disadvantages that they require to be added to the fire more frequently than coal, because of their lightness. Low-temperature coke fires have bright flames, but the flames from gas coke are faint and uninteresting; even so, there are many people who think a gas-coke fire to be of a particularly cheerful appearance.

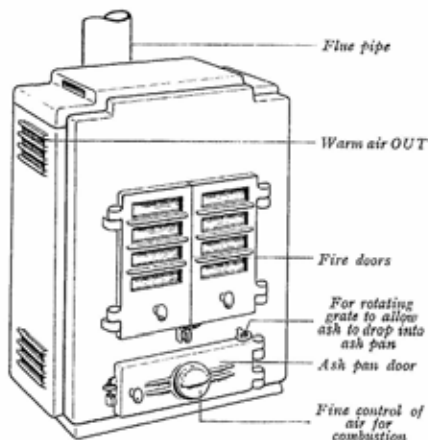


Fig. 38. Openable stove (Courtesy of Bennett's Ironfoundry Co., Stockport).

*The Openable Stove.* Two objections to any form of open fire are that it must be relighted every day, and that its rate of burning is difficult to control. These objections are met by the small openable stove which has been gaining popularity in middle-class houses in Britain (see Fig. 38). The stove is of metal, partly lined with refractory material. It may stand well away from the wall or be built in the chimney place, and whether its front is open or closed, it delivers a considerable proportion of its heat by convection to the air of the room. Its rate of burning when it is closed can be varied easily and quickly; it may be left burning slowly for long periods, even overnight, yet the room remains warm

because little air is drawn up the chimney. The openable stove has an efficiency in average use of about 33 per cent; its efficiency is about 6 per cent higher when closed than when open.

Bituminous coal may be burnt in the openable stove, and by opening the front, secondary air may be admitted to help

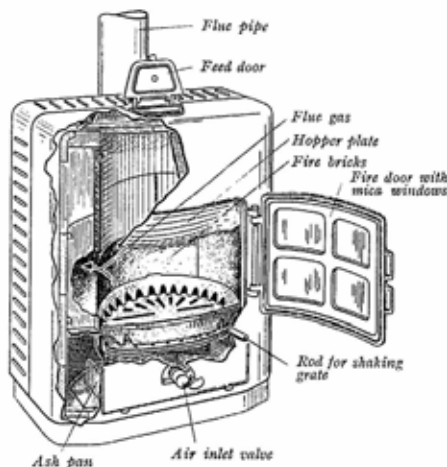


Fig. 39. Closed stove (Courtesy of Smith & Wellstood, Stirlingshire).

to burn some of the smoke; but when bituminous coal is used the flue pipe and chimney require frequent cleaning. Anthracite, coke and low-volatile coal are to be preferred.

At present, many openable stoves are designed to be fitted to the ubiquitous open fireplace and brick flue, but improvements in both appearance and efficiency have resulted from designing openable stoves as part of the house.

*The Closed Stove.* In addition, there are stoves on the British market which, though not dissimilar in appearance from the openable stove, are intended to be used with the front always shut (see Fig. 39). Very different in appearance is

the continental stove. This is a large cylinder of iron, or a tall beehive of firebrick decorated with glazed pottery, perhaps four feet wide and 5-10 ft high. Its working efficiency has been estimated at 48 per cent. It heats chiefly by convection, and emits only a small proportion of radiant heat. Rooms which are heated by a closed stove are seldom draughty, but tend rather to be inadequately ventilated.

Any fuel may be burnt—wood, lignite, coke or coal—and the stove seldom needs attention more than once or twice per day. The pottery variety may be charged once with fuel, lighted at the bottom, and allowed to burn itself out; it remains hot long after the fuel has been consumed. In the eyes of their owners, continental stoves are anything but ugly, and there is rivalry among housewives to possess the most beautiful and best kept stove—just as British housewives will take a pride in their decorative brick fireplace.

*Central Heating.* A more elaborate method of house warming than any of the methods considered above, central heating is used in all the temperate regions of the world. The aim is to transfer as much heat as possible from the burning fuel either to the air itself or to a circulatory system of water, steam or air; the circulating medium passes through "heat-exchangers" such as radiators or panels, suitably distributed in the building, where its heat is transferred to the air and the fabric of the building. Heat is delivered mainly by convection, and the term "radiator" is misleading. The efficiency of large boilers for central heating is about 45 per cent, and may exceed 60 per cent if the stoking is automatic. Central heating is particularly suitable for large buildings. Hot water for washing is best obtained indirectly by passing the circulating water through a calorifier (a heat exchanger for transferring heat from hot to cold water) as this reduces the risk of solid deposits in the circulatory system. As an example of the saving possible, in winter 1938 the cost of heating and providing hot water for a medium-sized flat in southern England as one of a centrally heated block of flats, was about 7s. per week, whereas the cost of heating and supplying hot water by the ordinary methods was about 13s. per week.

Practically any fuel may be used for central heating. Where oil and gas are cheap, they are the most suitable fuels, because their rate of burning is easily controlled with a thermostat. In parts of America remote from the oilfields, bituminous coal is burned with the help of small automatic stokers. These are usually of the screw-underfeed type, and are driven by electricity, the rate of combustion being thermostatically controlled. Even electricity is used for central heating, but current is taken only at night when the electric generators would otherwise be idle; a large volume of water is heated and stored until daytime, when it is circulated through radiators in the ordinary way. This is called electric storage heating.

The small central-heating boiler suitable for small houses in Britain is not so efficient as the large boiler. When fired by hand it has a working efficiency of about 33 per cent; but this may be increased to 46 per cent by introducing thermostatic control. On the continent, and in North America, domestic central heating has been steadily gaining popularity among the middle classes. It is still relatively uncommon in Britain, except in newly built houses, though gas-fired central heating has made an appearance in Rotherham, where an abundant supply of town's gas has been obtained from coke-ovens.

*District Heating.* The use of a single furnace to heat a large building is now well understood. It is only an extension of this idea if a single furnace is used to heat a number of buildings. Provided that the buildings are not too far apart, hot water or steam can be sent to them along well-insulated pipes at a cost similar to that of other forms of heating. District heating is employed in several countries, and is already used in housing estates in Dundee, Manchester and other places in Britain.

The waste heat from some industries can be used for domestic heating. For instance, at electricity generating stations very large amounts of heat are given up by the condensed steam before it can be pumped back into the boilers. This heat usually ends by warming a river or air drawn through cooling towers, but in residential areas some of it can be used for heating houses. Part of the waste heat



from the giant power station at Battersea is now being used for heating flats in Westminster, across the Thames. A rather similar but highly unusual form of district heating is being developed in Reykjavik, Iceland. Hot water is drawn by pipe line from the hot springs 10 miles away, and delivered to the houses. There is already a saving of about 30000 tons of coal a year.

*Gas Heaters.* In many districts where gas is specially made from coal it costs about  $2\frac{1}{2}$  times as much to heavy consumers as a thermally equivalent amount of coal. Britain is the world's biggest producer of town's gas, and in Britain the commonest appliance which uses gas for house heating is the open gas fire. This has the advantages that it can be fitted into fireplaces which were made for coal, that it heats largely by radiation, and that it provides some degree of ventilation. The efficiency of a gas fire is about 45 per cent. It can be made still higher by recovering waste heat from the flue gases, for example, by introducing a metal flue. High efficiency is also claimed for a new type of gas fire which will fit an ordinary fireplace, in which a simple heat exchanger is incorporated; the waste gases are made to pass through the heat exchanger, where they give up part of their heat to the air of the room.

If the gaseous products of combustion from a gas fire could be allowed to stay in the room, the efficiency is over 80 per cent. (The chief reason why it is not 100 per cent is because water vapour is one of the products of combustion; this does not usually condense into water droplets, so it retains its latent heat of evaporation.) But flueless gas heaters must be used with care, since the products of combustion include sulphur dioxide which may reach harmful concentrations. Although British gas companies are required by law to remove hydrogen sulphide from gas during its manufacture, they are permitted to leave organic sulphur compounds, and 100 cubic feet of gas may contain as much as 30 grains of sulphur in this form. It would probably be safe to heat an adequately ventilated room entirely by flueless gas heaters if the gas contained no more than 5 grains of sulphur per 100 cubic feet. At present, however, it is safe only to use small flueless

gas heaters, except in entrance halls or other places where ventilation is brisk.

*Electric Heaters.* In districts where electricity is made from coal, it costs about 5 times as much to heavy consumers as a thermally equivalent amount of coal. The high cost is offset, however, by the labour-saving nature of electric heaters and their high efficiency. All normal electric heaters are equally efficient, for they convert all the electrical energy they receive into heat. In the estimates, given above, of the working efficiency of other heating appliances, allowance was made for the heat wasted when a room is inadvertently made unnecessarily hot, and when heat is delivered to other parts of a house where it may not be wanted. On this basis, electric fires and radiators have a working efficiency of about 86 per cent, provided that they are placed well away from the fireplace, to prevent excessive volumes of warm air from escaping up the chimney.

Four or five times the efficiencies of normal electric heaters are realizable with electrically driven "heat pumps". These are heat engines driven backwards, and they "recover" heat in the same way as a prime mover "loses" it. Unfortunately they are costly to build and maintain.

*Appliances Combining Several Functions.* There are many open fireplaces in Britain which are designed either to serve two rooms, or to provide hot water, or to supply heat for cooking in addition to their normal duty of house heating. Even with the most careful management, many of these appliances may be uneconomical. For instance, if space heating is ignored, the efficiency of fire-back boilers has been estimated as 7 per cent; and that of old-fashioned kitchen ranges and back-to-back grates is probably about the same.

It is easier to make closed or closeable stoves serve two purposes efficiently, because combustion is under much better control than in an open fire. Some prefabricated bungalows contain stoves which heat almost the whole dwelling and at the same time provide hot water. The tendency for the water to boil, and so waste fuel when requirements of hot water are small, can be avoided if radiators are installed. Central heating systems, too, can obviously be used to supply

hot water as well as heat. There are several designs of heat-storage cooker for burning smokeless solid fuel, from which spare heat is used for water heating. Overall efficiencies of over 75 per cent are claimed for these combined cookers and water heaters, and they have the advantage that both hot water and cooking are needed all the year round.

Many dual-purpose appliances are unsuitable for use in warm weather, and supplementary appliances are needed, for which gas and electricity are usually the most suitable fuels. A high proportion of gas geysers (instantaneous water heaters) and electric immersion heaters are used chiefly in the summer. These and similar appliances are discussed in a later paragraph.

*Domestic Heating in America.* Although winter conditions of temperature, humidity and sunshine are different in Britain from those of the east and middle west of the United States, a study of domestic heating in America reveals the direction in which future progress may be made. The American idea is to heat the whole house, with comparatively low fuel consumption; and to this end the modern house is open in planning, internal doors, if they exist at all, being left open most of the time. There is generally a single heating appliance for the whole house, which is often placed in a non-habitable basement.

The three main types of heating appliance are (a) pipeless systems, such as a single closed stove, centrally placed, (b) ducted systems, in which warm air is led or driven from the central stove to suitable points in the house, and (c) hot-water radiators. Some form of thermostatic control is used in the majority of American houses where the heating system is suitable. Mechanical stokers are relatively common in the larger houses.

There is a widespread appreciation of the value of thermal insulation, specially incorporated in the structure of buildings, from the point of view of increased comfort, in addition to anything it may do to reduce fuel consumption. The standard of ventilation, by which a minimum of fresh air from outside enters the house, is very much less than in Britain, but this is not generally considered a bar to the comfort which the American demands above all else in his home.

### DOMESTIC HEATING AND ATMOSPHERIC POLLUTION

In Table 15 are given some data about ways of heating a living room of ordinary size. Since no two families have identical habits or heat requirements, the figures in the table are necessarily approximate, but they will at least serve to indicate the probable consequences, both in fuel cost and atmospheric pollution, of introducing different heating appliances in the home.

Table 15. *Heating the living room: Fuel used and pollution made*

Method	Effy %	Fuel per week	Fuel cost	Smoke per week	SO <sub>2</sub> per week	Ash per week
Open fire:						
Coal . .	20	2.0 cwt at 5s.	10s.	6.0 lb.	5.4 lb	0.6 lb
Coke . .	22	2.0 cwt at 5s.	10s.	0	5.6* lb	1.1* lb
L. t. coke	22	1.7 cwt at 7s.	11s. 10d.	0	4.7* lb	0.8* lb
Gas (33% flucless) .	57	10 therms at 10½d.	8s. 9d.	small*	0.5* lb	small*
Electricity .	86	200 kWh at ¾d.	12s. 6d.	0	7.4* lb	2.0* lb
Closeable stove . .	33	Coal: 1.2 cwt at 5s.	6s.	3.6 lb.	3.2 lb	0.4 lb
Closed stove . .	48	Anthracite: 0.8 cwt at 6s.	4s. 10d.	0	1.4 lb	0.3 lb
Central Htg:						
Coke . .	60	1.0 cwt at 5s.	5s.	0	2.8* lb	0.5* lb
Gas . . .	60	9.6 therms at 10½d.	8s. 5d.	small*	0.5* lb	small*
Oil . . .	60	5.7 gallons at 1s. 9d.	10s.	0	4.0 lb	0

\* including pollution made during manufacture of fuel.

A high standard of heating is assumed in this table, requiring 580000 effective B.Th.U per week, and the degree of comfort attained is as nearly as possible the same for the different methods. Most of the figures of fuel consumption are calculated from data in "Heating and Ventilation of Dwellings", which has supplied much of the information in this chapter.

The cost of fuel varies considerably in different parts of Britain, but wherever gas and electricity are made from coal, the prices of coal, coke, gas, and electricity should be in roughly the same proportion as in Table 13. From a selection of towns it was found that the prices per B.Th.U of coal,

coke, gas (in quantity), and electricity (in quantity) were approximately in the proportion 2:2:5:10, and the prices in the table are in the same proportion. The prices of anthracite and oil in different localities are not proportional, however, to the price of bituminous coal.

Though fuel is generally the main expense in heating a room, it is not the only one. Other expenses are the cost of the appliance in which the fuel is burnt, the cost of fitting it, and its reduction in value with age; also the cost of the labour of lighting the fire, stoking it, and removing the ash and dust. No attempt has been made in the table to allow for these expenses. Their total cost varies from the equivalent of about 3d. per week for an electric fire to 1s. 0d. per week for closeable fires and central heating.

Since other considerations as well as cost and atmospheric pollution must be taken into account when the system of heating a living room is chosen, it is not possible to make a decision from Table 15 alone, even after modifying it to allow for local prices of fuel. The indications of the table are, however, strongly in favour of closed or closeable stoves in houses, and central heating in blocks of houses and flats where large boilers may be used with advantage.

The quantities of pollution made as a result of each method of heating are given in Table 15, but no allowance has been made for the reduction in ash and sulphur dioxide effected at power stations where flue gases are specially treated for the removal of pollution. It can be deduced that in winter, in districts where on an average one open fire is burning in each house, every group of 380 houses emits about a ton of smoke per week, and nearly as much sulphur dioxide. If the open fires in these houses were replaced by appliances burning smokeless fuel, there would be an immediate saving of a ton of smoke per week; the change in the emission of sulphur dioxide would depend on the type of smokeless fuel used.

### HOT WATER AND COOKING

Incidentally to the discussion of the choice of heating appliances, the main types of cooker and water heater which combine several functions have been mentioned. The appliances

specially for water heating or cooking include a number which may be easily installed after a house is occupied, with the result that the housewife often has a freer choice of water heaters and cookers than of methods of house heating. There have been such rapid developments since 1919 that in most homes a constant supply of hot water, and a self-regulating cooker, are regarded as essential.

Gas may be used in two ways to provide immediate hot water. The *instantaneous water heater* (geyser) burns gas only when the water is turned on, heat being transferred to the water as it runs through a finned or a coiled pipe (see Fig. 40). The *storage water heater* burns gas whenever the water in a tank cools below a specified temperature, and this happens when hot water is drawn from the tank and replaced by cold water. Gas is not burnt as fast as in the instantaneous heater, and after a whole tank full of water is used there is an interval of perhaps 40 minutes before the water is fully hot again. The first newly-heated water, however, collects in the top of the tank, and small quantities of hot water are available after a few

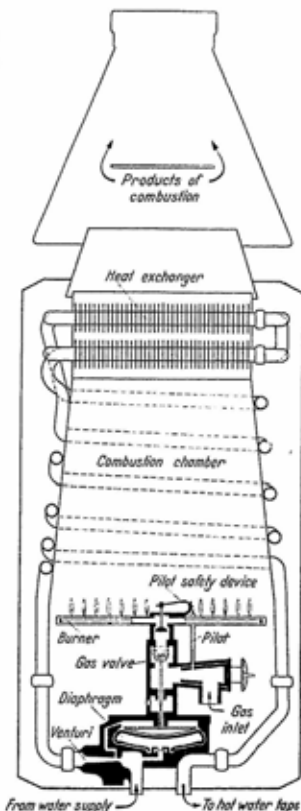


Fig. 40. Instantaneous water-heater  
(Courtesy of Ascot Gas Water Heaters Ltd.).

minutes. Both appliances have a heating efficiency of up to 75 per cent if several gallons of water are required; but they are much less efficient whenever small quantities are used at a time. The average in general use might be about

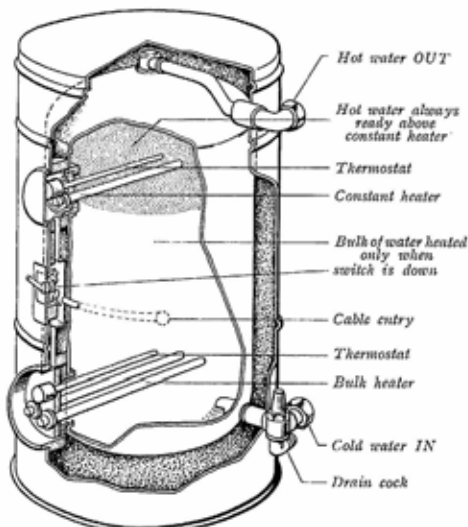


Fig. 41. Storage water-heater (electric) (Courtesy of Heatrac Ltd., Norwich).

50 per cent. For comparison, the efficiency of a gas ring in heating a kettle is about 40 per cent.

Water may be heated by electricity in the same two ways. An electrically heated storage water-heater is illustrated in Fig. 41. The efficiency of the electric appliances is about 98 per cent; i.e. practically all the potential heat of the current is transferred to the water, the only losses being due to the finite resistivity of the wiring. It is often simple to convert a hot-water tank into an electric storage heater by adding an immersion heater, but the tank should be thermally

insulated with a generous layer of lagging if electricity is not to be wasted.

The small independent hot-water boiler, a water-jacketed closed stove burning coke or anthracite, has been increasing in popularity. Its efficiency is about 33 per cent when it is used continuously in an ordinary small household. There

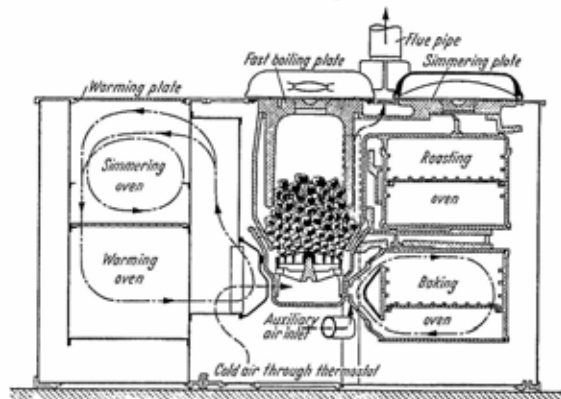


Fig. 42. Heat storage cooker (Courtesy of Aga Heat Ltd.).

is a minimum rate of burning, below which the fire goes out and, if the system is compact and well insulated, there is a tendency for the water to boil, particularly in summer with coke as the fuel. In winter, excessively hot water may be passed through small radiators in the hall or living room, and heat from the stove and its flue pipe may be used for warming the kitchen or scullery.

Gas and electric cookers are too well known to need any description. In the course of trade rivalry between gas and electricity companies, their potentialities have been very well developed, and the coal-fired cooker has lost most of its former prestige. There would be advantages in having an electric oven with gas rings for heating kettles and saucepans, and perhaps an electric grill and toaster. Fig. 42 illustrates



a modern heat-storage cooker, burning smokeless solid fuel. Some of these cookers have hot plates on which a 2 pint kettle can be boiled in two minutes after the overnight banking.

Table 16 contains rough estimates of the quantities and costs involved in different methods of cooking and water heating. The figures of fuel consumption are taken from "Heating and Ventilation of Dwellings" and are calculated from the requirements of a family of four. It is assumed that the hot-water tank and the flow and return pipes are covered with heat-insulating material, and that the consequent saving in fuel is 40 per cent.

Table 16. *Cooking and hot water: fuel used and pollution made*

Method	Fuel per week	Fuel cost	Smoke per week	SO <sub>2</sub> per week	Ash per week
Cooking:					
Coal range .	1.2 cwt at 5s.	6s.†	3.6 lb	3.3 lb	0.4 lb
Heat storage-anthracite .	1.1 cwt at 6s.	6s. 7d.†	0	1.9 lb	0.4 lb
Gas . . . .	1.7 therms at 10½d.	1s. 6d.	small*	0.1 lb*	small*
Electricity .	34 kWh at ¾d.	2s. 1d.	0	1.3 lb*	0.3 lb*
Oil . . . .	1 gallon at 1s. 9d.	1s. 9d.	0	0.7 lb	0
Water Htg:					
Fireback boiler—coal	4.0 cwt at 5s.	20s.†	12.0 lb	10.8 lb	1.2 lb
Independent boiler—coke	0.8 cwt at 5s.	4s.†	small*	1.2 lb*	0.4 lb*
Gas . . . .	4.8 therms at 10½d.	4s. 3d.	small*	0.2 lb*	small*
Electricity .	92 kWh at ¾d.	5s. 9d.	0	2.4 lb*	0.9 lb*

† no allowance has been made for secondary uses of the appliance.

\* including pollution made during manufacture of the fuel.

Two important conclusions are evident in the light of Table 16. By comparison with Table 15 it is seen that a very appreciable part of the household fuel is used for providing hot water, and a smaller part for cooking. Secondly, almost without exception the smokeless fuels are much more economical than coal for cooking and water heating. In the last 30 years the realization of this fact has been growing rapidly in Britain. Between 1919 and 1938 there was an increase of about 4 million in the number of consumers of gas, and of about 10 million in the consumers of electricity, the majority being domestic consumers. Gas cookers in use

in 1948 numbered about 9 million, gas water heaters about 1 million, electric cookers about  $1\frac{1}{2}$  million, and electric water heaters about  $\frac{1}{2}$  million. Except in the colliery districts, cooking by soft coal is no longer favoured, and there is every reason to expect that the smokeless fuels will rapidly come into use for water heating.

*Coal Economy.* If an individual householder wishes to choose a heating appliance, he may use data similar to those given in Tables 15 and 16. But the choice, particularly of the method of room heating, is first made by a builder, an architect, a local authority, or a government department. A question then arises which may be put as follows: What type of domestic heating appliance should be encouraged in the national interest? To answer this question it is important, besides atmospheric pollution, to consider the economic use of coal. The efficiencies given in Table 15 refer to the actual fuel used, whether primary or derived, and those referring to derived fuels would all be lower if coal were considered as the starting point.

The heat lost at gasworks in converting coal into coke and gas at present averages about 27 per cent, i.e. the average efficiency of conversion is 73 per cent, but modern gasworks achieve 80 to 85 per cent. A figure of 80 per cent may be used, for example, if a national plan is being prepared which would entail the building of a number of new gasworks. Low-temperature coke can also be produced with an efficiency of 80 per cent. The efficiency of generation of electricity averages just under 20 per cent, but the newer plants which are rapidly increasing in number achieve about 25 per cent.

On multiplying these efficiencies of conversion by the efficiencies in use of the derived fuel, an important figure is reached which has been termed the coal-economy efficiency. The coal economy efficiencies of the appliances in Table 15 are approximately as follows:

Appliances burning coal or anthracite . . . . .	unaltered
Open fire, burning coke or low-temperature coke . . . . .	18 %
Gas fires (33 per cent flueless) . . . . .	46 %
Electric heaters . . . . .	22 %
Coke or gas in central-heating boilers . . . . .	48 %

The best appliances for the conservation of coal are therefore closed stoves and large central-heating boilers, but there are other important considerations besides the relatively simple one of using the minimum total coal. Although 20 per cent or more of the heat content of coal is lost at gasworks, by-products are made which are now almost indispensable. It can be stated, too, that the coal burnt for the generation of electricity is unsuitable for the extraction of by-products, and much of it would be difficult to burn satisfactorily in domestic or in most industrial appliances.

At present it is not easy to foretell the rate at which the open fire will be replaced by smokeless room-heating appliances. There is now a high proportion of municipal building, and when difficulties of supply have been overcome local authorities will be able to apply considerations which the private builder was liable to disregard. They can make allowance not only for the average occupier's present tastes, but for his possible future tastes in domestic appliances. They are provided with a "list of approved domestic appliances" maintained by the Ministry of Fuel and Power, which is based on tests and specifications including fuel consumption and freedom from incipient defects. It seems likely that there will be a sharp rise in the number of new houses heated by methods which are relatively efficient and smokeless. In existing houses the replacement of open fires by improved appliances is retarded by considerations of availability and cost of the appliance, and the design of the house. When the conversion of open fires in existing houses exceeds a few per cent per year, it can fairly be said that the end of the open fire as the chief British heating appliance will be in sight.

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## Chapter IX

### ATMOSPHERIC POLLUTION

The country dweller entering a large town can usually detect, by the nose, the eye, or the sensation of the skin, a definite deterioration in the quality of the air. The deterioration is more noticeable in some towns than others, and in any particular town it is more noticeable on some days than others; but even when town air is at its best the country air is better still. It is commonly believed that town air is stale by reason of having been breathed by so many people, yet in the most densely populated areas the hourly breath requirements of the people would be satisfied by a layer of air about  $\frac{1}{4}$  inch thick. The only detectable chemical differences between town and county air are differences due to atmospheric pollution.

The composition, by weight, of air is given in Table 17. The density of each component is given in grammes, or milligrammes, per cubic metre. Among the major constituents, water vapour is extremely variable, its amount depending strongly on temperature and relative humidity. The concentrations of the major constituents are expressed as per cent by weight, and the minor constituents in units that are ten thousand times smaller: parts per million.

The average density and concentration of atmospheric pollution are given in the third section of the table, in the same units as for the minor constituents. Although apparently small, these amounts are far from negligible; they may be compared with the smallest densities of odours that can be smelt—e.g. mercaptan,  $4 \times 10^{-6}$  mg/m<sup>3</sup>; skatol,  $4 \times 10^{-7}$  mg/m<sup>3</sup>; vanillin,  $2 \times 10^{-7}$  mg/m<sup>3</sup>.

As a rough indication of the toxicity to human beings of some of the more dangerous components of atmospheric pollution, the maximum concentration allowable for prolonged exposure are given in section (iii) of Table 17. The

Table 17. *Approximate Constitution of the Atmosphere at 10° C and normal pressure*

(i) Major Constituents			(ii) Minor Constituents		
	g/m <sup>3</sup>	Per cent (by weight)		mg/m <sup>3</sup>	ppm (by weight)
Air . . . . .	1172	100	Neon . . . . .	14	12
Nitrogen . . . .	879	75	Krypton . . . .	4	3
Oxygen . . . . .	269	23	Helium . . . . .	0.8	0.7
Argon . . . . .	15	1.26	Xenon . . . . .	0.5	0.4
Water vapour . .	8	0.70	Hydrogen . . . .	0.05	0.04
Carbon dioxide .	0.5	0.04			

## (iii) Impurities

	Maximum concentration allowable for prolonged exposure mg/cm <sup>3</sup>	On a hazy winter day		In Summer	
		Town mg/m <sup>3</sup>	Country mg/m <sup>3</sup>	Town mg/m <sup>3</sup>	Country mg/m <sup>3</sup>
Sulphur dioxide . .	26	1.2	0.15	0.2	0.03
Combustible solid and liquid particles . .		1.0	0.24	0.2	0.05
Incombustible solids		0.2			
Carbon monoxide . .	120	10.0		2.0	
Sulphur trioxide . .	3	0.01*		0.001*	
Ammonia . . . . .	60		0.01*		
Hydrogen chloride . .	15				
Hydrogen fluoride . .	2				
Hydrogen sulphide . .	28				

\* Orders of magnitude only. (From A. R. MERTHAM and A. C. MONKHOUSE, "Atmospheric Pollution and the Chemist", *The Industrial Chemist*, July 1947, with figures of maximum allowable concentration added from HENDERSON and HAGGARD, "Noxious Gases".)

highest amounts ever likely to be encountered at street level in British towns are about five times the concentrations given in the table for a hazy winter day. Although dangerous concentrations are therefore most unlikely to occur in normal street air there is presumably a very slight risk that some abnormality of weather may arise in which the concentration of sulphur dioxide, carbon monoxide, or possibly sulphur trioxide may reach the danger level. The information in section (iii) is unfortunately incomplete, and there are substances, such as hydrochloric acid, hydrogen sulphide, and

fluorine compounds, which are known to be emitted to the atmosphere but whose concentration in the air is unknown.

Nearly all the atmospheric pollution in Britain is made by the burning of coal and coke, although there are contributions from fuel handling, oil and petrol burning, chemical processes, and natural sources. From the 180 million tons of coal used each year is made some 9 million tons of atmospheric pollution, excluding carbon monoxide. Table 18 shows a rough estimate, based mainly on data given in "Heating and Ventilation of Dwellings" (1945), of how much pollution is produced by three classes of coal user. Pollution emitted both during the burning and manufacture of gas, coke, and electricity is included in the table according to the way in which the manufactured fuel is burnt; thus, much of the coal entering gas and electricity works is regarded as coal used domestically.

Table 18. *Pollution Emitted from Coal in Great Britain, million tons per year*

	Coal used	Smoke	Ash	Sulphur dioxide	HCl and other chlorides
Domestic purposes:					
fires . . . . . 45	65	1.2	0.2	1.5	0.1
gas and electricity 20					
Industrial boilers . . . .	65	0.9	0.3	2.1	0.2
Other industrial uses . .	50	0.3	0.1	1.6	0.2
Total	180	2.4	0.6	5.2	0.5

The figures cannot be at all accurate, and those for ash seem likely to be low, but the table accords with what would be expected from a consideration of the fires and the fuel used. From coal used for domestic purposes, including 42 million tons burnt in open grates, there is a lot of smoke and relatively little ash. From industrial boilers on an average there is rather less smoke and more ash. From coal put to other industrial uses there is less smoke and ash, because about half the coal used in these sections of industry is converted to gas and coke before being burnt. It will be noted that the emission of sulphur dioxide is roughly in proportion to the coal used by each class of consumer.

## SMOKE

Before going at all deeply into detail about atmospheric pollution, it is essential to have a clear understanding of the differences between smoke, ash, sulphur dioxide and other important forms of pollution. Smoke is the term normally applied to the visible products of imperfect combustion. The smoke trail from a chimney may be long or short, but ultimately the smoke becomes so well mixed with air that it ceases to be visible, except possibly as a bluish haze which obscures distant objects. After such attenuation smoke remains, however, a potential cause of dirt and damage, and it can still be measured with the help of instruments. In this book it is still called smoke when it has become diluted by so much air that it is invisible.

Coal smoke contains a high proportion of carbon, and when viewed in bulk it is nearly black. It also contains tarry hydrocarbons, which add to its sticking powers and its tendency to form sooty deposits in chimneys and elsewhere.

Smoke has the important property that, because of the small size of its particles, it behaves in many ways like a gas and has the same powers of penetration. The average diameter of a smoke particle is shown in Chapter X to be about 0.075 micron, or 3 millionths of an inch. This is too small to be seen in the best microscope, and smoke particles have only recently been photographed with the help of an instrument of very high resolving power, the electron microscope. From STOKES' Law of the flow of fluids past spherical objects, it can be shown that all particles smaller than about 10 microns are easily supported by the bombardment of air molecules. They do not fall to the ground by their weight, but are swept this way and that by every current of air. So, when air enters a house through windows, ventilating bricks, or even through cracks round the doors, smoke enters too; and some is deposited as dirt on walls and ceilings, curtains and furniture. Air molecules are continuously bombarding the walls and other surfaces; so are the smoke particles, but while the gas molecules bounce off, the smoke particles tend to stick and make the surface dirty.

Smoke also sticks to the outside walls of buildings, for rain will not wash it away, unless the stone is slightly soluble or very smooth. Although on one or two particular buildings small deposits of smoke have been considered rather attractive, smoke is responsible for the dingy appearance of very many urban buildings. A striking effect occurs on smooth walls of white limestone; in places under projections which protect them partially from the rain, the smoke sticks and produces a half-washed appearance (see Fig. 77).

Quite obviously, smoke does not remain permanently in the atmosphere, and the average time for which a smoke particle remains in suspension has been estimated as one to two days; and a considerable proportion of Britain's smoke is probably blown to sea. It has been suggested that many of the particles deposited on land are caught near the edges of objects such as blades of grass and the leaves and twigs of trees, where small eddies of wind may occur. Electrostatic attraction may also play a part in the process.

Smoke is not the only form of atmospheric pollution which consists of extremely small particles, though it is the most abundant. Some of the ash particles which escape from chimneys are so finely divided that they, too, remain suspended in the air. In dry windy weather, fine dust may be blown up from the ground, and also drops of sea spray will evaporate, leaving minute particles of salt which may be blown far inland. But on analysis the suspended matter in town air has been shown to be about 85 per cent smoke, and only 15 per cent ash. It is often convenient, as will be evident in later chapters of this book, to think of suspended matter in the air as being synonymous with smoke.

### ASH

Ash is the unburnable solid material that is set free when a fuel is burnt. The sparks, which fly upward from a fire, are red-hot particles of ash. In a fire or furnace where the fuel is coal or coke much of the ash falls through the fire grate into the ash pit, but an appreciable proportion escapes with the flue gases. Coal contains from two to ten per cent or more of mineral matter, but only a fraction of this is



released in a finely divided state when the coal is burnt on a grate, and the ash which is small and light enough to be carried up the flue represents, on a very general average, about 0.3 per cent of the coal. If the coal is finely ground and bunt as pulverized fuel, however, most of the ash passes into the flues.

Assuming there is no grit arrestor, the maximum size of particles carried up any particular flue depends on the velocity of the flue gases or, more strictly, on the velocity at the point in the flue-system where flow is slowest. Industrial flue gases have velocities up to about 40 ft per second, fast enough to carry up particles as large as a tenth of an inch (0.2 cm, or 2000 microns) in diameter. Hence the streets and houses near industrial chimneys are liable to be sprayed with particles of all sizes up to a tenth of an inch, the largest of which are falling at a speed of 40 ft per second. Most industrial chimneys are less than 200 ft high, so, in the absence of freak wind currents, the largest particles of ash remain in the air for less than five seconds. Because of their short time in the air, large particles of ash do not form a substantial part of the "suspended impurity" in the air, but they do contribute appreciably to the pollution deposited on the ground.

In the chimneys of open fires, the flue gases seldom have a velocity exceeding five feet per second, and the particles escaping are all less than about three thousandths of an inch (75 microns) in diameter. All larger particles remain in the grate or the ash pit, and this is why only a relatively small amount of ash is emitted in the domestic use of coal. According to Table 18, over half a million tons of ash particles are emitted each year from British chimneys; and it is likely that this figure should be increased to conform more nearly with the 1.5 million tons which, it is estimated, are deposited each year. Only about one-fifth of the atmospheric ash comes from domestic chimneys; the remainder, including nearly all the largest and most unpleasant of the particles, comes from a variety of industrial sources.

*Other particles* besides true ash may become a nuisance. Small particles of coal or coke may escape from the combus-

tion zone of a fire and pass up the chimney. From certain installations where pulverized coal is burned as much as half the grit emitted is combustible matter, and the particles recovered from the flues and electrostatic precipitators constitute a fuel of considerable calorific value, although its practical uses are limited.

The amount of grit blown from ash heaps and coal dumps depends very much upon the wind, the sizes of particles present, and the dampness of the heaps. Clouds of particles may also be set free when coal, ash, or other materials are being loaded or unloaded. As a general rule, however, grit from sources such as these is not a large contribution to the pollution of a town, though it may be a nuisance within a few hundred feet of its place of origin.

In Europe, where sandstorms are rare, the amount of natural dust raised by the wind is generally small, and in cities only quite a small fraction of the deposited matter is of natural origin. Even in a rural situation near Godalming, where a field was ploughed up and a series of crops raised on light sandy soil, less than half the insoluble matter entering a deposit gauge, whose collecting bowl was four feet six inches above the soil, was found to be due to wind-blown dust.

### SULPHUR DIOXIDE

Sulphur dioxide is formed in considerable quantity when coal, coke or certain fuel oils are burnt, and to a lesser degree when purified gas or petroleum is burnt. Though it is not so chemically active as the sulphur trioxide, hydrochloric acid, and fluorine compounds which are also liberated during the combustion of coal, it is emitted in much greater quantity and is thus capable of doing more harm.

The average sulphur content of British coal, and also coke, is about 1.5 per cent, with extreme values of about 0.9 and 4.0 per cent. When the fuel is burnt, only a small amount of the sulphur remains with the ashes, and the rest is released as sulphur dioxide in the flue gases. Of this a small amount is usually retained in the flues and the rest is emitted to the atmosphere.

From a consideration of atomic weights, it is seen that a molecule of sulphur dioxide weighs twice as much as an atom of sulphur. So for each ton of sulphur in the fuel there are nearly two tons of sulphur dioxide in the flue gases, and it is estimated that an average of nearly 3 tons of sulphur dioxide is emitted from every hundred tons of coal or coke burnt. Over five million tons of sulphur dioxide are emitted each year from chimneys in Britain, about a quarter being from domestic chimneys.

Sulphur dioxide is a gas, with a choking smell. It is easily smelt in the flue gases from coke fires and gas fires, but its smell is often obscured by smoke in the flue gases from coal fires. In the open air of industrial towns, sulphur dioxide frequently reaches high enough concentrations to be faintly smelt. Like smoke, sulphur dioxide penetrates indoors, where it tarnishes metals and makes fabrics tender and easily torn after washing.

Sulphur dioxide is soluble in water, and it is particularly liable to attack paint, metals, stone work, and slates when water is present. When rain water wets the surfaces and interstices of a building, and sulphur dioxide is present in the air, a very dilute solution of sulphur dioxide is formed which becomes more concentrated later as the water begins to evaporate. Further, in the presence of air this solution is soon oxidized to form sulphuric acid which is a very reactive substance. It appears probable that the corrosive action of sulphur dioxide is chiefly due to the formation of sulphuric acid.

Some sulphur dioxide is removed from the air by solution in cloud droplets, falling rain, and in surface water, but less than one-fifth of the sulphur dioxide emitted to the atmosphere is brought down with rain. A similar quantity escapes from Britain by being blown to sea. It is thought that much of the remainder is dissolved in the water on buildings, soil and vegetation, both after rain and at other times. The average time during which sulphur dioxide remains in the air has been estimated as less than 12 hours.

*Other Pollution from the Combustion of Fuels.* Concentrations of carbon monoxide from 10 mg/m<sup>3</sup> upwards have been observed near busy crossroads, and in vehicular tunnels; con-

centrations of 120 mg/m<sup>3</sup> or more are considered dangerous. Most of it is due to the incomplete combustion of petrol and oil in internal combustion engines. Although the incomplete combustion of coal and coke also produces carbon monoxide, it is doubtful whether enough of this could reach street level to be a danger to health.

Among its numerous mineral constituents, coal contains up to 0.7 per cent of chlorine and up to 0.01 per cent of fluorine. When the coal is burnt, both these elements probably escape to the atmosphere in the gaseous forms HCl (hydrochloric acid), HF (hydrogen fluoride) and SiF<sub>4</sub> (silicon tetrafluoride). All these compounds, particularly those containing fluorine, can do harm to men, animals, and materials, but it is doubtful whether dangerously high concentrations would be reached at street level as a result of chimney emissions from the burning of coal.

#### POLLUTION FROM OTHER SOURCES

*Gases from Chemical Works.* In the very early days of the Alkali Industry, sodium carbonate was made by the Leblanc process, involving the strong heating of a mixture of sodium chloride and sulphuric acid; and the hydrochloric acid gases were allowed to escape into the atmosphere. The damage to vegetation and property was so great that the hydrochloric acid had to be recovered by solution in water, in coke-packed towers down which water was sprayed. The solution of hydrochloric acid was soon found to be commercially useful, and an important by-product industry developed. To ensure the adequate removal of hydrochloric acid the first Alkali etc. Works Regulation Act was passed in 1863, specifying a condensation of 95%, and an additional Act in 1874 limited the escape to one-fifth of a grain of muriatic acid (hydrochloric acid) per cubic foot of flue gas. Without the incentive of this Act it is possible that through less thorough methods of recovering hydrochloric acid there might be a threat to public health. In its present form the Act protects the public against all harmful substances liable to be emitted from industrial sources other than from fuel burning (see Chapter XV).

Among other gases from chemical works which cause atmospheric pollution are oxides of sulphur, sulphuretted hydrogen, carbon bisulphide, nitrogen oxides, chlorine and hydrogen fluoride. Concentrations and other conditions are so different that not only each polluting gas but each process has had to be considered individually, as concentrations and conditions vary, in order to develop a satisfactory method of reducing the polluting gas and, if possible, producing a useful product.

Sulphur dioxide is emitted, for instance, from the roasting of sulphide ores. It may be recovered and converted into sulphuric acid by the contact process. On the other hand, from the large-scale manufacture of sulphuric acid, emissions of sulphur dioxide and sulphur trioxide can best be reduced by scrubbers of high efficiency.

Sulphuretted hydrogen is evolved in numerous processes, such as the carbonization of coal, the distillation of tar and ammonia liquor, the distillation of petroleum, and the manufacture of artificial silk and paper by the viscose process. This poisonous gas can be recovered by absorption by iron oxide placed in layers in large boxes or "purifiers". The iron sulphide collected in this way by the carbonization industries is used for the production of sulphuric acid, yielding annually in Great Britain some 270 000 tons of acid out of a total of 1 800 000 tons.

Carbon bisulphide in the vapours from certain waterproofing processes can be absorbed by active carbon, and subsequently recovered by steaming the carbon. In low concentrations both sulphuretted hydrogen and carbon bisulphide are difficult to absorb, and recovery processes become impracticable if large volumes of gases are to be treated. In such cases the only practical safeguard may be by combustion, forming sulphur dioxide which, though harmful, is less noxious than either sulphuretted hydrogen or carbon bisulphide.

Oxides of nitrogen, which are liberated in many nitrogen processes, and the chamber sulphuric acid process, are dangerous gases. They are most effectively absorbed by first

oxidizing the nitric oxide to nitrogen peroxide and then scrubbing the gases in towers irrigated with water.

Escapes of chlorine are usually only accidental as the gas is readily absorbed either in soda solution or milk of lime. Emissions of fluorine and its compounds from superphosphate works and hydrofluoric acid works are adequately controlled in Great Britain by the provisions of the Alkali etc. Works Regulation Act. Recently there have been emissions of fluorine from factories manufacturing aluminium, near which concentrations of 0.02 to 0.1 mg of fluorine per cubic metre were measured. Fluorine compounds are also emitted, in small amounts, at brickworks and pottery kilns, and from the calcination of ironstones, if fluorine is a constituent of the raw materials used.

Although on a first consideration the gases liable to be emitted from chemical works are very alarming, there are two redeeming features. First, most gases which have a rapid chemical action in the human being also react rapidly with water or other substances, and so they are usually easy to remove from the effluent gases. Second, reactive chemicals are nearly always useful, and there is an incentive to the manufacturer to recover them. Thus the pollution of the atmosphere by chemical works, although it remains a serious problem, is not so great an evil as might have been expected.

*The Offensive Trades.* This is the title given in the Public Health Act, 1936, to trades concerned with the sterilization and drying of animal, fish and vegetable refuse to produce valuable feeding stuffs. The gases evolved have a very objectionable smell, as they contain aliphatic amines and sulphuretted hydrogen. They may either be passed with the air of combustion through a furnace, where they are completely oxidized by burning, or they may be treated with chlorine or hypochlorite.

*Particles.* In industry there is the risk of polluting the air, not only by gases, but by solids. Examples are blast furnaces, cement kilns, smelting works, and coke ovens. Solids are removed by devices similar to those adopted for the removal of solids in the combustion of coal. The most common are

the cyclone, the wet washer, and the electrostatic precipitator. The last is particularly useful for recovering valuable metallic dusts.

In this book no attempt is made to discuss what is described as the industrial dust hazard. Nearly all cases of pneumoconiosis, including asbestosis, silicosis in coal mines and other industries, and byssinosis in the cotton and flax industries, occur as a result of breathing dust indoors or in confined spaces. The simplest way of avoiding a dusty atmosphere is often by drawing the dust, with ventilating hoods, away from the place where it is generated. The dusty air from the ventilating hoods may be filtered and recirculated, to conserve the warmth which it possesses, although this procedure is risky, since few filters completely remove those particles, smaller than one or two microns, which do most damage to the lungs. It is generally safest to emit the dust into the open air, where it is usually so rapidly diluted that little harm is done. Complaints of harm or discomfort from the dust emitted to atmosphere from ventilating systems are rare.

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## Chapter X

# MEASUREMENT OF ATMOSPHERIC POLLUTION

Potential atmospheric pollution can be traced and studied with considerable accuracy while near the fuel bed and on its way up the chimney, but when it emerges from the top of a chimney its individuality begins to be lost and it rapidly becomes unidentifiable among the pollution from other chimneys and other districts. For this reason accurate experiments with pollution in the open air can only be made with great difficulty. Nearly all that is known of open-air pollution is the result of observation and measurement, taking conditions as they are, rather than of experiments in which pollution is specially produced (though O. G. SUTTON has recently published mathematical discussions of a series of experiments on a limited scale).

For the scientific study of pollution on a full scale the same general methods are used as in studying weather. Systematic observations are made at selected places, over many years, and the accumulating data are examined month by month and year by year. Since 1914 a large number of measurements of atmospheric pollution have been made in Great Britain, mostly by local authorities, government departments, and firms. Many of the results have been published annually by the Stationery Office, on behalf first of the Air Ministry and later of the Department of Scientific and Industrial Research, where the tasks were undertaken of co-ordinating and collating observations, as well as of devising methods of measurement and investigating the properties of atmospheric pollution.

In two important respects, atmospheric pollution is different from weather and climate. The climate of any particular place changes only very slowly, but the atmospheric pollution may alter considerably within a few years; observations of



pollution are particularly important where industrial or residential development is taking place, or where special efforts are being made to improve the purity of the air. Secondly, the amount of pollution is often quite different in adjacent districts, whereas the rainfall, barometric pressure, temperature and other aspects of weather are often nearly the same over large areas. It is therefore important to study the distribution of pollution, i.e. its variation from district to district. A survey of atmospheric pollution in Leicester was made in 1937-39. Since then a number of smaller surveys have been made in other localities to deal with particular aspects of pollution.

The three principal types of open-air pollution are smoke, deposited matter, and sulphur dioxide. Where they constitute a nuisance they can often be seen or smelt, and simple observations can be made without instruments. For the purposes of records and comparison of observations, however, standard methods of measurement are necessary, and it is now general practice in the British Isles to adopt the methods recommended by the Atmospheric Pollution Research Committee of the Fuel Research Board of the Department of Scientific and Industrial Research. The general aim of the Committee has been to devise methods which are simple and labour-saving. From most points of view it is preferable to have a large number of approximate measurements of pollution rather than a few extremely accurate ones. Indeed, pollution varies so much with time and place that great accuracy would be needed only if an extremely large number of observations was being made.

#### MEASUREMENT OF SMOKE

In Chapter XV a short account is given of the part played by local authorities in smoke abatement. One of the duties of the smoke inspector or the sanitary inspector responsible for matters relating to atmospheric pollution is the taking of "smoke observations". The inspector observes any particular chimney from a suitable direction and distance for a definite period, usually half an hour. He makes a note of the periods when, in his opinion, the chimney emits smoke,

soot, ash or gritty particles in such quantity as to be a nuisance. In some districts a bye-law provides that if "black" smoke is emitted for two minutes in the aggregate, within any continuous period of 30 minutes, there shall be presumption of a nuisance. In some districts the permissible period is extended to three minutes.

Observations such as the above are of great practical value in enabling local authorities to limit the emission of smoke, but they hardly deserve to be described as measurements. Attempts have frequently been made to assist the eye and judgment of the observer by instruments and scales. The Owens Smoke Meter, for example, is a spinning sector wheel whose open fraction can be varied until the sky, when seen through it, matches the smoke. Ringelmann Charts are a set of white paper sheets criss-crossed by black lines of differing thickness; when held at a distance the black and white merges into shades of grey which can be matched with smoke.

Unfortunately none of these, not even instruments incorporating photoelectric cells, can be said to have succeeded in sufficiently raising the standard of measurement of smoke at the chimney top. For want of a more exact unit, engineers refer to the Ringelmann number of smoke emissions, but unless instruments are installed within the chimney stack itself (as, for example, in Fig. 24) truly quantitative measurements seem to be out of the question.

The general concentration of smoke in the air, as distinct from the weight of smoke emitted from any particular chimney, can be measured in a number of ways. If air is drawn through filter paper, practically all its solid matter is removed and remains embedded in the filter paper, mostly near the surface. After about 50 cubic feet of air have been drawn through a circle of white filter paper one inch in diameter (or 250 litres of air through a circle 1 cm in diameter), the solid matter on the paper is usually visible as a grey stain, sometimes tinged with brown. In a country district in summer the stain is usually rather faint, but in a town, on a still day in winter, it may be nearly black.

The material collected in this way consists mainly of small particles, because large particles fall out of the air in a relatively short time and have little chance to be drawn into the apparatus. The material may be roughly analysed by finding the proportions which are combustible (like smoke and soot) or soluble in carbon bisulphide (like the tarry hydrocarbons). In samples taken at Leicester during October 1938 about 85 per cent was combustible, including 14 per cent which was soluble in carbon bisulphide. The high proportion of carbonaceous matter explains why the darkest filter stains are nearly black rather than a pale grey or brown, and is the justification for regarding the material collected by filter paper as representing the smoke in the air. Much of the knowledge which has so far been accumulated about atmospheric smoke has been deduced from measurements of "smoke" stains. It would have been a far harder task to obtain the same knowledge by the more laborious method of analysis.

The amount of matter on a very dark smoke stain can be weighed on a sensitive chemical balance, but the technical difficulties of weighing are considerable. It has been found that the degree of blackness (i.e. the reduction in optical reflection coefficient) corresponds reasonably well with the weight of matter which has been collected; and for many purposes it is convenient to estimate the weight by comparing the stained filter paper with a standard set of shades, each of which corresponds under average conditions to a known weight of the material.

For readings of greater accuracy, the optical reflection coefficient of the stained filter paper may be measured with a photoelectric cell. Perfectly clean filter paper, of the variety normally used, has a reflection coefficient of 85 per cent. For small weights of smoke, the weight is directly proportional to the amount by which the reflection coefficient falls short of 85 per cent. When greater weights of smoke are collected, successive increments of smoke make less and less difference to the reflection coefficient.

For measuring the concentration of smoke in the open air filter paper is used in three of the four methods now to be described.

*Smoke filter.* The standard apparatus for measuring the daily average concentration of smoke is illustrated in Fig. 43. (It is shown combined with a bubbler for the volumetric estimation of sulphur dioxide, to be described later.) Air is drawn continuously through a filter paper, by a small suction pump which is operated by water-pressure or electricity. The filter paper is changed daily, and the area on

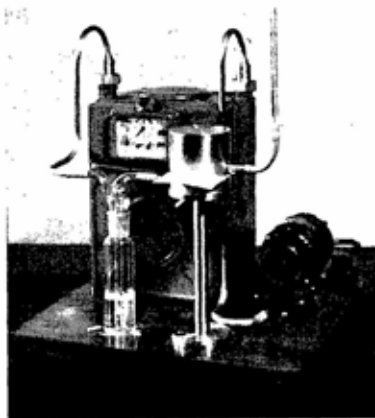


Fig. 43. Smoke filter, sulphur dioxide bubbler, gas meter and pump.

which the smoke is collected is a circle of diameter  $\frac{1}{2}$ , 1, or 2 in., according to the situation, time of year, and volume of air sampled each day. The volume of air is measured with an ordinary gas meter, placed between the filter and the pump. The main apparatus is under cover, usually inside a room, but the air which is being tested is drawn from out of doors through a glass tube which projects about three feet from the wall of the building and terminates in a small inverted funnel, to keep out quickly-falling particles and drops of rain. Little smoke is lost by deposition in the tube, provided that the flow of air is non-turbulent.

Normally there is a large diurnal variation of smoke in the atmosphere, with perhaps five times as high a concentration around 6-9 a.m. as at 1-5 a.m. The smoke filter, if used in the manner described above, will determine only the daily average concentration and it is important that the period of exposure should cover one complete cycle; i.e. the filter paper should be changed at the same time each day. Generally 12 noon is a convenient time. If the instrument is installed in a building which is closed on Sundays, it may be allowed to run for 48 hours at the week-end. The alteration in the amount of smoke from week-days to week-ends is a pointer to the origin of the smoke.

For determining the average concentration of smoke collected by a filter, the stain is matched with a standard set of shades. The only standard set of shades at present available is one which has been calibrated on the assumption that each smoke stain is 0.32 cm ( $\frac{1}{8}$  in.) in diameter and has been produced by the smoke in two litres of air. The instruction is given that the "shade number", which ranges from 1-20, should be multiplied by 0.32 to convert to concentration of smoke in milligrammes per cubic metre. In view of the different diameter of the smoke stains obtained with the standard filter, and the measurement of air in cubic feet, the conversion formula is rather more complicated, the concentration of smoke in milligrammes per cubic metre is given by

$\frac{5.78 \times \text{shade number}}{\text{cu. ft of air}}$	if the smoke stain is 2" in diameter
$\frac{1.445 \times \text{shade number}}{\text{cu. ft of air}}$	if the smoke stain is 1" in diameter
$\frac{0.361 \times \text{shade number}}{\text{cu. ft of air}}$	if the smoke stain is $\frac{1}{8}$ " in diameter

Readings are usually expressed to the nearest hundredth of a milligramme per cubic metre or, to avoid decimals, results can be given in milligrammes per hundred cubic metres.

Once the smoke filter has been installed, regular daily readings may be taken with the expenditure of less than five minutes per day. Although the results are of considerable

usefulness and interest, too great an accuracy should not be claimed for them. Errors may be caused (1) by inaccuracy of the gas meter, particularly as it is working at a slight under-pressure, (2) in matching a smoke stain with the standard scale of shades, (3) by applying the calibration of



Fig. 44. Automatic filter (Courtesy of C. F. Casella & Co. Ltd.).

the scale of shades, which was made in London in winter, to other atmospheres. As a general rule, it would be unsafe to attribute an accuracy within 15 per cent to any single determination of the concentration of smoke in the air, unless special precautions were taken. The ratio of two determinations taken in similar circumstances could probably be relied on to within about 5 per cent, provided that each determination involved the measurement of ten or more smoke stains.

*Automatic Filter.* Though it requires attention only once daily, this instrument provides an hourly record of the

concentration of smoke, and is particularly useful for studying the daily cycle. It was designed by Dr. J. S. OWENS in 1918, and it has been widely used ever since. The instrument is illustrated in Fig. 44, and Fig. 45 is a simplified diagram showing its details of operation. It usually placed indoors,

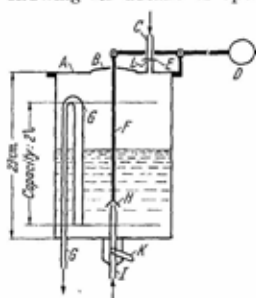


Fig. 45. Automatic filter. *A* Tank; *B* Leather diaphragm; *C* Air inlet tube (Air in during syphoning); *D* Counter-poise; *E* Filter paper. Rotated by clock during filling. Clamped at *L* during syphoning; *F* Central rod (Up during filling, down during syphoning); *G* Syphon (water outlet). Water out during syphoning; *H* Water valve. Open during filling, closed during syphoning; *I* Water inlet pipe. Water in during filling; *K* Control valve; *L* Tube clamp. Gap between two tubes during filling, closed during syphoning.

and air is brought to the inlet tube *C* by an arrangement similar to that of the smoke filter. The instrument is connected at *I* by a metal pipe to a water supply, and suitable provision is made for the outgoing water from *G* to be drained away. For effective operation, the outlet pipe *G* is connected by a short length of rubber tubing to a glass tube, about a foot long, which is allowed to hang freely in a vertical position.

The tank *A* is repeatedly filled with water and emptied again, the syphon *G* being of a self-operating type, and the whole mechanism is governed by the filling and emptying. During syphoning, two litres of air is drawn through the

filter paper *E* on which it leaves a smoke stain 0.32 cm (1/8 in.) in diameter. During filling, the filter paper is moved to a new position by an arrangement of a clock and weight, which is not shown in the diagram. The filter paper is circular, diameter 18 cm (7 in.), and the hours 0 to 23 are printed near the edge; the smoke stains are produced within 1 cm of the edge of the paper, as may be seen in Fig. 46.

The weight of smoke in each stain is found by visual comparison with a standard scale of shades. The "shade number" is multiplied by 0.32 to convert it to an estimate of smoke concentration in milligrammes per cubic metre of air.

In districts such as Kew and Teddington, which are relatively free from smoke, there is frequently insufficient smoke in two litres of air to make a readable stain. The automatic filter may easily be modified to draw three to five times as

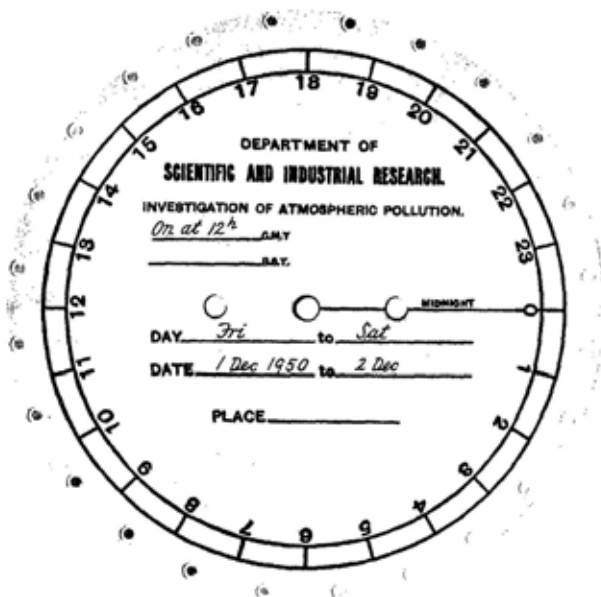


Fig. 46. Typical automatic filter chart (diameter 18 cm).

much air at each syphoning: a scaled tank, of suitable diameter, is placed at the same level as the tank *A*, and connected to it by pipes at the top and bottom. The conversion factor is then  $\frac{0.32 \times 2}{V}$ , where *V* is the volume syphoned, in litres.

*Portable Smoke Filter.* It is possible to measure the concentration of smoke at any particular place in 5–10 minutes. With a suitable pump, two or more litres of air are drawn



through filter paper, leaving a smoke stain 0.32 cm ( $\frac{1}{8}$  in.) in diameter. The pump may be operated by hand, by foot, or by electric motor driven from a car battery. The volume of air may be measured with a gas meter, or in the case of a hand or foot pump, the volume pumped at each stroke may be measured in a separate test.

Portable filters are useful for measuring the distribution of smoke in a town or district. To avoid the more rapid

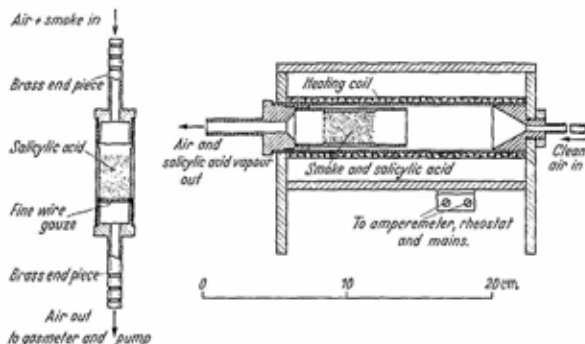


Fig. 47. Salicylic acid filter and furnace.

changes of the daily cycle of smoke, measurements should be made in the afternoon. A series of points, from half to one mile apart in the area to be surveyed, is chosen. A smoke stain is taken at each point in turn, and then a second series of stains in the reverse order. The average of the readings of the two smoke stains at each point is then practically independent of any general increase or decrease of pollution during the period of the observations. Results may be conveniently presented on a map, showing contour lines of equal smoke concentration (see Fig. 68).

*Weighable Smoke Filter.* It is usually necessary to draw air through a filter for several days at least, before a quantity of smoke suitable for weighing can be obtained. Filter paper has been used, but only with difficulty, because it tends to

become choked, and because it retains a quantity of moisture, often weighing much more than the smoke, which varies according to the humidity of the air. Asbestos fibre is superior to paper as it is not hygroscopic, and it can be readily made into a filter pad through which only a very small proportion of smoke particles can pass.

An alternative method, which may prove most useful, is to make a filter pad of a fine volatile powder such as 99.99 per cent pure salicylic acid. After smoke has been collected from, say, 2500 cubic feet of air, the mixture of salicylic acid and smoke is transferred to a small electric furnace, through which filtered air at a temperature of  $110^{\circ}\text{C}$  is gently blown (see Fig. 47). The salicylic acid gradually distils away, and disappears in twenty-four to forty-eight hours, leaving the smoke free from any filtering material, apart from the 0.01 per cent of impurity whose weight can usually be neglected. It is unlikely that much of the weight of smoke is lost from the distillation of tars which are volatile below  $110^{\circ}\text{C}$ . The smoke, which amounts to 1–20 milligrammes per thousand cubic feet of air, is weighed on a sensitive balance.

#### MEASUREMENT OF ASH AND OTHER DEPOSITED POLLUTION

If a sheet of glass, covered with a thin film of vaseline, is exposed in the open for an hour or less in an industrial district, it will collect a number of particles of grit. The sample may be preserved by placing a second sheet of glass over it and binding the two together at the edges. Grit samples collected by this or a similar technique are useful visual records of a kind of pollution that often gives cause for public complaint. They do not as a rule provide satisfactory numerical records since, although the particles above a certain size may be counted, the total weight of particles cannot be estimated, because of the difficulty of separating them from the vaseline.

To collect a weighable amount of deposited matter it is necessary to expose the collecting vessel for 24 or 48 hours during dry weather. Such a technique is described later in the chapter, for making rapid surveys of deposited solid

matter. If it is necessary to collect the material deposited during rain, the vessel should be exposed in the open for about a month; there will then usually be sufficient material for a satisfactory analysis to be made.

*Deposit Gauge.* In 1912 a number of Local Authorities in Britain agreed to unify their procedure in measuring deposited

atmospheric pollution. The deposit gauge which they adopted has been reduced a little in size, and undergone other slight modifications, but remains in essentials the same. It is illustrated in Fig. 48. For best results, the position of the deposit gauge must be chosen to represent the surrounding districts as fairly as possible. Buildings and trees create upward and downward currents of wind, causing abnormal deposits, so they should be at least twice their height from the deposit gauge.

The solid and liquid material, including rain, which falls within the 12-inch diameter circle of the glass collecting bowl, passes down the connecting pipe, of rubber and stainless steel, into the glass bottle.



Fig. 48. Deposit gauge (height overall, 1.5 metres).

Material which falls on the outside of the collecting bowl and on the galvanized iron stand is prevented from entering the bottle by the inverted stainless-steel funnel. The galvanized wire screen gives some protection to the bowl and serves to prevent birds from settling on its edge.

On the first day of the calendar month the deposit gauge is set up with a perfectly clean collecting bowl, connecting pipe, and bottle. The bottle contains 10 cc of a 0.02 per cent solution of copper sulphate, or about 1 gramme of para-

chlorophenol, to prevent the growth of algae which would alter the chemical nature of the materials collected. On the first day of the following month the gauge is examined, and any identifiable "foreign matter" such as leaves or insects is removed. A burette brush is passed downwards through the connecting pipe and the outlet of the collecting bowl is blocked with a bung, through which the wire of the brush penetrates. About a pint of the collected water is poured into the bowl and the deposited matter adhering to the inside of the collecting bowl, which may sometimes amount to more than half the total, is dislodged with a rubber squeegee. The bung is removed, and the water with the solid matter in suspension is allowed to run into the collecting bottle, while the inside of the connecting pipe is cleaned with the brush.

The bottle which has been exposed for one month is handed, with particulars of site, period of exposure, and the exact area presented by the collecting bowl, to a qualified analytical chemist. The following are the steps of the analysis, technical details being omitted.

(1) The volume of water is measured.

(2) The pH value of the water is measured with Universal Indicator, a mixture of dyes which, like litmus, changes colour in a solution which changes from acid to alkaline (pH is defined as being the logarithm of the reciprocal of the hydrogen-ion concentration, minus 7).

(3) The collected material is separated, by decanting and filtration, into insoluble matter and filtrate.

(4) The total insoluble matter is dried and weighed.

(5) The weight of "tarry matter", i.e. insoluble matter which is soluble in carbon bisulphide, is found.

(6) The insoluble matter which remains after extraction with carbon bisulphide is ignited by heating to 800° C (about 1500° F) in a crucible, and the residual ash is weighed.

(7) The weight of combustible matter, other than tar, is found by difference.

(8) A measured fraction of the total filtrate is evaporated to dryness, dried at 100° C (212° F) and weighed.

(9) The weight of calcium in a measured fraction of the total filtrate is found.

(10) The weight of chloride is found, similarly.

(11) The weight of sulphate is found, similarly, after oxidation of any sulphites which may have been present.

The analyst records the results on a special form, and they are converted to convenient units, as the example in Table 19 shows. Corrections are made for the small volume of water and the small weight of sulphate which were originally put into the bottle to prevent the growth of algae.

Table 19. *Material collected by Deposit Gauge in one month: example of analysis*

	litres	38 mm/month	1.48 in./month
1. Volume of water	2.73		
Rainfall . . . . .		7.1	
2. pH value . . . . .	grammes	g/sq. dekametre	tons/sq. mile
4. Total undissolved matter . . . . .	0.1873	258	6.58
5. "Tarry matter" . . . . .	0.0043	6	0.15
6. Ash . . . . .	0.1098	151	3.86
7. Combustible matter, other than tar . . . . .	0.0732	101	2.57
8. Total dissolved matter . . . . .	0.0846	116	2.97
9. Calcium . . . . .	0.0096	13	0.34
10. Chloride . . . . .	0.0173	24	0.61
11. Sulphate . . . . .	0.0415	57	1.46
12. Total Solids (total of undissolved and dissolved matter) . . . . .	0.2719	374	9.55

*Notes:* The numbers 1-11 in the table correspond to the numbers of the steps of analysis, in the text above.

The diameter of the collecting bowl was 12½ in. The factor for converting grammes to grammes per square dekametre was 1290; and the factor for converting grammes to tons per square mile was 32.88.

In the right-hand column of Table 19 there are estimates of the weight of material falling on a square mile. As a rule, it is uncommon to find uniform deposits over so large an area, and observations during dry, calm weather have shown that in typical built-up areas, deposit gauges placed a quarter of a mile apart will usually collect significantly different weights of deposit. The custom of quoting deposit gauge

results in tons per square mile is therefore a little misleading in that it exaggerates the area of the district represented by a deposit gauge. There is no doubt, however, that if a number of instruments were distributed over a square mile they would show that in some districts 50 or even 100 tons of solid matter is deposited on a square mile in a month.

Nearly all the general types of pollution, which were referred to in Chapter IX, are collected by the deposit gauge. Thus, the ash of insoluble matter is the ash and grit emitted from chimneys, sometimes with the addition of small quantities of wind-blown dust. Quantitative information is scarce, but it has been estimated that in urban districts the contribution of wind-blown dust is not likely to exceed 10 per cent, on an average, of the total deposit of ash. Similarly the sulphate in solution is mainly derived from the sulphur dioxide emitted from chimneys, with an addition of perhaps 5 per cent blown up from the sea by gales. The chloride in deposit gauges in Britain comes on average in roughly equal proportions from the sea and from chimneys. There is also a connexion between deposits of combustible matter (including tar) and the smoke emitted from chimneys, though the combustible matter in the deposit may include particles of unburnt coal and coke.

It is important to recognize that the three main types of pollution (ash, smoke and sulphur dioxide) do not reach the deposit gauge in the relative proportions in which they escape from the chimneys. Ash, consisting chiefly of particles which fall fairly quickly, is usually deposited close to its place of origin and is fairly sampled by the deposit gauge. Thus, if the chimneys in a square mile emit  $A$  tons of ash per month, gauges in the district may be expected to receive an average deposit equivalent to about  $A$  tons of ash per square mile per month. The same is true of particles of coal or coke, but it is not true of smoke or sulphur dioxide. As was pointed out in Chapter IX, smoke and sulphur dioxide are not removed from the atmosphere entirely by direct deposition or the effect of falling rain; the trees, vegetation and buildings near a deposit gauges must collect several times as much smoke and sulphur dioxide per unit horizontal area as the deposit gauge itself.

The deposit gauge is most valuable for measuring deposits of ash, grit, and particles which fall quickly but, in spite of the limitations referred to in the previous paragraph it is also useful measuring in sulphates, other soluble constituents, and combustible matter. If the emission of any form of pollution increases, the deposit will increase; and if there is a high rate of emission in a particular district, the deposit in that district will also be high. It is true that some of the measurements are necessarily on an arbitrary scale, but many of the most useful scientific instruments measure relative rather than absolute quantities.

Results of a single month's observations with a deposit gauge can only be relied on within a standard deviation of about 20 per cent, because of errors of sampling. When a deposit gauge is exposed for a number of consecutive months at the same site, it is found that the successive monthly estimates of each type of pollution vary by more than 20 per cent. The standard deviation is at most places about 40 per cent of the average: this means that about one reading in three is different from the average by more than 40 per cent. This large variation has been found to be due partly to changes in the rate of emission from chimneys, but mostly to fluctuations in meteorological factors such as monthly rainfall, and direction and speed of wind.

The effect of the large variance is to render necessary a long period of observations before significant conclusions can be drawn about the rate of emission of pollution. In practice, the most useful conclusions have been drawn from five-year groups of 60 monthly observations, though significant changes have sometimes been detected within a few months of their occurrence.

*Rapid Surveys of Deposited Matter.* The deposition of solid particles in a given place depends on the rate at which particles are emitted from the surrounding chimneys, but it also depends very strongly on weather, and changes in deposited matter from day to day or month to month are often much greater than any change likely to occur in the rate of emission of pollution. Some means is therefore needed of separating the effect of weather changes from the effect of chimney emission.

As has just been described, the more general way of achieving this is to take observations with a deposit gauge over such a long period that fluctuations in weather can be largely averaged out, revealing any long-term trends due to changes in the emission of pollution. A second way is to make observations only in special conditions of weather. It is not yet certain that weather conditions are sufficiently repeatable for comparisons to be made between the emission of pollution at two different times, but comparisons between one part of a city and another have already been made with considerable success. The technique has proved particularly valuable for making rapid surveys of the deposition of solid matter in the different residential areas of a town.

The most convenient sampling instrument is the petri dish, a round glass dish with short vertical sides, provided with a lid similar in shape but slightly larger. A diameter of 9 cm (about  $3\frac{1}{2}$  in.) is a convenient size. Besides a supply of petri dishes, the only apparatus required is a good balance, two small watch glasses, and a small camel-hair brush.

At least nine, but normally more, sites for dishes are chosen every 400 m ( $\frac{1}{4}$  mile) within the area to be surveyed, care being taken to select sites, preferably about 3 m (10 ft) above the ground, where interference by the public or by animals is unlikely. The distance from every object (such as trees and buildings) should be at least twice the height of the object above the level of the dish.

When anticyclonic conditions prevail, and there appears to be reasonable prospect of enjoying at least 24, and preferably 48, hours of dry, calm, weather the dishes are polished clean and distributed. The lid may be inverted and placed beside each dish. After 24 or 48 hours, the dishes are collected and labelled, each being inverted and placed inside its lid, so that none of the solid matter is lost. If the dishes are distributed and collected in the same order the period of exposure is approximately the same for each one.

Weather conditions during the exposure of the petri dishes should be carefully watched, for the smallest amount of rain or a gust of wind at more than about 5 m/sec (12 mi/hr) will spoil the experiment. At intervals observations should



be made of any change in weather or of any special source of pollution. The wind direction should be noted by observing smoke from a tall chimney; weather cocks, flags near the ground, and even clouds are not always reliable indicators. The wind velocity should be estimated roughly according to the standard Beaufort scale of the Meteorological Office, the relevant part of which is summarized in Table 20.

Table 20. *Beaufort Wind Force, and equivalent velocity*

	Force (arbitrary units)	Velocity	
		mi/hr	m/sec
Calm; smoke rises vertically . . . . .	0	0	0
Direction shown by smoke drift only, no pronounced sensation of air movement . . . .	1	2	1
Wind felt on face; leaves rustle . . . . .	2	5	2
Leaves and small twigs in constant motion; light flag extends . . . . .	3	10	4
Dust and loose paper raised (Experiment invalidated by dust blown into and out of the dishes) . . . . .	4	15	7

In the laboratory the contents of each petri dish and lid are brushed on to a watch glass with a dry brush, and weighed in the watch glass to an accuracy of 0.1 milligramme. This degree of precision can best be obtained if a clean watch glass of similar size is placed in the weight pan and used as a counterpoise to prevent errors from changing humidity of the air. The two watch glasses should be touched only with tweezers or a gloved hand, and should be kept in the balance case when not in use.

Besides the weight of material collected in each dish, it is necessary to know the period of exposure and the area presented by the dish. For the degree of accuracy required, which is about 5 per cent, it is usually sufficient to take the period and the area as the same for all dishes. Deposits are calculated in tons per square mile per month, or in grammes per hundred square metres per month, for easy comparison with any measurements with the deposit gauge which may be available. A map is then drawn on 3 in. to the mile, 1 in 25 000, or a similar scale, the amounts of deposit recorded at each site of observations, and contour

lines of equal deposit are drawn by interpolation. Fig. 49 shows a typical result. It shows at a glance where deposits were heaviest and where they were least during the period of exposure, and may readily be compared with maps showing the built-up area or the location of industry in the district.

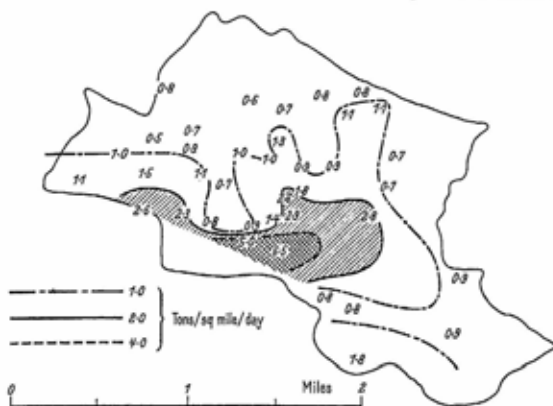


Fig. 49. Petri-dish survey of deposited matter in Bilston, 14-16 Dec. 1943. Mean wind: NE, 4-3 mi/hr. Weather cold, with frosts and heavy mists. Note the effect of heavy industry in the middle southwest; and the improving effect of a small park  $\frac{1}{2}$  mile north of the heaviest deposits (readings in the park: 0.7, 0.8, 0.9).

The effect of a chimney from which excessive quantities of solid particles are emitted is to produce a region of heavy deposit within a few hundred yards downwind, which would be instantly noticeable on a map such as Fig. 49. Petri dishes may therefore be used to help in accumulating evidence against a chimney which is suspected of causing a nuisance, but for this purpose it is best to expose dishes at intervals of about 220 yards in the affected area.

Compared with the deposit gauge, petri dishes have the advantages of numbers, speed in producing useful results, low initial cost and cost of operation. Their main disadvantages are the exacting nature of their demands on personnel, the uncertainty that suitable weather will prevail and that,

since observations can only be made in particular weather conditions, petri dishes cannot be used for observing average rates of deposit. Though samples taken with petri dishes cannot be analysed as thoroughly as with the deposit gauge, the proportion of combustible matter and ash can be found; prior to analysis, a general idea of the nature and origin of the particles can be got by microscopic examination as described in a later paragraph.

### MEASUREMENT OF SULPHUR DIOXIDE

As part of the analysis of deposited matter collected each month by the standard deposit gauge, the weight of sulphate in solution is determined. Most of this sulphate is formed by the solution and oxidation of sulphur dioxide which has been emitted from chimneys as a gas. It can be imagined in a similar way that sulphur dioxide must be collected by the roofs and walls of buildings, and be oxidized in the presence of water to sulphuric acid and sulphates. The weight of sulphates collected in a deposit gauge is therefore an index of the amount of sulphuric acid, derived from sulphur dioxide, which damages the external surfaces of buildings, and also corrodes metals and other materials exposed in the open.

Sulphur dioxide is, however, harmful in other ways which are not so satisfactorily measured by the deposit gauge. It is important to know (1) the rate at which the gas attacks sheltered surfaces, including the internal walls, ceilings and furniture of houses, and (2) the concentration of sulphur dioxide in the air breathed by men, animals, and plants. Of these, (1) is estimated empirically by the lead peroxide method, which will be described later, and (2) is measured by a direct chemical method.

*Volumetric Estimation of Sulphur Dioxide.* Air from outside a building is drawn at a steady rate of about 2 cubic metres per day (approximately 50 cubic feet per day) through a bubbler, the volume of air being measured with a gas meter. The bubbler contains a dilute solution of hydrogen peroxide, about an inch in depth, 25–40 cc in volume. All the sulphur

dioxide is effectively removed from the air bubbles by this small quantity of liquid, and sulphuric acid is formed:



At the beginning of the test, the solution of hydrogen peroxide is brought to a pH value of 4.5, by the addition of small amounts of acid or alkali, using a special indicator liquid which is pink at pH values less than 4.0, grey at 4.5, and blue at values greater than 5.0. At the end of the test, which usually lasts 24 hours, the pH value is less than 4.5 because of the sulphuric acid which has been formed in the solution, and the amount of alkali of known strength is measured which is required to bring the pH value back to 4.5. In practice, the alkali is sodium hydroxide or, better, because of its superior keeping qualities, borax of strength N/250 (i.e. containing 1/250 gramme-equivalent of the reagent in a litre of water). For N/250 alkali, the average concentration of sulphur dioxide during the period of the test is calculated by the formula

$$\text{Concentration of SO}_2 \text{ (p.p.m.)} = 1.582 \times \frac{\text{cc of N/250 alkali}}{\text{cu ft of air}}.$$

Here the abbreviation p.p.m. represents parts per million (by volume) e.g. the number of cubic centimetres of sulphur dioxide which could be extracted from a million cubic centimetres of air. The concentration of sulphur dioxide in p.p.m. may be converted to milligrammes of sulphur dioxide per cubic metre on multiplying by 0.00286. Strictly the latter units are to be preferred because they are absolute, whereas the factor 1.582 in the formula for concentration in p.p.m. should be subject to a correction for atmospheric temperature and pressure.

It is usual for the bubbler of the volumetric sulphur-dioxide apparatus to be preceded by a smoke filter, as in Fig. 43. The average daily concentrations of smoke and sulphur dioxide can be conveniently measured with the combined apparatus, and it has been found that a negligible amount of sulphur dioxide is absorbed from the air as it passes through the filter paper. Many ordinary materials, however, including soft glass, brass, and rubber, absorb

sulphur dioxide quickly enough to affect the volumetric determination appreciably. It is therefore important to use hard-glass tubing, and to apply a coat of vaseline to the internal surfaces of rubber and brass.

Provided that there is no absorption by the inlet tubing, all the sulphur dioxide entering the inlet funnel is caught by the bubbler. This can be demonstrated by having a second bubbler in series with the first. The main limitations of the method are due to the absorption in the bubbler of other gases which are acid or alkaline.

Carbon dioxide from the air is moderately soluble in water, forming a weak acid (carbonic acid). All difficulties from this source are removed, however, by the choice of 4.5 as the initial and final pH value. A saturated solution of carbon dioxide in pure water has a pH value of 4.5, and dilute solutions having this pH value are not appreciably changed in pH value by the addition or removal of carbon dioxide. In addition to sulphur dioxide and carbon dioxide, air usually contains traces of ammonia, hydrochloric acid, and sulphur trioxide. It is doubtful whether sulphur trioxide (which becomes sulphuric acid in solution) is trapped by the bubbler, since it occurs in the atmosphere as sulphuric-acid mist which will be caught by the filter, but in any case the amount of sulphur trioxide is small, perhaps a hundredth of the sulphur dioxide in the air.

There is usually more of the alkali ammonia in the air than there is hydrochloric acid. If both these gases are efficiently trapped in the bubbler, as seems likely, the ammonia will neutralize all the hydrochloric acid and in addition a little of the sulphuric acid formed from the sulphur dioxide. The concentration of ammonia in the air is generally not more than 0.01 volume per million, sufficient in the absence of hydrochloric acid to neutralize 0.005 volume per million of sulphur dioxide. Therefore, although estimates of sulphur dioxide are often expressed to the nearest 0.001 volume per million, the last figure is doubtful. Another possible way of looking at the matter is to regard the estimates as determinations of the total acidity of the air. To affect plants,

animals and materials, sulphur dioxide must as a rule go into solution in the surface moisture which is always present; but ammonia, being more soluble, is likely to be taken up first. Hence the sulphur dioxide in solution will probably have to neutralize this ammonia before the rest of it can attack other substances or be oxidized to sulphuric acid. There is therefore some justification for the view that the total acidity of the atmospheric gases is of more practical significance than the total sulphur dioxide. In towns the two interpretations differ so slightly that there is little risk of confusion.

The standard deviation of a single observation has been variously estimated at from 0.001 part per million in summer to 0.005 part per million in winter, or about three per cent of the average concentration in towns of 200000 to 300000 inhabitants.

*Sulphur Dioxide by the Lead Peroxide Instrument.* In 1932 at the Building Research Station a method of estimating atmospheric sulphur dioxide was devised in which the gas was absorbed by a solid surface in much the same way as it is absorbed by building stone. The surface was prepared from lead peroxide, which absorbs sulphur dioxide according to the reaction



Not only does this reaction proceed at a convenient and uniform rate, but both the reagent (lead peroxide) and the product (lead sulphate) are insoluble in water, a great advantage when they are exposed in the open air. A possible disadvantage arises from the fact that only a small fraction of the sulphur-dioxide molecules which collide with a lead-peroxide surface are absorbed. As in most reactions between a gas and an insoluble solid, the exact fraction of effective molecular collisions (the reactivity) is liable to be altered by small changes in the physical or chemical conditions. It was therefore necessary to make numerous tests on the reactivity of lead peroxide with sulphur dioxide, both in the laboratory and in the open, in the course of which the following conclusions were reached:

(1) The yield of lead sulphate is proportional to the concentration of sulphur dioxide, for all concentrations up to one part in a thousand parts of air.

(2) The reactivity depends appreciably on the depth of lead peroxide beneath the surface.

(3) When air containing a constant proportion of sulphur dioxide is blown slowly past a test surface of lead peroxide, the reaction goes on at a uniform rate until more than 15 per cent of the lead peroxide has been converted.

(4) The reactivity is practically independent of the speed at which air is blown past in the laboratory, up to the maximum speeds reached: 5.5 m/sec or over 12 miles per hour.

(5) A rise in temperature of 5.5° C (10° F) was calculated to increase the reactivity by 2 per cent.

(6) When exposed in the open, under a small cowl, a cylindrical surface of lead peroxide, with its axis vertical, collects about 35 per cent more sulphur dioxide on the windward side than on the sheltered side.

(7) Although no significant alteration in reactivity accompanies normal changes in the humidity of the air, the reactivity increases by from 10 to 90 per cent when the lead-peroxide surface is wet.

(8) Surfaces prepared from different batches of lead peroxide have appreciably different reactivities, probably because of differences in the size and surface properties of individual particles of lead peroxide.

Of the above conclusions, only (2), (6), (7), and (8) raise difficulties in the design of a satisfactory lead-peroxide instrument, and these are not insuperable. To deal with (2), the instrument is made to have a constant depth of lead peroxide, by spreading a definite weight over a definite area; (6) is avoided if the area is made in the form of a cylinder, with its axis vertical. Because of (7) it is necessary to protect the cylinder from rain, while allowing free access of air. Perhaps the most serious difficulty is (8) and this is overcome by keeping a uniform stock of lead peroxide, which is used for all sulphur-dioxide measurements; when a stock is nearing exhaustion, a new supply is obtained,

mixed thoroughly and put into bottles, and then carefully calibrated against the old stock before going into use.

The instrument now in use is illustrated in Fig. 50. It is usually exposed in the open air, either at ground level or on a low roof away from chimneys, in an open situation. The proximity of trees and buildings is not so detrimental

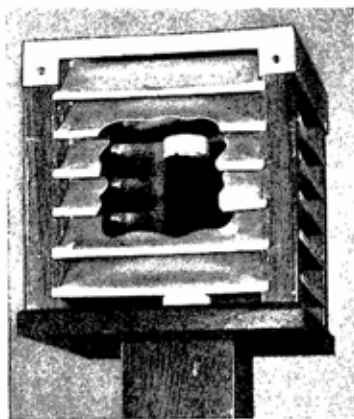


Fig. 50. Lead-peroxide instrument. The louvers are partly cut away to show lead-peroxide cylinder; the box is approximately an 18 cm cube).

as to the deposit gauge; but it is generally possible to find sites where no obstruction projects more than about  $45^\circ$  above the horizon. Any good deposit-gauge site is clearly suitable for a lead-peroxide instrument which, like the deposit gauge, is usually exposed for one calendar month.

Two or three days before the first of the month, a lead-peroxide cylinder is prepared for each instrument in use, and one extra to serve as a chemical control. The materials required are porcelain cylinders (or glass boiling-tubes) of 10 cm circumference, sulphur-free cotton gauze of 1 mm mesh, standard lead peroxide obtainable from the Fuel Research Station, and pure gum-tragacanth mucilage. In a room



where the air is as free as possible from sulphur dioxide, a paste is made for each cylinder from 8 grammes of the lead peroxide, and enough gum mucilage to produce a suitable consistency. A 10 cm square of the cotton fabric is sewn in place round the porcelain cylinder of glass boiling-tube, and the paste is applied evenly over it and smoothed with the finger. The prepared cylinders are dried slowly in a desiccator or a bell-jar with a dish of quicklime.

On the first day of the month the cylinders are taken in airtight brass containers or a wooden box to the sites of observation; and on the first day of the next month they are replaced by unexposed cylinders and removed to the laboratory for analysis. To make sure that none of the materials have been contaminated by sulphur dioxide, and to enable an allowance to be made for any small amount of sulphur dioxide that is collected during preparation and handling, the control cylinder is treated in exactly the same way as the others, except that it is stored in a sulphur-free container while the others are exposed.

The analysis of the exposed cylinders should be carried out by, or under the supervision of, a qualified analyst. The surface area of each cylinder is measured, and the duration of its exposure, to the nearest whole day, is noted. The mixture of lead peroxide, lead sulphate, gum, and fabric is digested with a solution of sodium carbonate, to convert all the sulphate into sodium sulphate in solution. After filtration, the solution is acidified with hydrochloric acid and barium chloride is added. A precipitate of barium sulphate is produced, which is filtered off, washed, ignited, and weighed.

The weight of barium sulphate from the control cylinder should not exceed two milligrammes; it is subtracted from the weight of barium sulphate from each exposed cylinder. According to season and locality, the amount of sulphur dioxide collected during the exposure corresponds with from 0.01 to 0.25 gm of barium sulphate. The result of each analysis is reported as *milligrammes of  $\text{SO}_2$  per day per 100 cm<sup>2</sup> of "Batch A" lead peroxide*. To reach a figure in these units the analyst multiplies the weight of barium sulphate in milligrammes by (a) the weight of  $\text{SO}_2$  (sulphur

trioxide) which could be produced from unit weight of barium sulphate, divided by the number of days' exposure, (b) the area of lead-peroxide surface exposed, divided by 100, and (c) a factor, supplied by the Fuel Research Station, to convert from the particular stock of lead peroxide to the original stock (Batch A).

Table 21. *Comparison of sulphur-dioxide measurements by three methods*

Position	Deposited per day		Collected per day by Lead Peroxide		Concentration in atmosphere	
	mg SO <sub>2</sub> per sq. metre of ground		mg SO <sub>2</sub> per sq. metre of PbO <sub>2</sub>		mg SO <sub>2</sub> per 1000 m <sup>3</sup>	
	Summer	Winter	Summer	Winter	Summer	Winter
Glasgow:						
Trongate . . .	21	42	174	203	155	316
Newcastle:						
Dean Street .	17	19	217	378	293	357
Salford:						
Regent Road .	24	32	248	459	100	334
Sheffield:						
Surrey Street .	22	28	217	443	299	538
Teddington:						
National Physical Laboratory	8	13	39	153	30	160

In Table 21 above, some typical measurements of sulphur dioxide, by the three methods which have just been discussed, are expressed in units as nearly equivalent as possible. The values given are averages for a full summer (May to September) and a full winter (November to March). It will be seen that, in an average day, about as much sulphur dioxide enters a deposit gauge as will be found in a column of air 100 metres high over the gauge; and that ten times this amount would be collected by a surface of lead peroxide of an area equal to the collecting area of the gauge. The difference between summer and winter values is proportionally greatest for the concentration of sulphur dioxide in the atmosphere, and least for its rate of deposition. Evidently the deposit gauge, the lead peroxide instrument, and the volumetric sulphur-dioxide apparatus measure different properties of sulphur dioxide which respond differently to the variations of weather. The deposit gauge collects sulphur dioxide which

is washed out of the air by rain or deposited in any other way; it has the advantage of requiring attention only once a month. The lead peroxide instrument collects sulphur dioxide by a chemical process; it, too, requires only monthly attention, and it is quick and simple to use, but the method of use must be carefully standardized. The volumetric sulphur-dioxide apparatus gives results in units which have a definite meaning,

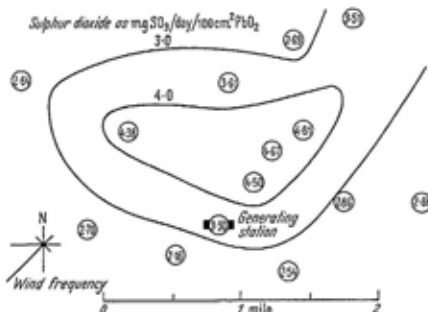


Fig. 51. Distribution of sulphur dioxide in the vicinity of an electricity generating station in London. (From *J. Roy. San. Inst.* 1951 Vol. 71, p. 221).

and for a few minutes' attention each day will provide daily averages of the concentration of sulphur dioxide, but it can only be used, as a rule, within easy reach of a laboratory. *Surveys of Sulphur Dioxide.* Of the three alternatives available, the lead peroxide method is much the most suitable for determining the average distribution of sulphur dioxide within a town or district. The map, Fig. 51, was produced by placing the instruments about a mile apart over the area to be surveyed. It represents the average for quite a short period, involving only 70 observations spread over five months. Although the units of measurement are empirical, the map shows that the most sulphur dioxide was near the centre of the area, and the least in the south. The winds in the period were mainly from the W, SW, and S, blowing from the electricity generating station towards the places where most sulphur dioxide was found.

The most striking feature of all, in connexion with surveys of sulphur dioxide by the lead peroxide method, is the great similarity of the maps which can be drawn from observations in successive months. Although the effects of winds and

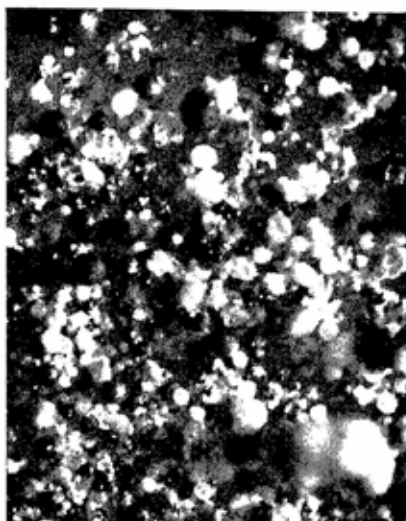


Fig. 52. Fly ash from a boiler fired by pulverized fuel ( $\times 63$ ).

seasons are noticeable, the general appearance of the contours is nearly the same in each month. This can only mean that the distribution of sulphur dioxide is very closely related to the distribution of chimneys emitting it, due allowance being made for the heights of different chimneys and the quantities they emit.

#### MICROSCOPIC EXAMINATION OF GRIT

The microscopic appearance of gritty deposits of atmospheric pollution is often a clue to their origin (see Fig. 52). Samples for the microscope may be collected by scraping some of

the deposit into a glass tube, but a better way is by exposing petri dishes for a suitable period in dry calm weather. Petri-dish samples are more free from contamination and can be related to the weather at the time of their collection. At about the same time as outdoor samples are taken, it is advisable to collect control samples of the grit inside the flues of any furnaces suspected of causing the pollution. If possible the control samples should be taken from inside the chimney stack at the base, or from some other position where there is an accumulation of particles just too heavy to be lifted out of the stack.

Representative portions of the samples, including the controls, should be mounted in canada balsam on microscope slides, with cover slips lifted clear of the largest particles by mounting rings of about  $\frac{1}{2}$  mm thickness. The specimens should be examined in a microscope with strong top illumination and fairly strong sub-stage illumination, of such magnification and resolving power as to show clearly any particle of a size between about 5 and 100 microns (0.005 to 0.1 mm). The size range of particles in each specimen should be noted. A description follows of the distinguishing features and manner of formation of various particles likely to be met.

*Coke spheres* are formed when small particles of coal, swept up from the fuel bed by the gases of the combustion chamber, become semi-molten and rounded, but escape before being burnt. Sometimes the spheres contain blow holes made by volatile matter escaping from within them just before they harden. Not only coal particles, but oil droplets also, may produce coke spheres if they are imperfectly burnt; coke spheres from oil burning are characterized by their roundness, uniform size, and numerous blow holes. When the chimney of a stoker-fired or oil-burning installation continuously emits black smoke, the "smoke" invariably contains a high proportion of coke spheres.

*Coke spheres with fly-ash markers* occur if smaller particles of fly ash come in contact with the coke particles while they are semi-molten. Fly-ash markers are a sure sign that the particles come from the burning of coal.

*Unrounded or partly rounded coke particles* are formed when partly burnt coal falls through the grate into the ash pit of a furnace.

*Coke fragments* from coke-oven or gas coke are very dense, and highly reflective. Since they are usually broken from bigger pieces they have sharp edges and corners.

*Ash spheres* occur if the furnace is hot enough to melt the particles of fly ash in the combustion chamber. Most large industrial furnaces but practically no domestic fires attain the requisite temperatures. There is an important distinction between ash spheres from pulverized-fuel installations and from those with an ordinary fuel bed supported on a grate. During the combustion of a fuel bed the different minerals in the fuel are well mixed, and the ash is a mixture of the aluminium silicates of iron and calcium. As a result the ash spheres from a fuel bed are coloured, yellow if mainly of calcium and red if mainly iron.

When coal is pulverized and burnt suspended in air, as in a pulverized-fuel furnace, there is no opportunity for the minerals of different particles to mix and the shale and pyrites are kept apart. The shale forms white or colourless spheres and the pyrites form black spheres of magnetic iron oxide. Brownish or greyish spheres can be formed if a pulverized coal burner is operated with too little air for combustion, but they originate more frequently when fine coal is burnt on a travelling grate and particles are lifted off the grate before coking sticks them down.

*Microscopic Examination of Suspended Matter.* Suspended particles are mostly too small to be examined for shape and colour, and many of them are too small to be graded according to size or even to be seen in an ordinary microscope. If they are collected by allowing them to settle on to a microscope slide, the sample contains a grossly unfair proportion of larger particles. It is even less satisfactory to collect the particles by drawing air through a filter paper and putting the filter paper under a microscope, because they form aggregates in which the individual particles are indistinguishable. A number of instruments have been devised,

however, for taking microscope samples of the particles suspended in the air of factories or mines. The Owens Jet Dust Counter is a suction pump in which air is drawn through



Fig. 53. Thermal precipitator. (Courtesy of C. F. Casella Ltd.).

a chamber having walls of damp blotting paper and then drawn rapidly through a narrow slit to impinge upon a microscope cover slip. Most, though not all, of the particles between 5 microns and 0.25 micron diameter are caught on the cover slip, and may be examined with a high-power microscope.

The Thermal Precipitator, illustrated in Fig. 53, was described in 1935 by H. L. GREEN and H. H. WATSON. It depends upon the principle, noted in the 19th century by AITKEN,

that when a hot body is placed in a dusty or smoky atmosphere, it can be seen with a lens to be surrounded by a dust-free space. The boundary of this dust-free space is quite definite, and dust is prevented from penetrating within it by the bombardment of fast-moving air molecules. The

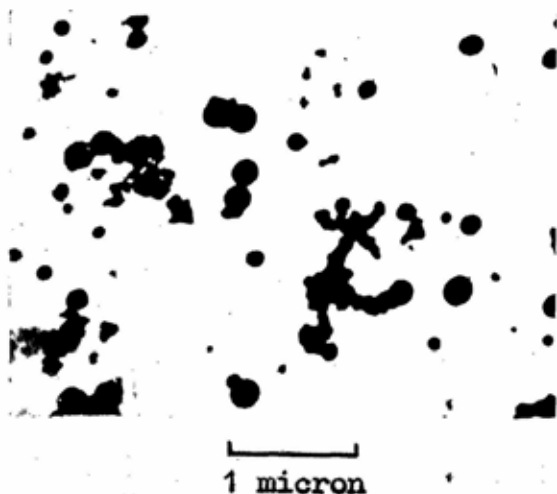


Fig. 54. Electron microphotograph of smoke particles. (From *Q. J. Roy. Met. Soc.* 1950, vol. 76, p. 360.)

thickness of the dust-free space depends on the temperature, and is about 0.1 mm if the hot body is 80° C warmer than the air. Therefore if dusty or smoky air is drawn slowly through a sufficiently narrow slot, at the centre of which is a hot wire, the air will go past the wire but the particles will be unable to pass and will be deposited on the sides of the slot.

The Thermal Precipitator is designed on the above principles. Air is drawn through a slot, at a rate not exceeding 7 cc a minute, past a wire heated by an electric current to 100° C.



The suspended matter is deposited on two microscope cover glasses accurately located on opposite sides of the wire. The action of the Thermal Precipitator is very gentle, so the particles are probably unchanged during their deposition.

The microscope is not a perfect instrument for examining small particles, because only particles larger in diameter than about 0.25 micron ( $1/100\,000$  inch) are visible in it. When ordinary pollution of the open air is collected with the thermal precipitator, most of the particles that can be seen are but little over this limiting size, strongly suggesting that many invisible particles are present. With the electron microscope, however, smaller particles, down to about 0.025 micron, can be "seen". An electron microphotograph of smoke particles is shown in Fig. 54. When records containing about 100 000 particles were examined, it was found that half the individual smoke particles were smaller than about 0.075 micron; but half the weight of smoke was in particles larger than about 0.51 micron. Some of the properties of smoke depend on the area it can cover; half the surface or sectional area of the smoke was in particles larger than about 0.35 micron. There is a definite tendency, as Fig. 54 shows, for smoke particles to stick together in chains, perhaps one micron long.

### MEASUREMENT OF DAYLIGHT

There are many instruments for recording daylight, from the CAMPBELL-STOKES hours-of-sunshine recorder to spectrophotometers and pyrhemeters which require special laboratories for their maintenance. The only instruments which can be conveniently applied to the study of atmospheric pollution are those which are simple enough for several to be used in different parts of a town, and at the same time sensitive enough to record the difference between the daylight received in a clear and a smoky district. Three such instruments will be briefly discussed, which are typical of three different general methods of observing daylight.

*Potassium Iodide Method.* This is one of several photochemical methods. When an acidified solution of potassium iodide is exposed to light, iodine is liberated and the solution turns

brown. The amount of iodine can be readily measured by the quantity of sodium thiosulphate, in dilute solution, which is needed to redissolve the iodine.

In practice, a standardized solution of potassium iodine is exposed daily in two-ounce stoppered glass bottles. At least one bottle should be in the town, and one in less smoky air of the country. The difference between the amount of iodine liberated in town and country is a measure of the loss of daylight due to smoke. Since the amount of iodine liberated is not proportional to the daylight received, it is not safe to make quantitative deductions from observations by the potassium iodide method.

*Photographic Methods.* Of the simple photographic instruments which have been developed, Dr. ASHWORTH's Ultra-violet Ray Meter is a good example. In it a specially prepared sensitized paper is darkened by the ultra-violet light transmitted by a standard glass filter. The amount of light is measured with an optical wedge, which reduces it by steps until it is insufficient to darken the sensitized paper.

When exposed horizontally the ultra-violet ray meter measures chiefly light from the sky near the zenith and in the latitudes of Britain the sun climbs high enough to affect it only in midsummer. The results are in arbitrary units, requiring a special calibration before they can be converted to units which may be compared with the results of other instruments; but the readings are proportional to the amount of ultra-violet daylight received, and give considerable information as they are, without calibration. A matched pair of instruments will measure approximately the fraction of ultra-violet daylight lost each day in a smoky town.

*Photoelectric Methods.* Instruments which record the total amount of light received as a number or a counter are in use in certain research establishments. The light is made to fall on a photoelectric cell which passes a current proportional to the amount of light it receives. The current is used to charge a condenser to a fixed voltage at which it is discharged by a radio valve. Each discharge of the condenser is made to operate an electrical impulse counter,

increasing the number registered by one unit. So the number of units counted is proportional to the light received.

It seems likely that similar instruments could be made suitable for continuous use out of doors. They could be expected to be accurate within one per cent, if they underwent a periodical test with a standard lamp. They could be made to record ultra-violet or visible light, from either the zenith sky or the whole hemisphere. Instruments of this type would probably meet the needs of meteorological observatories as well as those of local authorities who wish to keep a record of the loss of daylight due to atmospheric pollution.

*Use of Measurements of Atmospheric Pollution.* Like all routine observations, measurements of atmospheric pollution are liable to be forgotten after they have been once examined, arranged in a table or a graph, and perhaps published. If they have been well planned, they are worth more care than this, for with proper treatment they will yield information about both the local or general trends of pollution and the effects of particular conditions of weather. Some of these tests are simple, but others are more elaborate and the technique of making them is yet to be fully developed. There are many examples, in the next two chapters, of inferences which may legitimately be drawn from sets of observations of atmospheric pollution. Other inferences, of general and local interest, may be made wherever a sufficient number of systematic measurements have been taken.

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## Chapter XI

### DISTRIBUTION OF POLLUTION

It is important, so long as pollution is allowed to escape into the air, to know the amounts encountered, particularly in streets, houses, and places of work. It is necessary, therefore, to study how atmospheric pollution is distributed. By the methods described in the last chapter, a great many observations have been collected by Local Authorities and others in Great Britain. Though these are still not sufficient to provide a detailed knowledge of the distribution of pollution, they enable a number of conclusions to be drawn which are of general interest. They have been published by H. M. Stationery Office in 26 Annual and Five-yearly Reports of the Investigation of Atmospheric Pollution. At the suggestion of Dr. G. M. B. DOBSON, Chairman of the Atmospheric Pollution Research Committee, the Department of Scientific and Industrial Research made an intensive survey of the pollution in and around a particular town in 1937-39, under the guidance of this Committee. The Committee's report, entitled "Atmospheric Pollution in Leicester" was published in 1945. Much of the information in it is applicable, in general terms, to other towns where no such survey has been made; and it includes an account of a short war-time survey of smoke and deposited solids in Hyde Park. By reference to the Annual Reports and the Leicester Report, the differences in magnitude between the pollution of town and country can be stated in broad terms; and consideration in rather more detail can be given to the variation of pollution within a town and within an open space surrounded by a built-up area.

#### DISTRIBUTION IN BRITAIN AS A WHOLE

*Deposited Matter.* The maps, Figs. 55-58, have been prepared from data in the Annual Reports of the Investigation of Atmospheric Pollution and published in the Quarterly Journal of the Royal Meteorological Society. They show the distribution of undissolved ash and combustible matter, and

of dissolved sulphates and chlorides collected by deposit gauges in country districts well away from large towns or some miles to the west or south-west of the nearest source of pollution. The deposit of ash, undissolved combustible matter, and dissolved sulphates appears to be least in the west and south of England; that of chlorides, which must be due more to sea spray than to chimney pollution, is greatest near the west-coast. There is unfortunately no information for Wales, South-West England, Sussex, Kent, East Anglia, or the Scottish Lowlands and Highlands.

The units in Figs. 55-58 are grammes per hundred square metres per month, the same as in Table 19. They must be multiplied by 0.306 to convert them to tons per square mile per annum. As would be expected, the deposit increases as we go from the country into the suburbs of a town, and increases still more if we enter an industrial area. For example, if the insoluble ash deposited within towns were plotted in Fig. 55, a number of small areas would be shown with deposits over 1000 grammes per 100 square metres per month.

The scale of the increase from country to town is not by any means the same for all types of deposited impurity. It is much more rapid for insoluble matter than for sulphates or other forms of dissolved matter. The deposit of ash (i.e. incombustible undissolved matter) in a typical suburb is fifteen to twenty times as heavy as in a clean country district, and in the average industrial district it is two to three times heavier still, while in extremely polluted industrial districts the fall of ash is hundreds of times as heavy as in the country. The urban deposit of dissolved matter is seldom more than double the rural deposit, except where special water-soluble waste products are emitted from industrial chimneys.

These observational results have a simple explanation. Insoluble deposited matter includes a high proportion of large particles which fall to the ground by their own weight and are seldom carried far from the chimney where they are emitted. Soluble deposited matter is mostly made up of material which passes from the fire into the flue as a gas, vapour, or suspension of very small particles. Thus, much of the soluble matter emitted from urban chimneys is blown



Fig. 55. Ash.



Fig. 56. Combustible matter.



Fig. 57. Sulphates.

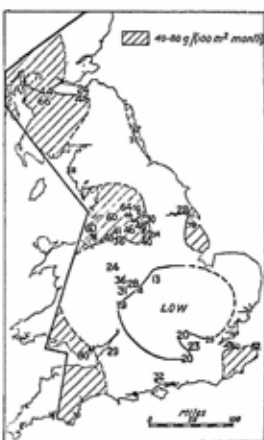


Fig. 58. Chlorides.

Figs. 55-58. Pollution deposited in country districts,  $\text{g}/(100 \text{ m}^2 \text{ mth})$ . ( $\times 0.306$  to equal tons  $\text{mi}^{-2} \text{yr}^{-1}$ ). In Fig. 58 small numerals are used to indicate sites where the ash deposit exceeds  $120 \text{ g}/(100 \text{ m}^2 \text{ mth})$ . (From *Q. J. Roy. Met. Soc.* 1950, vol. 76, p. 360.)

into the surrounding country. Some of the soluble impurities in the air, particularly chlorides, come from the sea, since it frequently happens that drops of sea spray are swept into the air during gales. If the air is unsaturated, these evaporate, leaving minute specks of salt which may be blown far inland, where they are equally likely to be caught in a rural or an urban deposit gauge.

Table 22. *Pollution deposited in Great Britain*  
Average values, in tons per square mile per month  
(multiply by 39.2 to convert to g/100 m<sup>2</sup> month)

Type of district	Insoluble Matter		Dissolved Matter			
	Combustible	Ash	Total	Chlorides	Sulphates	Calcium
Country . . . . .	0.9	1.3	6	0.9	1.3	0.3
Residential suburb . .	4	5	7	2	2	0.7
Central park . . . . .	4	6	9	2	3	1
Industrial . . . . .	7	12	9	2	3	1
Extreme industrial . .	30	110	30	4	11	10
Pollution emitted (average for G.B.) .	3	0.8	—	0.6	10	—

The average quantities of the deposit in various types of district are given in Table 22. The table should be used with great caution in estimating the probable deposit in a single month in a particular neighbourhood, for which purpose it cannot replace direct observation, but it confirms the general conclusions of the preceding paragraphs. The quantities found in extreme industrial districts vary very much, and depend upon the nature of the industry; in particular, the deposit of calcium would not reach the value of 10 tons per square mile per month except near lime and cement works.

At the foot of the table are added the rates of emission per square mile per month, calculated from the data of Table 18. They are expressed as averages for the whole of Great Britain east of the thick line in Figs. 55-58, area 65900 square miles. If allowance is made for the area occupied by each type of district, it can be shown that the total deposit of ash is apparently 2.5 times the amount emitted;

it seems likely that the estimate of the emission of ash, given in Table 18, is too low. The total deposits of combustible matter and sulphur dioxide are much less than the amounts emitted. This suggests either that much of the sulphur dioxide and some of the smoke is blown out to sea



Fig. 59. Summer mean.



Fig. 60. Winter mean.

Figs. 59-60. Smoke in surface country air,  $\text{mg}/(1000 \text{ m}^3)$ . (From Q. J. Roy. Met. Soc. 1950, vol. 76, p. 366).

or, as has been pointed out in Chapter X, that the standard deposit gauge may collect less than a fair share of the fine smoke or sulphur dioxide which is deposited in its neighbourhood. An argument that both alternatives occur was put forward in the Quarterly Journal of the Royal Meteorological Society. The total deposit of chloride is, as might be expected, rather more than the amount emitted from chimneys.

**Smoke and Sulphur Dioxide.** Smoke is not easily observed by eye, except from outside and above the smoky area. While the airman's opinion about the distribution of smoke will be approximately correct, therefore, that of the ordinary citizen may be false, being likely to be more nearly the distribution



of grit, which is easily observable. It is reported by airmen that smoke is visible sometimes for hundreds of miles downwind from densely populated industrial areas, and many thousands of feet above ground. A photograph taken in 1938 from the American stratosphere balloon, Explorer II, indicated that appreciable concentrations of smoke reach the



Fig. 61. Summer mean.



Fig. 62. Winter mean.

Figs. 61-62. Sulphur dioxide in surface country air,  $\text{mg}/(1000 \text{ m}^3)$ . Plain figures: volumetric method. Sloping figures: lead peroxide method. (From *Q. J. Roy. Met. Soc.* 1950, vol. 76, p. 366.)

top of the troposphere whose height varies from 8 km to 13 km (26 000 ft to 43 000 ft) but do not enter the stratosphere. This would be expected, since air circulates vertically within the troposphere, but not as a rule within the stratosphere.

Practically all measurements of smoke and sulphur dioxide have been made in Britain near the ground. Country air probably contains appreciable quantities at all heights up to several thousand feet, but at moderate heights above a town the air is likely often to be nearly as pure as in the country. Figs. 59-62 show, as accurately as is at present

known, the summer and winter average distribution of smoke and sulphur dioxide in country districts. Although measurements in the towns are excluded, the maps show the effects of industrial areas in polluting the air of rural districts surrounding them.

In Table 23 are given average winter densities of smoke and sulphur dioxide at ground level in different parts of the country, and these are seen to increase rapidly as we go from

Table 23. *Smoke and sulphur dioxide in Great Britain*  
Average winter density. (For towns with more than one site of observations, the highest alternative is given)

	Smoke mg/100 m <sup>3</sup>	Sulphur Dioxide	
		mg/100 m <sup>3</sup>	vols. per 100 million
Leicestershire:			
in easterly winds . . . . .	6	3	1
in all winds . . . . .	10	5	2
Teddington, Middx. . . . .	14	17	6
Bilston, Staffs. . . . .	39	20	7
Leicester . . . . .	42	40	14
Glasgow . . . . .	66	34	12
London . . . . .	84	51	18

country to town, with a rate of increase intermediate between those of soluble and insoluble deposited matter in the previous table.

In all places in Britain where observations have been made, the density of smoke is between one and two times that of sulphur dioxide, in spite of the fact that British chimneys emit twice as much sulphur dioxide as smoke (see Table 18). But the density of pollution at ground level depends on other factors beside the rate at which it is emitted from chimneys. Two such factors are not necessarily the same for smoke as for sulphur dioxide: (1) the height of the chimney from which the pollution emerges, and (2) the rate at which the pollution is deposited or otherwise removed from the air. It is evident from Table 18 that an undue proportion of smoke comes from domestic chimneys, which are much lower as a rule than other chimneys, and it also seems probable (Chapter IX) that smoke is removed from the air less quickly

than sulphur dioxide. Both these facts help to explain why the density of smoke near street level is more than that of sulphur dioxide.

Most British households have open grates in which coal is burnt, and the quantity of smoke produced in a town is roughly proportional to its population. But because larger populations usually occupy larger areas of land, the average density of smoke in the centre of a town does not increase in direct proportion to the population. It has been shown that the density of smoke at the centre of a number of towns is proportional, within ten or twenty per cent, to the square root of their populations. A town of 30000 inhabitants probably has at its centre an average of about 15 milligrammes of smoke per 100 cubic metres in winter. A town of 300000, or ten times the population, has over three times this density of smoke. It is clearly an advantage, for the sake of limiting the density of smoke, to limit the size of towns, provided of course that each town is surrounded by open country.

Smoke and sulphur dioxide travel long distances across country, as can be inferred from Figs. 59-62. In rural districts near Leicester the quantities of suspended impurity were found to depend strongly on the direction of the wind. When a large group of observations was analysed, it was shown that the quantity of pollution depended on the size and distance upwind of the nearest densely populated region. For distances between 35 miles (the Birmingham district) and 90 miles (the London area) the pollution in Leicestershire was proportional to the population of the industrial area and to the inverse square of the distance. The inverse square law is to be expected if, during its journey, the pollution diffuses upwards and sideways.

### DISTRIBUTION WITHIN A TOWN

*Deposited Matter.* Although Table 22 gives some idea of how much deposited pollution to expect in different quarters of a town, it gives no clue to the detailed distribution. In most towns this must be extremely intricate, since round many factory chimneys there will be regions where deposits are heavier than normal. Pioneer work on the distribution of

insoluble matter has been conducted in Bilston, Staffordshire, by the Borough Health Department. From observations by the petri-dish method it was shown that there were real differences in deposited matter at places only a quarter of a mile apart; and hence that, in certain weather conditions at any rate, solid matter is deposited mainly within a quarter

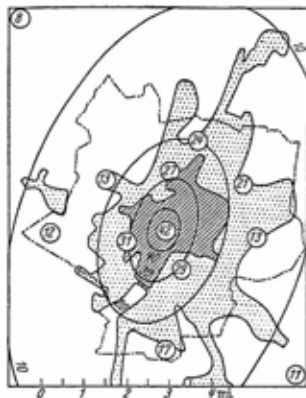


Fig. 63. Mean distribution of smoke.  
Concentration in mg/100 m<sup>3</sup>.

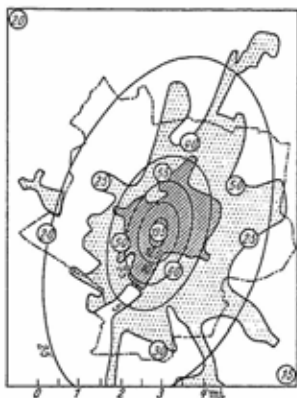


Fig. 64. Volumetric method.  
Concentration in parts per 100 million.

mile of its place of origin. The map reproduced as Fig. 49, Chapter X, showed that deposits in some districts of Bilston were more than ten times as heavy as in others only a mile away.

*Smoke and Sulphur Dioxide.* In the published report of the Leicester survey, there is much information about the general distribution of smoke and sulphur dioxide in a town, and about the effect of wind on the distribution. Figs. 63 and 64 show the average distribution of smoke and sulphur dioxide in Leicester, in winter, and this may be regarded as typical of what is occurring in other towns. The closely built-up area is represented by hatching, and the areas covered mainly by houses with gardens are stippled. Because of the relatively

few points of observation, contours of equal pollution have been drawn as ellipses; even so, they conform fairly closely to the shape of the built-up area.

Apart from a relatively small asymmetry due to the prevailing westerly winds, the average distribution of pollution in Leicester was little different from the distribution

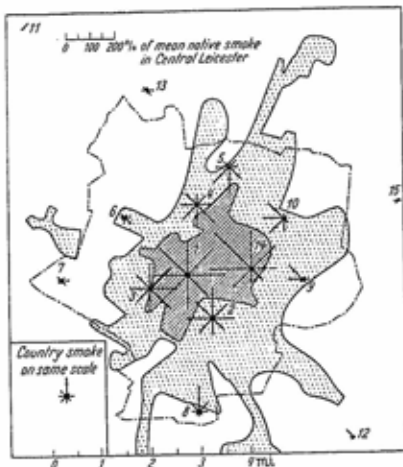


Fig. 65. Native Leicester smoke—moderate winds, 5-10 mi/hr—Winter.

of the chimneys emitting it. The factories and central-heating installations near the middle of the city apparently produced considerably more sulphur dioxide than smoke, and the distribution of sulphur dioxide in the figure shows a higher maximum at the centre than the distribution of smoke. The ratio of the concentration in the centre to that in the built-up suburbs was 3.4 to 1 for sulphur dioxide and only 2.2 to 1 for smoke.

The effect of wind on the distribution of pollution was analysed by grouping the observations in Leicester according to the speed and direction of the wind. It was also possible

to estimate the average pollution in the air entering the area, and so to determine approximately the amount of native Leicester pollution. Figs. 65 and 66 give representations of the native smoke and sulphur dioxide in eight wind directions, at the fifteen points of observations. For example, if attention is fixed on station 5, the length of the arm pointing south is

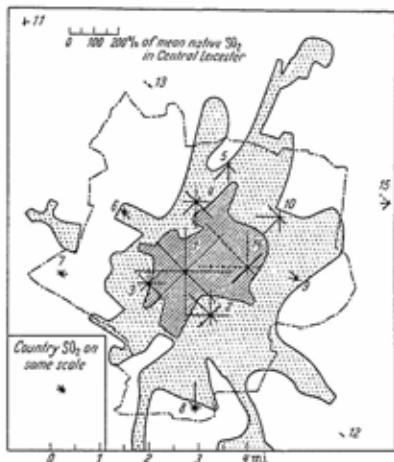


Fig. 66. Native Leicester sulphur dioxide—moderate winds, 5–10 mi/hr—Winter.

the average pollution at this station in south winds; i.e. the smoke is 110 per cent and the sulphur dioxide is 70 per cent of the average for Central Leicester (stations 1, 2, 3, and 4).

Figs. 65 and 66 represent winter conditions only, in winds of average speed between 5 and 10 mi/hr. They refer to pollution of local origin, the quantities of pollution entering the area being represented by a separate group of eight arms in the lower left-hand corner of each part of the figure. In other wind speeds, and also in summer, the observations lead to maps of similar appearance. All maps show two main features: (1) the largest arms are those of station 1 and in

some directions station 14, these being the two stations within the central built-up area, and (2) the longer arms of all non-central stations point inwards. At any suburban station a sudden reversal of wind, so that the wind blows directly from Leicester, may send up the native pollution from three- to five-fold.

The effect of wind direction on pollution cannot easily be seen from Figs. 63 and 64, since during the period for which they represent the average the wind blew in all directions. The left-hand half of Fig. 67 gives the average distribution of smoke in winter, in a symmetrical town the same size as Leicester, in three different speeds of wind. It was calculated from all the available Leicester observations. The highest density is in each wind speed very near the centre of the town (marked by the intersection of two lines at right angles); this was not merely an average result, for it was true almost every day. In the suburbs, of course, the pollution depended very appreciably on the direction of the wind. At distances of between  $1\frac{1}{2}$  and 3 miles from the centre, the pollution in winds blowing directly from the centre was about twice as great as in winds blowing in from the country; and if air has been perfectly clean on entering the town, as was assumed in drawing Fig. 67, the ratio would have been greater still, about five to one.

The observed result, that the centre of Leicester nearly always had the highest density of pollution, is interesting. It suggests that suspended or gaseous pollution must be rapidly removed from near street level; but removal sideways is out of the question near the centre of a large town, and removal downwards—i.e. deposition on the ground—takes place too slowly to produce the observed result. So it seems that the pollution escapes upwards. Until samples of pollution are taken at considerable heights, this conclusion can best be tested by measurements of daylight at the ground, since smoke above the chimneys tops cuts off just as much daylight as smoke nearer the ground. In the right-hand half of Fig. 67, the winter-average losses of daylight due to smoke are given. The maps show quite clearly that the greatest loss of daylight occurs at a point downwind from the centre, usually about a mile. This

confirms the conclusion that smoke rapidly escapes upwards from street level. Beyond a mile downwind, it seems likely

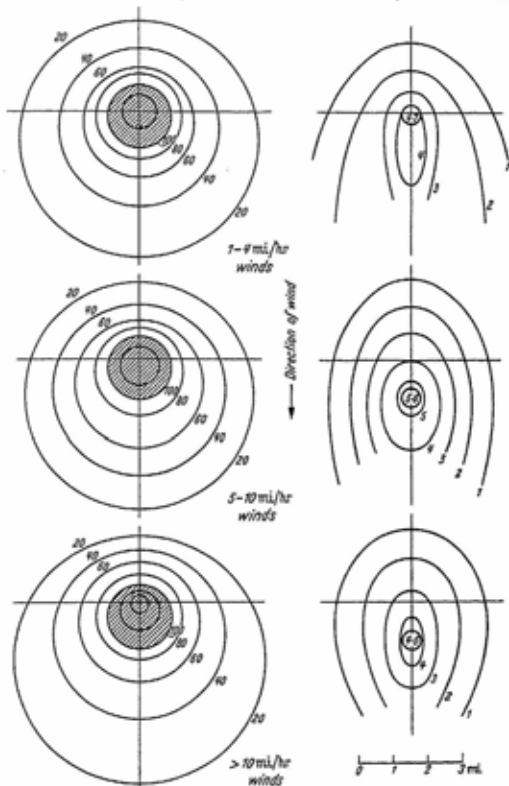


Fig. 67. Distribution of smoke and ultra-violet daylight.

that the pollution spreads sideways sufficiently for the total weight of smoke over unit area of ground to begin decreasing.



From the practical point of view, the upward diffusion of smoke and sulphur dioxide is particularly important, because it is the main factor in preventing the accumulation of pollution in disastrous concentrations. If we were foolish enough to build a roof 100 ft high over one of our cities, shortening any tall chimneys to less than 100 ft, the concentration of sulphur dioxide would be 5 volumes per million about one hour after the fires and furnaces were lit, and the density of smoke at the same time would be about 5 milligrammes per cubic metre. Even if there was a wind blowing, these amounts would be reached in leeward districts whenever the wind took more than an hour to pass right through the town. And if, as often happens, the wind dropped below one or two miles per hour, the concentration of sulphur dioxide would exceed 10 volumes per million, which some authorities regard as dangerous to health. That such concentrations rarely occur in towns is due to the diffusion of polluted air upwards and of clean air downwards. More is said about turbulence and diffusion in the next chapter.

#### DISTRIBUTION IN PARKS AND SMOKELESS ZONES

We are all glad to escape at times, with our dogs and children, from built-up areas into parks and other open spaces, but is the air cleaner there? Certainly, less atmospheric pollution is deposited in parks than in the streets around them. The deposit on laurel leaves at the centre of Hyde Park is only about a tenth of that less than a mile away, at points round the perimeter.

Unfortunately, the air itself is at times little cleaner in parks than in the streets. Measurements of smoke in Hyde Park have shown that in average conditions the density of smoke at the centre is about two-thirds the density in the surroundings (see Fig. 68). When the upward diffusion of air is particularly rapid, the fraction may be as low as one-quarter, but when diffusion is sluggish, the ratio may exceed five-sixths. The same general results are likely to be true for sulphur dioxide, though this has not yet been investigated. It is well known that densities of smoke and sulphur dioxide are highest in hazy or foggy weather, when the air diffuses

most slowly, and this is also when there is least improvement in pollution if we try to escape from it by entering urban parks. In such times the only way of escape is to the country.

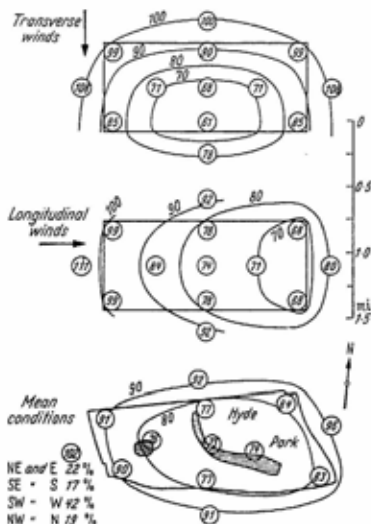


Fig. 68. Smoke in Hyde Park, expressed as a percentage of smoke concentration upwind.

Hyde Park is an example of a "smokeless zone", namely a district where no smoke is produced, surrounded by smoke-producing areas. In view of the movement towards progressive smoke abatement by the creation and extension of statutory smokeless zones (see Chapter XV) the observations in Hyde Park are of special interest. Though they cannot in any way undermine the fundamental merits of smokeless zones, they serve as a warning to the onlooker that he should not expect obvious improvements in the atmosphere, at any rate during hazy weather, until the smokeless zone has reached an area

considerably more than that of Hyde Park and Kensington Gardens (about one square mile). The best way to study the improvements in atmospheric pollution in a smokeless zone is to make systematic measurements by methods such as those discussed in Chapter X.

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## Chapter XII

### CHANGES IN POLLUTION

The study of atmospheric pollution is admittedly an untidy science. It is analagous to some aspects of history, economics, medicine, and meteorology, because it cannot be properly developed by the neat experimental methods which are so successful in physics and chemistry. Much of what has been learned about atmospheric pollution has been acquired by making series of observations and examining them after a large number have been collected. If a set of observations shows some unusual trait, a tentative explanation is offered, and this is tested by making other sets of observations, often quite different in character from the original set. There is seldom much difficulty in offering an explanation; the difficulty is normally to decide which of a number of explanations is nearest the truth, and to obtain confirmation by demonstrating that the unusual trait is without exception the consequence of the particular cause offered in the explanation.

The relatively new technique of Statistics is an invaluable help in studying sets of observations of atmospheric pollution. It can be used for testing the closeness of the relation between suggested cause and effect, by means of the correlation coefficient; by this means some of the conclusions near the end of the present chapter have been reached, about the effect on atmospheric pollution of wind, temperature, rain and other factors.

In addition, Statistics can be used to prevent undue waste of time in investigating changes in pollution which are due to a chance concurrence of many different causes, and also to ensure that the maximum information is extracted from each set of observations. Anyone who makes regular observations of atmospheric pollution will have experienced the difficulty of "knowing where to begin" in analysing the lists of results—and, still more, the difficulty of knowing when

to stop. The particular branch of Statistics which is used for these purposes of control is known as "significance testing". Briefly, the method is to estimate how large a change is likely to occur as a result of chance concurrences of different causes, and to pay further attention only to those changes which are too large to be of this kind, i.e. to those changes which are "significant". For example, in Fig. 69, it might

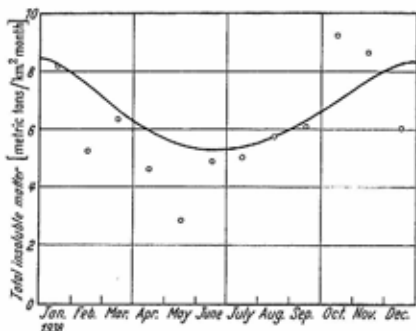


Fig. 69. Monthly total insoluble deposit at Leicester Town Hall (1938). Note: the smooth curve is from six years observations ended March 1939.

be thought that some real change in the emission of pollution must have caused the succession of nine months when the total insoluble matter was equal to or below the average, represented by the smooth curve; but the degree of scatter of the individual points in the figure is so great that it can be shown, by significance tests, that the succession could easily be due to chance concurrences of the same characteristics (perhaps variations of weather) which produced the scatter.

By a study of the significant changes in atmospheric pollution, it has been possible to attain a clearer understanding of both human and other factors which affect pollution. A general example may help to illustrate the method.

Suppose regular observations at a fixed point indicate that there has been a change in pollution. We infer that there has been a change in either (1) the rate of emission

of pollution from one or more of the sources from which it can reach the point of observation, or (2) the mechanism by which the pollution from these sources is brought there. The mechanism is mainly a matter of weather—wind speed and direction, atmospheric turbulence, rain, and so on. We can eliminate the effect of any change in the effect of weather by averaging observations over such a long term that all types of weather are represented in about their normal frequency. The longer the term, the more nearly is weather eliminated; and if the change in pollution is still evident, the more certain is it, according to tests of significance, that there has been a change in the average emission from the chimneys whose pollution can reach the point of observation. It is usually more important, however, not to wait until we can be absolutely certain, but to be reasonably certain in the shortest possible time. In this case statistical tests of significance are indispensable, since they enable degrees of certainty to be expressed in terms of mathematical probability. A probability of 95 per cent or more is usually regarded as "significant".

To continue the example, suppose the change in pollution was due to a change, not in the amount emitted, but in the weather. This could be part of a periodic change, such as the seasonal variation of weather from winter to summer, or it could be an irregular happening, for example the persistence of easterly winds for two exceptionally long spells during 1947. We investigate periodic changes in the same way as we investigate changes in emission, by averaging a large number of observations. For instance, from the averages of the observations in a large number of Januaries, Februaries, etc., separately for each month, we can deduce the average seasonal variation of pollution. To investigate the effect of a change of wind or any other irregular change, we collect observations until the change has been repeated many times and then determine the coefficients of correlation and regression. These are the general methods, in outline, of examining a change in the pollution at any point of observation. Particular examples will now be considered of changes which have been shown to be significant.

## CHANGES IN DEPOSITED MATTER

Of all the instruments for measuring pollution, the deposit gauge has been longest in regular use. At a number of places in England and Scotland, regular monthly observations have

Table 24. *Trends of deposited matter:—Examples*(a) *Insoluble ash*

Period	London Finsbury Pk.	Rothamsted (Herts)	Sheffield Attercliffe
April-March	average as tons per square mile per month		
1914-1919	15.3	—	—
1919-1923	8.7	2.6	—
1924-1929	9.4	2.8	—
1929-1934	7.6	2.4	11.1
1934-1939	6.5	1.7	14.0
1939-1944	4.5	1.4	19.0
1944-1949	4.9	1.3	19.5
	Decreasing to 1944	Decreasing	Increasing

(b) *Carbonaceous matter*

Period	Glasgow Ruchill	Newcastle Upon-Tyne Westgate	Stoke-on-Trent Leek Road
April-March	average as tons per square mile per month		
1914-1919	4.5	—	—
1919-1924	3.4	—	—
1924-1929	3.2	7.3	2.8
1929-1934	3.7	6.6	3.9
1934-1939	3.2	5.6	4.5
1939-1944	2.9	4.3	4.4
1944-1949	3.2	4.3	3.6
	Decreasing to 1944	Decreasing	Increasing to 1939

been made since 1914. Though these give but little information—and that only indirectly—about the complicated day-to-day fluctuations in the rate at which pollution is deposited, they are useful for studying the trends and the yearly cycle of deposited matter.

The trend of pollution may be defined as its tendency to increase or decrease steadily as time goes on. Observations are usually needed for several years to verify that a steady

change in pollution is taking place but, once conclusively established, a trend in atmospheric pollution implies that there is a similar trend in the rate at which pollution is being emitted. It is thus possible to tell from observations whether

Table 24 (Continued)

## (c) Tar

Period	London Victoria Pk.	Marple (Cheshire)	Salford Ladywell
April-March	average as tons per square mile per month		
1914-1919	0.1	—	—
1919-1924	0.2	—	—
1924-1929	0.2	0.6	1.2
1929-1934	0.3	0.3	0.5
1934-1939	0.3	0.2	0.3
1939-1944	0.2	0.1	0.2
1944-1949	0.2	0.2	0.3
	Increasing to 1934	Decreasing to 1944	Decreasing to 1944

## (d) Total dissolved matter

Period	Birmingham West Heath	Leeds Park Square	St. Helens
April-March	average as tons per square mile per month		
1914-1919	—	—	27.5
1919-1924	—	9.0	14.8
1924-1929	6.0	11.1	13.6
1929-1934	8.9	9.7	12.8
1934-1939	6.0	11.0	12.8
1939-1944	4.6	11.8	12.2
1944-1949	6.1	—	11.3
	Maximum 1929-1934	Increasing after 1929	Decreasing

in any neighbourhood the emission of pollution is increasing or whether, on the contrary, effective steps are being taken to reduce it.

Examples are given in Table 24 of 5-yearly averages of deposited matter for each of which up to 60 observations were made. The figures were taken from annual reports by the Department of Scientific and Industrial Research on "The Investigation of Atmospheric Pollution" (London, H.M. Stationery Office). Tests have shown that, in the particular



examples quoted, the minimum change which could be accepted as significant is one of between 20 and 50 per cent; thus all the trends indicated in the table are significant. It must however be remembered that the deposit at any one situation is not necessarily typical of a whole town. Instances have occurred of the deposited pollution increasing at one situation while decreasing at another within a few

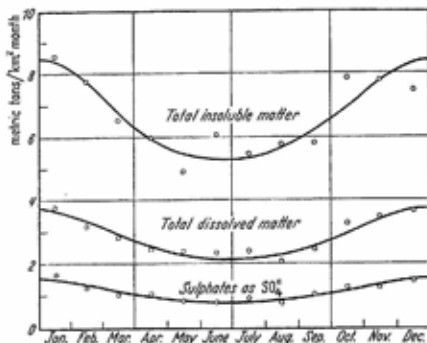


Fig. 70. Yearly cycle of deposited pollution at Leicester Town Hall; six years ended March 1939.

miles. The pollution collected by a deposit gauge, particularly the undissolved solid matter, is chiefly of local origin.

**Yearly Cycle.** The average rate at which pollution is deposited is in many places greater in winter than in summer, although the differences are seldom large, and there are districts where the reverse holds true. After five or more years' observations, if the average rate of deposit in summer is divided by the average winter rate, the ratio is almost certain to be between 0.5 and 2.0. This is true of total deposited matter, and of every constituent separately, except chlorides, for which the ratio tends to be higher, between the limits 1.0 and 2.3. Examples are given in Fig. 70.

The yearly cycle of deposited matter, though partly due to the body's need for artificial heat in winter, must be largely influenced by seasonal changes in industrial activity, which

may differ in different districts. The cycle of deposited chlorides is abnormal because it is appreciably affected by winter gales at sea; especially in the coastal areas, where more of the deposited chlorides come from the sea than from fuel.

### CHANGES IN SUSPENDED POLLUTION (SMOKE AND SULPHUR DIOXIDE)

There are three differences between deposited and suspended atmospheric pollution, which affect the ways in which their

Table 25. *Trends of smoke and sulphur dioxide:—Examples*

Winter only Nov.—March	Smoke: mg/m <sup>3</sup>		Sulphur Dioxide volumes per million	
	Stoke- on-Trent	Kew Observatory	Salford Regent Rd.	L.C.C. Crossness
1924-1927	0.62	0.30	—	—
1927-1930	0.63	0.23	—	—
1930-1933	0.79	0.26	0.159	0.074
1933-1936	0.98	0.30	0.176	0.085
1936-1939	0.79	0.16	0.089	0.046
1939-1942	0.69	0.23	0.089	0.030
1942-1945	0.56	0.22	0.119	0.050
1945-1948	0.53	0.16	0.131	0.037
	decreasing after 1936	decreasing as a whole	minimum 1936-1942	decreasing to 1942

changes can be discussed. First, the concentration of suspended pollution in any one place is even more influenced by weather than the rate at which pollution is deposited. It will be shown later that atmospheric turbulence—the rate of mixing of the air—is all-important in controlling the concentration of suspended pollution, but so far as is known, it has little effect on the rate at which pollution is deposited. Second, whether suspended pollution is a gas or extremely small particles, it comes on an average from much further away than deposited pollution, especially than deposited insoluble matter. So there is little chance of detecting local changes in the emission of smoke and sulphur dioxide from chimneys by observing their concentration in street air at a single place nearby; although much can be done with groups of observing stations. Also smoke can be seen, and much useful work has been done by systematic observation of the

smoke emerging from individual industrial chimneys. The third difference is that regular observations have been made of the hourly and daily average concentration of suspended pollution, whereas deposited pollution has been measured monthly. Hence it is possible to discuss the daily cycle, weekly cycle,

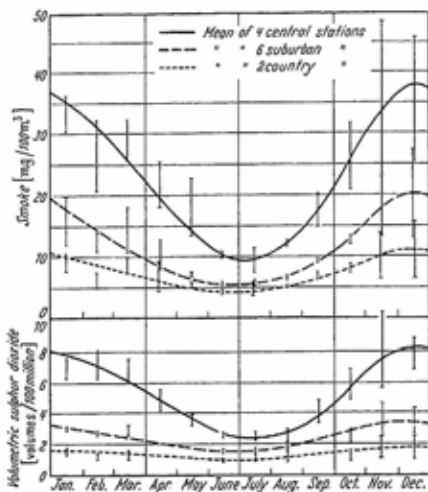


Fig. 71. Yearly cycle of suspended pollution at Leicester, 1937-39.

and day-to-day variations of suspended pollution with more confidence than the same aspects of deposited pollution.

Examples are given in Table 25 of 3-yearly winter averages of smoke and sulphur dioxide which show significant changes. In two of the examples an abrupt change appears to have taken place, but in the others the change was gradual. The average concentration of suspended matter at a particular spot can only be altered by making a substantial change in the rate at which pollution is emitted in a large area. This sort of change happens when a new town springs up, or when a staple industry enters into a period of boom or decline.

*The Yearly Cycle* of suspended pollution is much more definite than that of deposited matter. At most places the average concentration of smoke and sulphur dioxide in winter is 2-3 times the summer value. This is partly because of the extra fuel used in winter in nearly every locality, and partly because atmospheric conditions are more favourable in summer for the dispersal of smoke and gases away from street

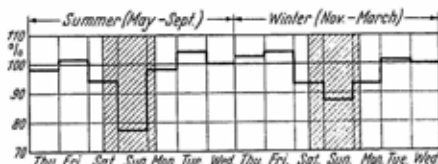


Fig. 72. Mean weekly cycle of smoke, Stoke-on-Trent, Leek Road, 1939-44.

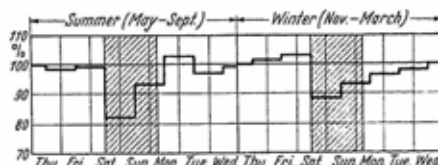


Fig. 73. Mean weekly cycle of sulphur dioxide, Sheffield, Surrey Street, 1939-44.

level into the upper air. Examples of yearly cycles are given in Fig. 71.

*The Weekly Cycle* of smoke and sulphur dioxide is characterized in urban districts by lower concentrations during the week-end, when the concentration may fall by from 20 to 40 per cent. Few observations from residential districts are available, but here a week-end rise might be possible. Regular variations between Monday and Friday are usually slight.

Because of the yearly cycle, it is better to study the weekly cycle of summer and winter observations separately; and because of the vagaries of weather, the weekly cycle can be adequately studied only from large groups of observations, covering several years. Examples are given in Figs. 72 and 73. Since over a long time there is no definite difference

between week-end and week-day weather, the lower concentration of pollution at week-ends in Figs. 72 and 73 must be entirely due to a diminution of pollution emitted.

*The Daily Cycle* of suspended pollution is one of its most interesting features because, as a rule, there are two maxima each day. In Fig. 74 the concentration of smoke rises to a maximum at 8 a.m. and again to a smaller maximum at

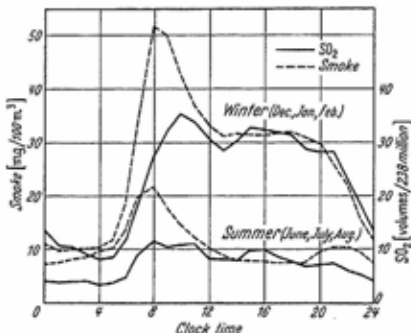


Fig. 74. Daily cycle of smoke and sulphur dioxide.

6 p.m.; the concentration of sulphur dioxide reaches approximately equal maxima at 10 a.m. and at 3 p.m. The difference between the intensities of the morning maxima is due to a fundamental difference between smoke and sulphur dioxide: sulphur dioxide is produced whenever coal is burnt; whereas smoke is produced only when combustion conditions are bad, and they are worst of all when fires are being kindled in cold grates. The examples given indicate that about half the smoke at 8 a.m. in Leicester was produced by the kindling of fires in cold grates.

In Fig. 75 a diagrammatic explanation is given of the way in which the daily smoke cycle is produced. The main causes are (1) the daily cycle in the rate at which coal is burnt, (2) the extra smoke emitted when fires are being lit in cold grates in the morning, (3) the effect of smoke blown from

outlying industrial areas, and (4) the daily cycle in atmospheric turbulence, whereby the concentration of pollution at street level diminishes during full daylight, and is intensified at night and in the early morning. Except for (2), the causes apply equally to sulphur dioxide. There is a further reference to atmospheric turbulence later in this chapter.

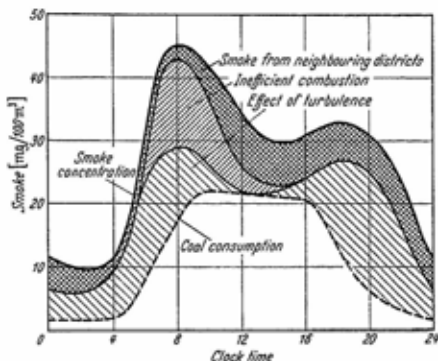


Fig. 75. Causes of the daily cycle of smoke.

### IRREGULAR VARIATION

This term is used to describe changes of pollution which do not fall into the categories of trends, or yearly, weekly, or daily cycles. In amounts of suspended pollution examples can be given of changes of up to 1.4 to 1 as a result of trends, 1.7 to 1 during the weekly cycle, 3 to 1 during the yearly cycle, and as much as 5 to 1 during the daily cycle. The irregular variation of suspended pollution can be greater than any of these, for irregular changes of 10 or 20 to 1 sometimes occur in the daily average density of smoke and sulphur dioxide, and even greater changes may occur in the density measured at some particular hour of day.

Because suspended pollution can conveniently be measured at daily or hourly intervals, its irregular variation has been studied more closely than that of deposited matter. At any

point which is not in the direct smoke trails of individual chimneys, the suspended pollution usually has come from an area of several square miles or even more. Casual changes in the rate of firing individual furnaces and fires in such a large area might cause slight differences in the observed concentration of pollution, but they could not conceivably cause differences so great as ten to one. Even systematic changes in the rate of firing, such as might be caused by a change of temperature, could not produce such differences in pollution. The chief causes of irregular variation in the density of suspended pollution are in fact meteorological. They will now be briefly considered in the order: direction of wind, temperature, rainfall, velocity of wind, and turbulence.

*Direction of wind* is the only meteorological variable which is likely to affect differently the pollution in different districts, for in certain circumstances the wind can produce murky conditions on one side of a town with bright sunshine on the other. Changes in wind direction cause the greatest fluctuations in pollution in suburban districts, because of the increase produced when the wind begins to blow from the centre of the town, having previously blown from some other direction.

The amount of fuel burnt for bodily heating is of course dependent on the *temperature* out of doors, and the yearly cycle of pollution is in part a consequence of the yearly cycle of temperature. Irregular changes in temperature are a common feature of the British climate, and it is to be expected that there are corresponding irregular changes in atmospheric pollution, the denser pollution being associated with the colder weather. This proves to be the case, and in the winter, a change from the warmest to the coldest weather may increase the density of domestic smoke more than five-fold. In summer, the effect of temperature on pollution is much smaller.

*Rain* plays an important part in cleaning the air of smoke and sulphur dioxide, though from existing observations it is difficult to form an estimate of how much of the irregular variation of suspended pollution is due to the spasmodic

way in which rain falls. It is probably fair to say that rain in summer or winter has about as much influence as temperature in winter; on a warm dry day in winter the suspended pollution is likely to be equal to that on a cold wet day.

*The velocity of the wind* might be thought to be by far the most important factor in causing irregular variations in every kind of atmospheric pollution. There is no doubt that it does control the distance travelled by large particles before they reach the ground, but in its action on suspended pollution near ground level, wind velocity is less important than might be supposed. Provided that the speed with which smoke and sulphur dioxide spread upwards is unchanged, alterations in wind speed do not strongly affect their density near ground level. In a large town, for instance, a mere increase of wind means that pollution is kept close to the ground for a longer distance from the chimney, and the fact that more air is passing the chimney tops is offset by the decrease in height to which pollution spreads above the town. In the centre of Leicester, the density of pollution in barely perceptible winds of  $\frac{1}{2}$  mi/hr. was found to be from two to four times the density in winds of 20 mi/hr, provided the turbulence in both cases was normal.

If an increase of wind is accompanied by an increase in *turbulence* (the eddy-motion of air which helps pollution to spread upwards and sideways), as often happens in practice, the density of pollution near the ground is considerably reduced. To understand the way in which turbulence influences the amount of suspended pollution in towns, it is necessary to consider what happens when a puff of smoke emerges from a chimney. The puff may be visualized as about a cubic foot of chimney gases, inserted into the stream of air blowing past the chimney top; and the total weight of smoke in the puff may be  $\frac{1}{4}$  to  $\frac{1}{2}$  gramme, corresponding to a concentration of about 10000 milligrammes of smoke in a cubic metre. If the stream of air were blowing with true stream-line motion, the puff would travel for miles, increasing very slowly in size and diminishing in blackness as the smoke particles near the edge are pushed outwards by the bombardment of air molecules.



Of course air never moves with stream-line motion past chimney tops. For one thing, by the presence of the chimney, eddies are set up similar to the eddies in a river flowing round and over a stone; and there are usually eddies of all shapes, orientations, and sizes in the wind, which have been caused by other obstacles in the path of the wind and by the heating of air in contact with the ground. It may be said about these eddies in general that they move along with the wind and slowly decrease in total energy as their motion becomes transformed into heat; but usually as they move along their energy is reinforced by newly formed eddies.

If the puff of smoke emerges from the chimney into a 7 mi/hr wind of about the average degree of turbulence, in two seconds it will travel 20 ft from the chimney, and it will have expanded so much in consequence of turbulence that it no longer screens from view objects behind it. The density of smoke will then be about 200 milligrammes per cubic metre. At about a hundred feet downwind from the chimney, the puff will cease to be visible, and the density of smoke will be about 5 milligrammes per cubic metre. Four miles downwind, about half an hour after being emitted, the smoke will have a density of about  $\frac{1}{10,000}$  milligramme per cubic metre if the air with which it mixes is perfectly clean. Country air in Britain usually contains between  $\frac{1}{100}$  and  $\frac{1}{4}$  milligramme of smoke per cubic metre, so the puff would probably become unidentifiable somewhere between 100 yards and half a mile from the chimney.

In average conditions, smoke is quickly dissipated by turbulence, as the above example has shown, and sulphur dioxide and other forms of suspended pollution are dissipated in the same way. The effect of turbulence on the density of suspended pollution in towns is not quite the same, however, as on single puffs of smoke, because there are so many chimneys emitting pollution in towns that the puffs quickly merge into one another horizontally, and form a fairly uniform layer of pollution. But some of the eddy motion of the air is upwards and downwards, and this has the effect of increasing the thickness of the layer of pollution by making it spread vertically upwards. The stronger the vertical eddy

motion, the more rapidly does the pollution spread upwards, and the lower is its density near the ground.

Most of the time there is enough eddy motion in the air for suspended pollution to diffuse upwards from towns and be partly replaced by cleaner air from above. There are times, however, when turbulence is nearly absent, and while there may be sufficient turbulence for pollution to diffuse down to ground level from the chimney tops, the upward diffusion may be very slow indeed. As a result of changes in turbulence which commonly occur, the density of smoke near the ground may change by as much as 10 to 1. The concentration of sulphur dioxide probably does not vary quite so much, because a relatively large amount of sulphur dioxide is emitted from high industrial chimneys and may be slow in diffusing down to ground level when there is little turbulence.

There tends to be little turbulence during calms or when the wind is light, because few eddies are then produced by trees and buildings in the path of the wind. Turbulence also tends to be less at night, because the ground is then often cooler than the air above it, and there is no possibility of turbulence due to local heating of the air. On cloudless nights, when the ground cools most rapidly, the surface layers of air cool also, and a condition is set up in which the air is warmer above than near the ground. This condition is known as an *inversion* (more strictly, a surface inversion). While there is an inversion, vertical eddy motion due to local heating of the air is impossible, and in addition, vertical eddies of any kind die out more quickly than usual.

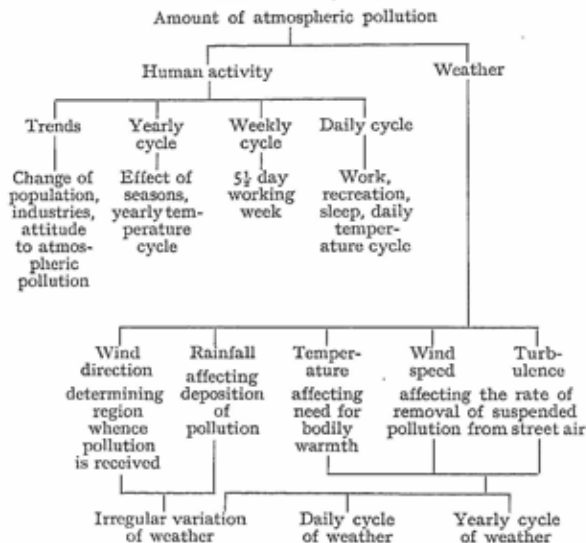
There is least turbulence of all, therefore, during calms or light winds accompanied by an inversion. These conditions occur most frequently at night, especially in autumn and winter, and they tend to persist into the morning. This is why, when fires are lit in the early morning, they often produce the greatest densities of pollution. High densities also occur in these weather circumstances in the evening after sunset, if a sufficient number of fires is still burning.

*Fogs.* When the surface air is cooled by contact with the ground, its temperature may be reduced below the dew point,

and dew or frost settles on the ground. If, however, a thick layer of air is cooled below the dew point, water condenses within the air to form extremely small droplets, and a fog is produced. Fogs occur most frequently in the early morning,

Table 26. *Causes of change in atmospheric pollution*

The chart should be read downwards, with the words "depends on" inserted at every step.



during calms or light winds accompanied by an inversion, and it should be noted that these are the very conditions which produce high concentrations of pollution. This is why, in towns, fogs are nearly always accompanied by abnormal densities of smoke and sulphur dioxide. It is quite wrong to say that smoke produces water-fogs, or that water-fogs increase the smoke, because although both fogs and abnormally dense smoke tend to occur in the same meteorological

conditions, neither has a strong direct influence on the other. It is a fact, however, that smoke and sulphur dioxide greatly increase the unpleasantness of fogs. The "London Particular", which happily is occurring less frequently now than 40-50 years ago, owes its dirt, its yellowish hue, and its acrid taste to atmospheric pollution.

*Summary.* Although there may be other causes yet to be discovered, the more important known causes of change in pollution have now been discussed, and they are recapitulated in Table 26. The rate of emission of pollution is affected by trends and casual variations, by yearly, weekly, and daily cycles, and by weather, especially temperature. The quantity of pollution at any particular place is affected by the rate of emission of pollution in an area the size and position of which depends on the direction of wind and other weather conditions; in addition, the quantity of pollution depends on rainfall, wind, velocity, and turbulence. The meteorological variables are subject to yearly and daily cycles as well as irregular variations.

All these causes come into play simultaneously, and they affect different forms of pollution differently. Perhaps it is not surprising that it was necessary to begin this chapter with the remark that the study of atmospheric pollution is an untidy science.

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## Chapter XIII

### EFFECTS OF POLLUTION

Complex as the relations are between atmospheric pollution and fuel, methods of combustion, human habits, and weather, a scientific study of its effects on everyday life is harder still. This is not because the effects are small, but because they are slow in operation and usually intermingled with other factors. The effect on health is particularly hard to assess. In the general level of health the differences between a poor district of a town and an equally poor rural community are often very considerable, but they are not entirely due to atmospheric pollution. Other factors, such as overcrowding, occupation, and habits play their part, and their consequences are not easily separable, even by statistical methods, from those of pollution. For quite a different reason, the effect of pollution on a normal, healthy individual is also difficult to measure. This is because the human system can compensate to a remarkable degree for departures from perfect health such as would be caused by an unsuitable environment. With careful study, however, the harm done by pollution to the sick, the young, and the aged is becoming increasingly well known.

Where the effects of pollution can be scientifically measured they are rather more easy to assess. The waste of unburnt fuel, the extra cost of artificial lighting attributable to smoke, the cost of cleaning and replacing smoke-soiled furnishings and clothes, the damage to building materials and paint have been estimated approximately in terms of monetary loss. The effects on metals and vegetation have been tested experimentally. In the present chapter, some instances are quoted of particular effects of atmospheric pollution; where possible, numerical data are given, but it must be recognized that the available information is far short of what is desirable.

*Health.* How much harm is done to public and individual health by urban atmospheric pollution is still a matter of opinion, though many authorities consider the total harm to be very serious indeed. Naturally, the effects of atmospheric pollution on the human system have been most closely studied in the severe and fatal cases, and it will be well to begin with the effects of the heaviest concentrations of pollution. The diseases caused by inhaled dusts in mines, works, and factories are now well understood. Under the general heading of *Pneumokoniosis* they include silicosis, a progressive inflammation of the lung tissue which, once it has begun as a reaction to the common substance silica, apparently cannot be arrested; and asbestosis and other forms of reticulosis, in which particles put out of action many times their volume of lung. Although it is a serious occupational disease, causing the deaths of about 430 men per year in Britain, there is no evidence that pneumokoniosis in any form has ever been contracted by breathing street air.

Particulate and gaseous pollution in the open air seldom reaches high enough concentrations to cause rapid death, but there have been two such disasters in the past 25 years. The first was in December 1930, in the Meuse Valley, near Liège, Belgium, occupied by a number of iron and steel works, zinc works, glass works, potteries, lime kilns, electric generating stations, and chemical works including phosphate works. For five days a fog persisted and the air within the valley seemed to remain stagnant. Sixty-three people died as a result of atmospheric pollution, the concentration of which was not measured. The victims all suffered from acute irritation of the respiratory system and vomiting, until death came through heart failure. Several hundred other people were severely attacked with respiratory troubles, and many head of cattle had to be slaughtered. In Table 17, Chapter IX, is a list of the maximum concentrations of toxic substances allowable for prolonged exposure, taken mostly from "Noxious Gases" by HENDERSON and HAGGARD. According to the *Lancet*, 1946, vol. 151, p. 835, the substances most likely to have caused the Meuse Valley disaster appear to have been fluorides emitted from phosphate works.

In November 1948 another 5-day fog at Donora, near Pittsburgh, caused the death of 19 people. The most probable cause was sulphur dioxide from a zinc-smelting works where ores of high sulphur content were roasted.

Less exceptional concentrations of pollution, such as occur during any winter in large towns, fortunately do not lead to such immediately disastrous results, although the total death-roll may be very high because of the large numbers of people involved. The people most affected are the very young, the sick, and the aged. In England and Wales, the mortality rate of children under five from bronchitis and pneumonia is about 20 per cent higher in industrial towns than in other towns, if allowance is made for geographical latitude and distribution of inhabitants according to density per acre and per room.

In the United Kingdom there are approximately 500 000 deaths each year. Of these about 19 000, or 3·8 per cent, are attributed to respiratory diseases. After heavy concentrations of pollution in towns such as London, Glasgow, and Leeds, the death rate from respiratory diseases is sometimes more than doubled, even when due allowance is made for the effect of foggy weather which usually accompanies the atmospheric pollution. In the nineteenth century the concentrations of pollution were probably worse than today; certainly the effects on the death-rate were considerably greater.

With the evidence at present available, it is not always possible to distinguish clearly between the effects on health of different forms of atmospheric pollution. Smoke is believed to be a cause of cancer of the respiratory system, from which over 500 people die each year in the United Kingdom, though atmospheric smoke may be generally less important than tobacco smoke. The wide differences between the death-rates in towns where there are similar concentrations of smoke suggest that one cause of this form of cancer must be some particular compound which is found in varying amounts in the smokes from different coals. Attempts are being made to determine whether the cause is an arsenical compound, benzpyrene, or some other compound.

The effect of sulphur dioxide on a group of healthy individuals was studied in 1932, when careful statistical tests were made on the health of 100 factory workers who were exposed, during working hours only, to sulphur dioxide at a concentration of 30 volumes per million. The test group of 100 was compared with an equal control group who worked in normal air, and was found to suffer from a significant increase in the incidence of (a) naso-pharyngitis and other symptoms of irritation of the respiratory tracts, and (b) abnormal urinary acidity, a tendency to increased fatigue, shortness of breath and abnormal reflexes. There was no significant change in the incidence of colds, but their duration was increased. The test group breathed as much sulphur dioxide as the ordinary citizen would breathe if the air contained a daily average of 10 volumes of sulphur dioxide per million ( $28.6 \text{ mg/m}^3$ ). The highest daily average observed since 1931 at Westminster Bridge was 0.74 volume per million.

*Animals* may be expected in general to suffer similarly as human beings, but sheep and cattle are particularly sensitive to fluorine. In districts where emissions occur, fluorine tends to accumulate in the grass; the teeth of grazing animals have been known to deteriorate so much through fluorosis that the animals were unable to feed.

*Plants* are more sensitive than animals to atmospheric smoke and sulphur dioxide, though this is not true of all forms of pollution. For instance, grass assimilates an appreciable proportion of fluorine without harm. Smoke is particularly harmful to plants, because it clogs the stomata through which atmospheric carbon dioxide, the main food of plants, has to enter. Research in Leeds showed how radishes and other plants lose from half to nine-tenths of their growth in a polluted atmosphere, if they survive at all; that soil loses its stock of accessory plant foods very rapidly under the action of polluted rain; and that the amount of pollution in any particular district may be inferred with remarkable accuracy from the type and condition of the vegetation.

On the effects of sulphur dioxide, research in Canada revealed that lucerne was injured by as little as 0.3 volume



per million and barley by 0.8 volume per million; in concentrations of over 1.0 volume per million, increasing proportions of the foliage and fruit were destroyed. The effects of both smoke and sulphur dioxide are probably enhanced during fog. In the hot-houses at Kew Gardens, plants were found to suffer from atmospheric pollution on foggy days although the concentration of sulphur dioxide can seldom reach 0.3 volume per million.

*Metals.* Iron rusts nearly three times as rapidly in Sheffield as in Farnborough, Hants; non-ferrous metals corrode about three times as fast in Birmingham as in Cardington, Beds; pylons, wires, railways lines, in fact all common metal objects corrode more rapidly in towns than in the country.

Experiments at the Chemical Research Laboratory, Teddington, have shown how rapidly, and in what circumstances, the different metals corrode. The rate at which iron rusts is greatly accelerated by traces of sulphur dioxide in the air, and by particles of smoke or ash; in the presence of these forms of pollution (but not otherwise) there is a very great increase in the rate of rusting when the relative humidity of the air rises above about 80 per cent. Rusting is most rapid when all three factors, humidity, sulphur dioxide and particles, are present together. For example, a specimen of iron carrying particles of carbon was exposed to a humid atmosphere containing traces of sulphur dioxide; it showed approximately a hundred times as much corrosion as a similar specimen, similarly exposed in the absence of sulphur dioxide. Another specimen of iron was exposed in a muslin cage which permitted air and sulphur dioxide to reach it, but excluded particles of pollution. Its rate of rusting was negligible compared with that of a similar specimen which was not inside the cage.

Other metals are attacked in different ways by atmospheric pollution. Nickel catalytically oxidizes atmospheric sulphur dioxide and accumulates a film of sulphuric acid; this reacts with the metal to form basic nickel sulphate. Chromium behaves similarly, and chromium plate will not deteriorate if it is frequently washed. Zinc slowly and steadily corrodes in a polluted atmosphere, forming basic zinc sulphate. Copper

tarnishes if it is kept dry indoors, forming copper oxide and copper sulphide; but out of doors it forms a "patina" of basic copper sulphate, and this protects it from further corrosion. Silver tarnishes like copper, and it is often worth while for silver articles to be rhodium-plated as a temporary protection, at a cost of about ten per cent of their selling price. Aluminium and its alloys form a protective film which resists the action of atmospheric pollution.

*Wool, cotton, and leather materials* are rotted in polluted atmospheres as a result of the absorption of sulphur dioxide and its oxidation to sulphuric acid, which attacks the proteins in the materials. In a humid atmosphere containing 10 volumes of sulphur dioxide per million, specimens of leather will rot in six weeks, unless they are protected by rubbing with a solution of potassium lactate or certain other organic salts. The deterioration is much slower in ordinary atmospheres, but is important, for instance, in leather book bindings, particularly in urban libraries.

*Works of art* can be most seriously affected by pollution. Smoke is harmful to paintings, particularly on wood; also to textiles, leather, and wax-film material. Sulphur dioxide affects oil- and resin-film material, leather, paintings (particularly on mud wall, paper, or wood) and vellum. The slightest deterioration of any work of art is naturally a matter for concern.

*Building materials* are both corroded and disfigured by atmospheric pollution (Figs. 76, 77.) Smoke particles stick on every surface of stone, brick, paint, or glass, whether horizontal or vertical, forming a film of soot which may or may not be partly removed by rain. The sandstone buildings of cities in the midlands and the north of England are blackened soon after they are built, the details of the architect's design disappearing into a dingy uniformity. Limestone buildings go into half-mourning, their more exposed surfaces being kept clean by rain. Some public buildings of polished stone and limestone are regularly cleaned by hosing.

Although some stones are relatively immune, certain sandstones, limestone, roofing slates, mortar, and reconstructed

stone are prone to attack by sulphur dioxide and the acid constituents of atmospheric pollution. Any building material containing carbonates suffers damage since the insoluble carbonates are converted by polluted rainwater into soluble sulphates or chlorides; the stone disintegrates underneath



Fig. 76. Weathering at Chelsea Hospital. Red brick pier showing exfoliation. (From *The Smoke Problem of Great Cities* by Sir NAPIER SHAW and J. S. OWENS, Constable & Co., London 1923.)

the surface and ultimately a large flake falls off. An authoritative estimate in 1930 put the cost of the damage by pollution to building property in the United Kingdom at two to two-and-a-half million pounds per year.

*Fog, Visibility and Sunlight.* For the reasons given in Chapter XII, smoke and gaseous pollution reach their highest concentrations during foggy weather, but although foggy town air seems to contain large quantities of water and dirt, the

weight of unwanted material is less than might be supposed. For example, 3500 cubic feet of air is enough to fill two rooms of an ordinary house, and weighs about 2 hundredweights. In a typical city fog the droplets of water in this quantity



Fig. 77. Unrestored and restored portions of stone-work, Henry VII chapel.

of air weigh less than 4 ounces (though over 20 ounces of water vapour remain, as an invisible gas, in the air). The smoke and sulphur dioxide each weigh about a hundredth of an ounce, and the sulphur dioxide is enough to make two to three drops of concentrated sulphuric acid. But the smallness of these quantities does not prevent fogs from having the harmful effects which have already been briefly

discussed, or from disorganizing transport or reducing daylight.

Visibility may be defined as the maximum distance at which scenery can be distinguished, in daylight, against the sky or air as a background. It varies in different conditions from a few yards to over a hundred miles, and the poorest visibility is always caused by fog, any smoke particles present being relatively unimportant. In the absence of water droplets, however, smoke is a frequent cause of poor visibility, and a real danger to aircraft which require a visibility of about half a mile when landing.

The part played by smoke particles in reducing visibility may be seen by considering the records of visibility, made by meteorological observers on days when there is no possibility of fog. On such days, the average visibility-distance in winter from Kew Observatory is twenty per cent less than in the country near London. The difference must be due to extra smoke in the air around Kew, and it should be remembered that Kew has not by any means the smokiest, nor the country round London the cleanest air in Britain. At Leicester it was found that when the concentration of smoke was doubled the visibility-distance was halved; and it was deduced that a ton of smoke (suitably placed) is sufficient to blot from overhead view nearly a square mile of country.

On smoky days in winter, townspeople often need artificial indoor lighting an hour or more before sunset, and may even need it all day, whereas in summer they can read by daylight until after sunset. The setting sun should always be equally bright, but in winter in many districts, and throughout the year in some, it is frequently no more than a dull patch of red. In this era of cheap and easy artificial lighting, it might seem that the loss of daylight causes no hardship other than an occasional unexpected lighting-load on the electricity generating stations. But the human body requires natural light and ultra-violet radiation to help in its perpetual struggle against micro-organisms and to produce vitamin D, and a considerable proportion of urban ill-health is attributed to lack of "sunshine". Insufficient visible and

ultra-violet radiation is believed by the medical profession to give rise to general ill-health, and especially to a high incidence of tuberculosis and rickets in children. From measurements in a number of British cities, by comparing the daylight received at points outside and inside the city, it is estimated that from 25 to 55 per cent is lost through smoke alone, in the five winter months November to March. The losses of ultra-violet radiation are similar. On the gloomier winter days, nine-tenths of all radiation is lost.

*The Cost of Pollution.* Although there is no way of evaluating the effect on health, many of the harmful effects of atmospheric pollution which have just been discussed can be measured approximately in terms of money. The following estimates have been made of the cost of atmospheric pollution from all assessable causes, including the loss of unburnt fuel in smoke, but excluding loss of health: Pittsburgh, Pennsylvania, 1912, 20 dollars or £4 per head per annum; London, 1924, 24s. per head per annum; Manchester, 1919, well over £1 per head per annum; Manchester, 1924, 30s. per head per annum; in the whole of Great Britain, 40 to 50 million pounds per annum in 1924, and about 100 million pounds per annum in 1947.

Certain individual items on the bill of costs are of special interest. Household washing is more troublesome in industrial cities than in country towns, not only because of the difficulty of drying white articles without getting them dirty from atmospheric pollution, but because on an average there are more articles to be washed. The extra cost in 1919 of the materials and fuel used for household washing in Manchester, compared with Harrogate, was 7½d. per week or £1 12s. 6d. per year per household. The extra time required for the household wash in Manchester was about one hour per week.

Exterior decorating is required by branches of multiple shops in the country every three years, in moderately smoky districts every two years, and in very smoky districts every year. Expenditure on cleaning and painting of buildings is 15 to 40 per cent more in badly polluted towns than in clean towns.

The value, as a fuel, of the 2.4 million tons of smoke made each year in Britain is about six million pounds at present prices, but this is not all. An example was given, in Chapter V, Fig. 22, of smoke that carried with it from three to five times its own weight of invisible combustible matter. If it is legitimate to generalize from this particular instance, the invisible combustible matter that accompanies smoke must be worth a further 20 million pounds, even after a generous allowance has been made for the combustible matter which is necessarily wasted under the optimum conditions of combustion in a furnace.

*Conclusion.* The harmful effects of atmospheric pollution are so widespread and varied that they are difficult to summarize. There is no doubt whatever that atmospheric pollution in the concentrations in which it is at present allowed to occur, particularly in urban areas, causes damage to property and makes living conditions generally less pleasant, nor that concentrations sometimes occur which can be held directly responsible for immediate serious damage to plant and even animal life. Since the advent of cheap transport the population has been drifting away from the centres of towns to the suburbs and the surrounding country, creating new and difficult social problems and throwing out of balance the original structure of the town. For many people, the advantages of living near to places of work and the amenities of a town no longer outweigh the disadvantages. Very high on the list of disadvantages is that of dwelling, with wife and children, within the smoke pall in which the wage-earner is generally required to work.

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## Chapter XIV

### PREVENTION OF ATMOSPHERIC POLLUTION

Although there are probably few people nowadays who seriously believe that pollution does no harm, there seem to be many who think remedial measures are not worth while. It is quite true that if cleaner air could be achieved only by sacrificing some still more important amenity—such as, for example, the artificial heating of homes—there would be nothing to be done; but there are many instances of pollution which could be reduced without any sacrifice of this sort. Evidently, the rational way to consider the prevention of pollution is to estimate whether the preventive measures would cost, in money, labour, comfort, and general amenity, more or less than the pollution which would be avoided. In general, such decisions may be difficult and open to differing opinions, but there are a number of cases where the issue may be clear cut. As one example, when the people in a neighbourhood are inconvenienced by pollution for which a few of their members are responsible, there is a likelihood, to say the least, that the offending few ought to go to the trouble of reducing the nuisance for the benefit of the many; to enable decisions to be reached on cases of this kind, there are laws, some of which are discussed in the next chapter. As a second example, there are numerous instances of pollution which costs money to the producer; once the change-over to new methods or new equipment has been paid for, money is saved by the concern which had been emitting pollution.

#### PREVENTING SMOKE

If it is to be considered whether the prevention of smoke is worth while, its cost must first be estimated. As was evident in the last chapter, there is no certainty about the cost of smoke to any community, but if half the total damage by



pollution is due to smoke, in Great Britain about 50 million pounds is paid each year to put right damage caused by some 2.4 million tons of smoke (see Table 18). This implies an average cost of about £20 per ton of smoke emitted, but the sum may need to be increased when further considerations are taken into account. For one thing it represents the trouble or expense people are prepared to go to in combating smoke, rather than the cost of reducing the effects of smoke to negligible proportions. Secondly, in densely populated areas the damage from each ton of smoke must be higher than the average, and, thirdly, no monetary account can be taken of the effect of smoke on health, happiness or comfort. If, therefore, a ton of smoke can be prevented by an expenditure of £20, this money or the labour it represents is well spent indeed. When it is considered that a ton of smoke may be made by a quite modest industrial concern in a week, or by ten domestic fires in a year, it is evident that for the sake of the community as a whole, the prevention of smoke is likely to prove well worth while.

The main points which have been made in this book about the production and prevention of smoke from particular sources are brought together in Table 27. It is technically not difficult to burn coal smokelessly in medium or large shell-type or water-tube boilers; and although instruments and labour of a relatively high standard are required, in many instances a reduction of smoke is likely to be achieved at a negative cost to the management.

Categorical statements are notoriously easy to refute, but this one is almost universally true: raw coal cannot be burnt in domestic grates, small vertical boilers, locomotives, or most existing types of heat-treatment furnaces, without making smoke. Resort should be made to alternative fuels. These are often advantageous in themselves; for instance, most metallurgical and other heat-treatment processes are more efficient and more controllable when fired by gas or oil, instead of coal.

Railways could, and in the opinion of many, should be electrified. Even through a very great capital expenditure is needed to electrify a railway, the saving of coal (estimated

Table 27. *Prevention of Smoke*(a) *Smoke from Bituminous Coal*

Open grate (nearly all types at present in use)	Smoke unavoidable. Smoke emitted per ton of coal burned is about twice as much as from the average industrial furnace. The only remedy is to burn a smokeless fuel.
Open grate (best possible design)	Smoke unavoidable when the fire is first lit. Possibility of a considerable reduction in the amount of smoke produced when fire is made up.
Closed and closeable stoves	Smoke unavoidable; may be reduced by admitting secondary air after refuelling; best to burn anthracite or coke.
Vertical boiler, Locomotive boiler	Smoke unavoidable except, e.g., by underfeed automatic stoking; coke and anthracite are possible alternatives to coal.
Lancashire and other shell boilers; all watertube boilers	Smoke avoidable by the following alternatives: (1) very careful hand-stoking of existing appliances, (2) fire-door with provision for admitting a large amount of extra secondary air after each refuelling, (3) automatic stoking, with proper control of combustion.
Metallurgical, brick, pottery, glass, etc. furnaces	Smoke generally unavoidable without a radical change of design; generally best to burn producer gas, by-product gases, town's gas, coke, oil, or electricity. See also Pulverized-coal burners.
Pulverized-coal burners	No smoke, but a strong tendency for particles of ash and unburnt coal to be emitted; these can be prevented by efficient grit arresters (see next Section, on Ash and Grit).

(b) *Smoke from other fuels*

Internal combustion engines	Relatively small amounts of smoke, chiefly from the lubricating oil.
Furnaces burning oil or other liquid fuel	Smoke entirely avoidable with proper control of fuel-feed equipment and combustion conditions.
Domestic or industrial appliances burning gas or "smokeless" solid fuels or electricity	Very slight smoke emission possible from anthracite, low-temperature coke, and gas coke. No smoke from metallurgical coke, or from any gaseous fuel or electricity. Smoke entirely avoidable in the conversion of coal to coke, gas, and electricity.

as nearly four-fifths, or 12 million tons per year for the British railways) and the improvements in amenities at passenger stations, engine sheds, and elsewhere, are powerful arguments. At the present time, economic conditions are strongly inhibiting all long-term capital investments but, to judge from experience gained in south-east England and other places, a time seems to be approaching when the electrification of section after section of the railway system will be financially worth while. The prospect of smoke abatement will then help very considerably to tip the balance in favour of electrification. Other smokeless fuels are likely to have their uses under special conditions. Oil-fired steam engines may be operated where fuel oil of low grade would otherwise be wasted, but diesel-driven locomotives are more generally useful, particularly in goods yards. It is worth noting that coke was used for a time in England as a locomotive fuel, but there was a reversion to coal when the inventions of the brick arch, the deflector plate at the fire-hole door, and the blower improved the conditions of combustion.

The problem of eliminating domestic smoke is a complex one, most particularly in Britain. In this country, there are open fireplaces in 12 million dwellings, many of which will still be habitable in 100 years. Some of the fireplaces will be converted for the burning of gas or coke; others will have low-temperature coke burnt in them as they are; others will become redundant as householders modernize their equipment, for example by installing cookers or water heaters using gas, electricity, or smokeless solid fuel. There are efficient, smokeless alternatives for every domestic coal fire, but smoke abatement seems to progress very slowly, and even many new houses are being equipped with fireplaces in which coal is burnt.

Why are we so unwilling to give up this open fire? Although we know perfectly well that it is costly, inefficient, and labour making, many of us do not grudge either extra expense or effort on behalf of the home, where we reserve the right to be extravagant if we please. We might change our minds if we paused to remember the draughts in winter, and the smallness of the space where we can sit in warmth;

and to consider how different all this would be if we employed a form of space heating instead of heating by radiation. We need, possibly, to be reminded of what we are missing, and to have opportunities to visit houses with differently designed heating systems. If so, we should pay more attention to the educative literature, demonstrations, and exhibitions on the subject of domestic heating, which are promoted frequently by both official and voluntary organizations.

Perhaps it is not out of place here to mention two new and important services which the Government provides for the benefit of local authorities, firms, individuals, and the nation generally. At the Fuel Research Station of the Department of Scientific and Industrial Research a new test laboratory has been built, in which all the measurable properties of domestic fires, cookers, and water heaters can be evaluated. For the first time, it is possible to trace accurately the many ways in which the heat liberated from the fuel, in any domestic heating appliance, passes into and out of the room for which it is intended. In contrast to this absolute approach, which inevitably leaves out the human element, the Building Research Station of the Department of Scientific and Industrial Research is conducting tests of different forms of house-heating in actual houses, occupied by ordinary families. The outcome of such investigations as these should be a decisive advance in the design of domestic heating equipment, and a clearer realization that bituminous coal is far from being the ideal fuel for such equipment.

There can be no doubt that the atmosphere of Britain will be very different when bituminous coal ceases to be burnt in private houses or on the railways, and when industrial boilers are operated smokelessly. In some districts, however, smoke from special industries such as pottery, metallurgical, or glass works is a major problem, and must be dealt with by special methods, some of which were outlined in Chapter VII. The general problem of preventing smoke is not an insoluble one, either technically or economically, and many citizens of today should live to witness striking improvements in the atmosphere of their towns.

## PREVENTING ASH AND GRIT

The type of pollution most apparent to the eye depends upon the point of view. People seeing an urban district from a neighbouring hill or from the air always notice smoke most easily because of its great power of absorbing and scattering light. If to people living in it, however, a district has the reputation for being heavily polluted, smoke is not usually the main cause. Unless there are chemical fumes with pungent smells the cause is nearly always traceable to a high rate of deposition of ash or grit; these are to them the most obvious form of pollution.

The total damage done by grit is probably only a few per cent of that caused by all forms of atmospheric pollution, but the damage occurs chiefly within a short distance of the source of the grit, and people who have cause to complain can usually indicate with some certainty the place of origin of the particles. Partly for this reason, perhaps, the immediate causes of grit emission have been closely studied and the development of industrial grit arresters has proceeded farther than that of all other devices for reducing atmospheric pollution.

Particles of ash and grit are emitted from chimneys if two conditions are fulfilled: if particles are available to mix with the gases in the combustion chamber, and if the velocities of the gases in the flues and the stack are sufficient to carry the particles away. The emission may be prevented or much reduced, therefore, by selection of fuel and by design and operation of the fuel-burning equipment.

*Selection of Fuel.* The washing and grading of coal at the collieries is clearly a useful way of reducing emission. In washing, much of the mineral matter, including a proportion of the finer particles, is removed. In grading, the coal dust is separated from the other sizes and can be burnt in specialized equipment. Particle emission is also reduced if the coal cakes on the fuel bed, when particles fuse together and are prevented from escaping. Where fine slack coal is burnt on chain-grate stokers, it is common practice to wet the fuel on its way to the grate with about 10 per cent of its weight of water or

steam; the purpose of the moisture is to hold the particles together until fusion begins.

The solid fuels, then, which are least likely to produce excessive emission of ash and grit, are washed and graded coal, and good caking coal. Coke and free-burning coal, especially when they contain a high proportion of fine breeze or dust, are liable to cause fly ash and grit. Unfortunately, one of the products of a coal-washing plant is "middlings"

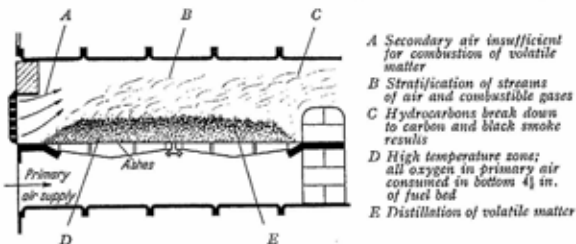


Fig. 78. Thick fuel bed.

(From *Water Boiler Plant* by F. J. MATTHEWS, Hutchinson, London.)

(or in some cases a slurry) which contains some of the coal mixed with a high proportion of mineral matter. Though perhaps not worth selling, this is generally a good enough fuel to be burnt in the colliery boilers.

The worst potential source of fly ash and grit is pulverized fuel, not only because it is entirely particulate, but because it is usually burnt while in suspension in the combustion chamber. All particles of mineral matter in it, together with the ash residue from each fragment of fuel and, usually, some partly burnt particles of fuel, are free to escape into the flues and the atmosphere, unless they are specially prevented.

*Design and Operation of Furnace.* Fuel is too valuable to be thrown away, and we must consider the next means of defence against emissions of ash and grit—in the furnace and flues. To begin with, in all boilers having grates, if primary air passes steadily and evenly through the fuel bed, the minimum number of particles will be lifted. If the fuel bed is too thick the conditions shown in Fig. 78 are

reached. When a boiler is being forced beyond its rated capacity, the rate of fuel burning is increased by admitting more air than is required for normal combustion. There is a faster air flow through and over the fuel bed and more particles are lifted, including fuel particles which might have had time to burn in the combustion chamber, but which are now swept into the flues without being burnt. In such cases the grit emitted contains a high proportion of unburnt and partly burnt fuel. These considerations apply to many other furnaces besides boilers, but they are especially applicable to large stoker-fired installations. In the present times of high industrial output, many chain-grate and retort-stoker installations are being forced, with the result that excessive quantities of "smoke" are emitted. The "smoke" may not be black enough to contravene the regulations, but it consists of minute spheres of coke and ash which are responsible for numerous minor eye injuries, and mar the neighbourhood.

Many of the particles lifted from the fuel bed may be trapped in the flues. If these are long, as in the Lancashire boiler, some of the particles will have time to drop to the bottom, where they will remain until the boiler is cleaned. Changes in direction and velocity, especially if the flow becomes turbulent, will precipitate particles; on the other hand a straight flue system, as used in some vertical boilers, is likely to emit much grit and ash. If a vertical part of the flue system is wide—for example at the base of the stack—the upward rate of flow of the gases is diminished so much that the larger particles cannot escape. Dust traps of this sort should of course be cleaned before the accumulation of dust limits their effective size and the larger particles begin to escape.

*Grit Arresters.* When the emission of flue dust cannot be prevented by other means, special grit arresters are required, of a type chiefly determined by the size of the particles to be traffed. The larger a particle is, the easier is its removal by mechanical means; and the largest particles of all, over about 0.1 mm (100 microns) in diameter, can be allowed to settle under gravity—for example, in the flues of a Lancashire boiler.

For particles between about 0.02 and 0.1 mm (20 to 100 microns), the acceleration of gravity is not enough in the time and space usually available, but an artificial acceleration can be produced by whirling the dust-laden gas round the inner wall of a cylinder. A cyclone dust-separator, which is based on this principle, is illustrated in Fig. 79. The gas enters at high speed tangentially at the top of the cylinder, and takes a course in tighter and tighter spirals to the bottom, where it passes up a central tube. The particles are thrown centrifugally to the walls of the vessel, and find their way to the bottom: they are discharged through an air lock if, as is usual, the gases within the cyclone are at less than atmospheric pressure.

In Fig. 80 a modern development of the cyclone is illustrated for which a high efficiency with still smaller particles is claimed. The number of spirals required before a particle reaches the wall of the cylinder is proportional to the diameter of the cylinder, so the air stream is divided and passes through a hundred or more cylindrical cyclones of about 15 cm (6 in.) diameter. In each component of a multicyclone the air passing up through the central tube contains a residue of fine dust but, because the air continues to travel spirally, most of the dust travels near the walls of the central tube. The air nearest the walls, up to about 25 per cent of the total, is therefore "skimmed" from the remainder, and passed through a secondary multi-cyclone with units of about 5 cm diameter. It is possible to replace the secondary multi-cyclone by an electrostatic precipitator (see below).

Small particles less than about 20 microns in diameter can be eliminated in the laboratory in a number of ways, for

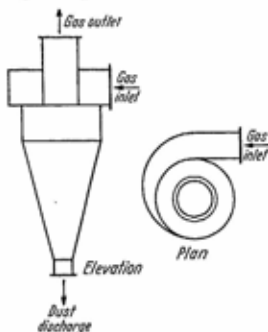


Fig. 79. Cyclone dust separator.  
(Courtesy of the Institute of Fuel.)



example, by thermal precipitation, as described in Chapter X, or after coagulation by the action of sound waves. Filtration, too, can be effective on a small scale, and cloth-bag filters are used for obtaining samples of flue dust for test purposes. But filtration is not usually a practicable method of extracting

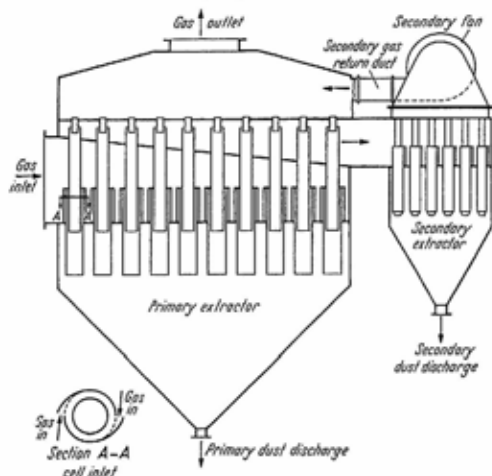


Fig. 80. Two-stage multi-cyclone. (Courtesy of the Institute of Fuel.)

dust from flue gases, because of the quantities of dust involved, the presence of corrosive substances, and the difficulties of cleaning or replacing the filters. The dust can, however, be successfully removed by spraying or scrubbing the gases with water. In the two processes for removal of sulphur dioxide, described in a later section of this chapter, the flue gases are thoroughly scrubbed by being brought into contact with a water film, and flue-dust particles of all sizes are removed.

Where it is important to remove a high proportion of particles smaller than 20 microns, the most widely used method is by electrostatic precipitation. Fig. 81 shows diagrammatically a typical electrostatic precipitator. The flue gases pass

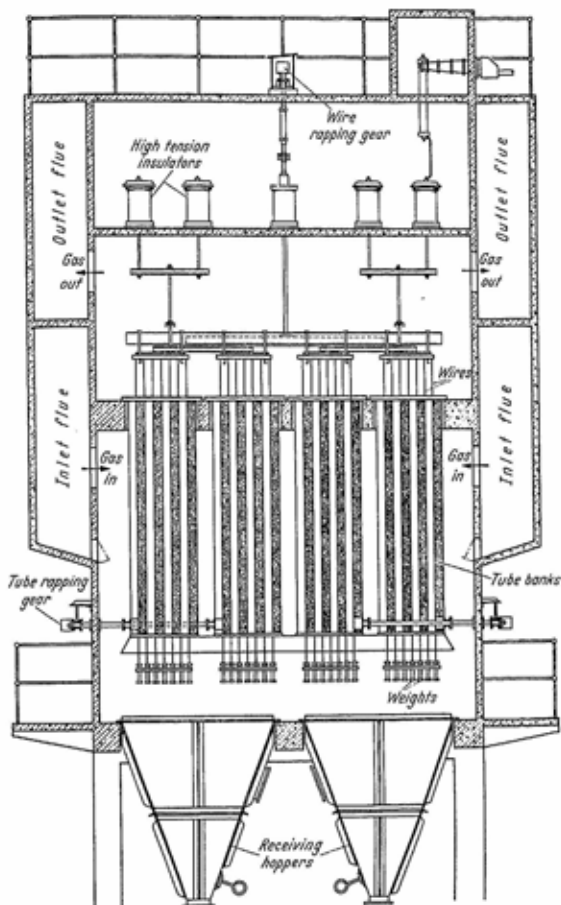


Fig. 81. Electrostatic precipitator, with vibrator rapping gear.  
(Courtesy of Sturtevant Engineering Co., London.)

in stream-line flow through earthed vertical tubes in parallel, in each of which is a central wire charged to about  $-40\,000$  volts. Ionized gas molecules, travelling at high velocity between wire and tube, collide with the particles in the gas stream and these, too, become electrically charged. Those that are negatively charged are driven to the earthed tubes where they stick. When the tubes are jolted by the vibrator rapping gear the particles, now coagulated into larger aggregates, escape against the flow of the gas stream while keeping near the walls of the tubes, into hoppers. Those particles which are at first positively charged are driven to the central wires from which they are released by the rapping of the wires. They have now the same charge as the wires, namely  $-40\,000$  volts, and they immediately join the other negatively charged particles in their migration to the earthed tubes.

Electrostatic precipitators are capable in practice of removing 95-99 per cent of the weight of dust from flue gases; they are rather more effective for removing mineral dust than carbonaceous dust such as particles of partly burnt coal. From a combustion chamber fired with pulverized coal there are very large quantities of particles, consisting of the entire mineral matter of the fuel, and in some cases nearly an equal amount of unburnt carbonaceous matter. Although up to about a half of this grit accumulates in the bottom of the combustion chamber the rest passes on with the flue gases and must be removed by some means. The usual way is by electrostatic precipitation, and though expensive equipment is required the costs of operation at electricity works are low. At other works there is a possibility that some form of multi-cyclone may prove cheaper and equally efficient.

In 1936 the Electricity Commissioners recommended that the dust concentration in the gases leaving power-station chimneys should not exceed 0.4 grain per cubic foot, and that not more than 0.15 grain per cubic foot should exceed 20 microns in diameter. Since then, electrostatic precipitators have become the accepted standard at power stations where pulverized coal is burnt, and stoker-fired boilers have been furnished either with electrostatic precipitators or efficient cyclone grit arresters.

One serious problem with any grit-removal plant is the disposal of the collected dust, which may amount to over 2000 tons per week at a single generating station. Disused quarries and ponds in the neighbourhood can be filled up, but precautions must be taken against the dust becoming wind-borne in dry weather; for example it can be covered with a layer of soil in which vegetation can take root. One of the few cases of a dust storm in England occurred when several acres of dust "lagoons" became so dry that the particles were lifted by the wind.

*Air Conditioning.* In areas where the emission of pollution is particularly high it may be necessary to purify the air before it enters certain rooms: e.g. in hospitals, or testing rooms for gas turbines. The task is relatively easy if in any case the air requires heating, cooling, or a change in its humidity, before it is ideal for human consumption. It is, however, a different problem from that of removing dust from flue gases: (1) the quantities of air to be treated are usually not so large, (2) since the air is to be breathed, it cannot be contaminated with poisonous substances, (3) the particles are usually smaller in size and (4) their concentration is much less than in flue gases. Frequently it is possible to use filters of cotton wool or similar material without having to renew the filters too often. Electrostatic precipitation is also used, but with reduced voltages, since it is important to prevent the electric discharge from producing ozone and oxides of nitrogen in objectionable quantities.

### PREVENTING SULPHUR DIOXIDE

In comparison with smoke and dust, sulphur dioxide is a form of atmospheric pollution which is most difficult to prevent, although there are simple ways of appreciably reducing the amounts emitted into the air. To begin with, therefore, it is advisable to have an idea of the cost of the damage attributable to sulphur dioxide. Apart from its effects upon health, it is probably costing Britain somewhere between 20 and 50 million pounds per year for its damage to metals, wool, cotton, leather, paint and building materials; that is

£4 to £10 per ton of sulphur dioxide emitted, or 3s. 4d. to 8s. 4d. per ton of coal burnt. In densely populated areas the cost will be much higher than the average, so it is reasonable to have in mind a figure of at least 10s. per ton of coal burnt, when considering the economics of reducing the emission of sulphur dioxide in towns. The hygienic, ethical and aesthetic aspects of the problem are too controversial to be considered in this book.

Some of the sulphur in coal is removed at the colliery during hand-picking and washing. Moreover the consumer who burns washed coal needs perhaps 10 per cent less in total weight and the weight of sulphur is correspondingly reduced. This usually turns out to be the major item in the saving of sulphur dioxide and, on an average, perhaps a total reduction of 45 per cent is achieved by burning washed coal. The economics of each colliery determine how much coal shall be washed but it is worth noting, by virtue of the preceding paragraph, that an altruistic consumer should be ready to pay an average of 1s. 6d. per ton more for washed coal than for the same coal unwashed; this is by reason of the reduction in sulphur dioxide, and does not take into account the reduction of ash. Considerations like these are, however, complicated by the great variety of coal available as well as of plant for burning it. The two power stations which are at present committed to limiting their emission of sulphur dioxide (see later paragraphs) need low-sulphur coal to avoid undue strain on their gas-washing plant; their requirements are best met, not by washed coals, but by unwashed coals from South Wales and Durham which contain much mineral matter but less than 1 per cent of sulphur.

It has been mentioned that the material removed from coal at collieries is often highly combustible, and that some of it is burnt in the colliery boilers. Some also is thrown on to spoil banks where it may catch fire spontaneously. In either case, the neighbourhood of the colliery is likely to suffer from sulphur dioxide, and the pollution of towns will have been relieved only at the expense of the colliery districts.

A second way of preventing sulphur in coal from being burnt is to prepare coal gas, when much of the sulphur is

converted to hydrogen sulphide and is removed in the purifiers. Unfortunately, carbonization would be a most uneconomical way to remove sulphur, if this were its main object. Coal gas costs 2.5 times as much per B.Th.U. as raw coal. In any case, only about a quarter of the calorific value of the coal reappears in the gas; about half is retained in the coke, whose sulphur content is much the same as that of the original coal. There are various processes for the complete gasification of coal, with sulphur removal, but they all result in relatively expensive fuels.

The removal of sulphur dioxide from flue gases, after coal containing about 1 per cent of sulphur has been burnt, has been undertaken on a large scale at two electricity generating stations in London. At Battersea Power Station the flue gases are scrubbed in towers with water from the River Thames. This contains calcium bicarbonate in solution (the cause of "temporary hardness" in water), and an extra 20 per cent or so of calcium is added in the form of chalk. Up to about 95 per cent of the sulphur dioxide is removed from the flue gases to form calcium sulphate in solution which is returned to the Thames. If a new plant were introduced today the cost of the process would be about 8s. 6d. per ton of coal burnt. The same process is to be installed at Bankside Power Station for scrubbing the flue gases from boilers burning fuel oil of high sulphur content. It is doubtful whether, in times of drought, there would be enough alkalinity in the Thames to satisfy the requirements of more than two giant power stations.

When Fulham Power Station was built, the same restriction as at Battersea was imposed on the emission of sulphur dioxide. This was prevented by a different process. The flue gases were passed up towers packed with wooden boards, down which trickled water containing lime in solution and in suspension. The sulphur dioxide combined with the lime to form calcium sulphate and sulphite in such quantities that the greater portion could not be dissolved by the water present. From the towers the water passed into settling tanks where a precipitate of calcium sulphate and sulphite collected, containing also much of the ash and grit from the

flue gases. The supernatant water was pumped to the top of the tower, recharged with lime, and used again. At frequent intervals the sludge had to be removed from the settling tanks. It was pumped in the form of a wet mud into boats, taken down the Thames, and deposited in the estuary; although calcium sulphate has some commercial value for the manufacture of sulphuric acid, in spite of claims to the contrary it is cheaper to use relatively pure mineral sulphates than to use this mud. The efficiency of the Fulham process for removal of sulphur dioxide from flue gases was comparable with that at Battersea but, if a new plant were introduced today, the cost of the process would be about 13s. 0d. per ton of coal burnt. About a tenth of this total cost would go to pay for the removal of the calcium sulphate mud, weighing eight per cent or more of the weight of coal burnt.

Many suggestions have been made, and some trials, of other processes for removing sulphur dioxide from flue gases. Research is still going on, and there is the possibility that an improved process will be developed in which the sulphur can be recovered for use commercially. It is unlikely, however, that the cost will be much less than that of the present Battersea process. There also seems to be little chance of finding any reasonably cheap substance which, when added to the coal before it is burnt, has the effect of retaining sulphur dioxide in the ash.

The difficulty of preventing the emission of sulphur dioxide from the combustion of fuel is much increased by the low concentrations of the gas in the flues. In smelters where sulphur dioxide is produced from the oxidation of sulphides of zinc and other metals the concentrations are much greater and there is more scope for the chemist. At Trail, British Columbia, where about 800 tons per day of sulphur dioxide are produced, equipment is available for flue-gas washing and for producing ammonium sulphate and sulphur as by-products. This equipment cannot be operated continuously, however, and an arrangement has been made for sulphur dioxide to be emitted to the atmosphere only in such amounts, and on such occasions, as to produce less than a definite

maximum concentration of the gas at ground level. The direction and type of wind flow is complicated by the fact that the plant is in a deep valley. The services of a resident meteorologist are necessary to take observations and to ensure that the plant engineers have adequate warning when a change of weather is imminent, particularly any change which will affect the flow of air down the valley and across the frontier into the United States.

A more generally applicable method of mitigating the effects of sulphur dioxide is to emit it from tall chimneys. The mathematics of the diffusion of gases down to ground level are difficult, but theoreticians calculate that (1) the maximum concentration at ground level occurs downwind at a distance, in average meteorological conditions, of 10 or more chimney heights from the base of the chimney (unless the chimney is less than about 2.5 times the height of surrounding buildings, in which case eddy currents set up by the wind in blowing past the buildings may engulf the flue gases and bring them quickly to ground level), and (2) the maximum concentration itself varies inversely as the square of the height of the chimney.

The diffusion of chimney gases is strongly dependent on the degree of turbulence, as was pointed out in Chapter XII. When turbulence is strong, diffusion is rapid, and the flue gases will reach the ground relatively near to the base of the chimney, but at a relatively low concentration. When turbulence is weak, the gases drift away from the chimney in a thin compact trail, so that the point of maximum concentration at ground level is much further downwind, but concentrations everywhere within the trail are higher and fall off more slowly with distance.

The effect of raising the height of a chimney is to reduce appreciably the concentrations of pollution at places within about ten chimney lengths of the base of the chimney, while increasing only very slightly the concentrations at large distances. Tests have been made over thirty years with chimney stacks of different heights at a number of American smelting and refining plants. They show that within two or



three miles of the stack, concentrations of sulphur dioxide may be reduced by from 25 to 50 per cent by doubling the height of the stack. At Selby, California, a smelter stack of 146 ft was replaced by one of 605 ft. The average concentration of sulphur dioxide at an observation post 2.6 miles away was reduced to less than half at all seasons of the year. If there had been no pollution from other sources the reduction would probably have been more than two thirds. None of the tests were sensitive enough to determine whether there was an increase in pollution at great distances when the stack height was raised.

The possible applications of the technique of raising the chimney height are limited in a number of ways. Many industrial plants are in valleys where the peculiarities of local wind currents will usually tend to reduce the advantages of an increase in chimney height. It should be recognized, also, that there can be no reduction by this method in the amount of pollution deposited. All sulphur dioxide which is emitted to the atmosphere is ultimately removed by deposition or direct reaction with objects on the earth's surface, and an increase in chimney height will generally have little effect on the total damage done by deposited sulphur dioxide.

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## Chapter XV

### THE LAW AND ITS ADMINISTRATION

Part of the legal system of England still depends on the Common Law, the unwritten law derived from ancient usage and a great number of judgments in the King's Courts. This has been more and more supplemented in the last century by Statute, i.e. Acts of Parliament; and like many other problems of an industrial age, atmospheric pollution is more easily and quickly dealt with by Statute than by Common Law. Certainly against the more insidious forms of pollution the public requires to be protected by direct legislation, administered if necessary with the help of specialists.

If atmospheric pollution is believed to cause a "nuisance at common law", an action may be brought, in a County Court or the High Court, for damages and an injunction to restrain the defendants from committing the nuisance. Such an action may be brought by an individual, or by a number of individuals, severally or together. If the nuisance is a "public nuisance", affecting a large number of people, the same form of action may be brought by members of the public or by a local authority; alternatively there can be an indictment for a misdemeanour, but this is rare. If a public nuisance injures no one in particular but causes inconvenience to many, it is necessary to obtain the fiat of the Attorney General, who will prosecute on the relation of individuals or a local authority. When an injunction is granted, the offender must stop the nuisance or be liable to more serious penalties. In extreme cases, an order for sequestration has to be made, removing the plant or premises where the pollution is produced from the control of the offender. It should be noted that the Common Law is the only way in which smoke from dwelling houses can be dealt with by law, but so far no successful action has been brought which might affect householders generally.

*History.* Although there was public agitation as soon as coal began to be burnt in the cities, and Proclamations were issued by Edward I and by Elizabeth, prohibiting the burning of coal in London while Parliament was in session, for a very long time no laws were passed affecting the emission of atmospheric pollution. A bill was prepared in 1661 at the instigation of John Evelyn, but never became law. There was a Parliamentary Committee in 1819 and Select Committees in 1843 and 1845 to consider smoke from furnaces and steam engines. This was the first part of a period of intense activity in the interest of public health, in which a leading part was played by Edwin Chadwick, civil servant and a disciple of Jeremy Bentham. As a result, locomotive steam engines and furnaces used in factories were required to be so constructed as to consume their own smoke; appropriate provisions were inserted in the Railway Clauses Consolidation Act, 1845, and the Town Improvement Clauses Act, 1847. The phrase "consume their own smoke" should be taken to mean "emit no smoke".

The first Public Health Act was in 1848, but the great Public Health Act, 1875, superseding 22 earlier statutes, made important advances. It speeded the means of litigation, placed the responsibility for its administration, and provided a safeguard against failure to carry out this responsibility. Any fireplace or furnace in trade premises which did not so far as practicable consume its own smoke was deemed to be a nuisance liable to be dealt with summarily by a Justice of the Peace. So was any chimney emitting *black* smoke in such quantities as to be a nuisance irrespective of practicable means for consuming the smoke within the furnace. Private dwelling houses, as well as certain specified trade premises and mines, were exempt from these clauses.

Local Authorities were responsible for administering the Act, and their representatives were empowered to enter premises for this purpose. Any person aggrieved by the smoke nuisance could, in the same way as a local authority, lay a complaint before a Justice of the Peace, with the same results. As a further precaution in case the local authority failed to carry out the provisions of the Act, the Local Govern-

ment Board, which was under the direct supervision of Parliament, could call on the police to take proceedings, and to recover costs from the defaulting Authority.

At about the same time, serious trouble had arisen from pollution of the air by chemicals. The chief offenders in the early days were alkali works from which hydrochloric acid gas was emitted to the atmosphere. Alkali, &c. Works Regulation Acts were passed in 1881 and 1892, and were amended and consolidated by the Act of 1906, which, with Works Orders of 1928-50, is still the law. It deals with the emission, both from flues and from chemical wastes of numerous gases and fumes; some of its clauses are discussed in a later section.

After a long period of effort by various smoke abatement societies, now merged in the National Smoke Abatement Society, and by a number of local authorities, the scope of the anti-smoke statutes was widened by the passing of the Public Health (Smoke Abatement) Act, 1926. It became no longer necessary to prove that smoke was black if its quantity was sufficient to constitute a nuisance. Bye-laws limiting the time of emission of black smoke could be made by local authorities, who could also combine into groups for purposes of smoke abatement. The Public Health Act, 1936, brought this and other legislation which had been enacted between 1875 and 1932 under one Act, and this is operative at the present day. Some of its clauses are considered in a later section.

The Public Health Acts of 1875 and 1936 did not apply to London or to Scotland: entirely separate statutes were made, the Public Health (London) Acts, 1891 and 1936, and the Public Health (Scotland) Act, 1897. Besides the acts which are applied to large areas, there are a number of local acts relating to atmospheric pollution, which are playing a considerable part in the work of smoke abatement. Reference is made later, for example, to the Manchester Corporation Act, 1946.

While the scope of statute law has been gradually widening, a corresponding evolution has been taking place in the machinery for its execution. Parts of the Public Health Act, 1848, were carried out by the Vestry of the Parish; and parts, including those relating to smoke abatement, by the Union

Board of Guardians. The latter were required to appoint fit and proper persons to be "Inspectors of Nuisances"; the term "Sanitary Inspector" first appeared in an act in 1855. By 1872 all England and Wales, except London, was divided into Urban Sanitary Districts and Rural Sanitary Districts, and in 1888 County Councils and County Borough Councils were established. In 1894 Urban and Rural District Councils were set up, and the authority of the sanitary districts was dissolved. The London Government Act, 1899, abolished vestries and district boards, and inaugurated the twenty-eight London boroughs.

Initially, the central government could intervene in matters of local public health and smoke abatement only by very roundabout methods, but the reformers of the Great Reform period were anxious to secure a closer government control. The Public Health Act, 1848, established a tentative General Board of Health which terminated after five years. In 1871 the Local Government Board was constituted; this was replaced in 1919 by the Ministry of Health, presided over by a Minister eligible to sit in the House of Commons. Since the office was created, the powers of the Minister have considerably increased, notably under the Local Government Act, 1933, the Public Health Act, 1936, and the National Health Insurance Act, 1947.

#### ALKALI &c. WORKS REGULATION ACT, 1906

This Act was designed to prevent the emission of harmful or offensive quantities of chemicals to the atmosphere, either directly or from drains. The works required to be registered under Section 9 (1) and the First Schedule of the Act (as extended by later Orders up to 1951) are as follows:

##### *List of Alkali, &c. Works (1951): Non-scheduled works*

I. *Alkali works*, that is to say, every work for—

(a) The manufacture of sulphate of soda or sulphate of potash, or

(b) The treatment of copper ores by common salt, or other chlorides, whereby any sulphate is formed, in which muriatic acid gas is evolved;

II. *Cement works*, that is to say, works in which aluminous deposits are treated for the purpose of making cement;

III. *Smelting works*, that is to say, works in which sulphide ores, including regulus, are calcined or smelted; and

*List of Alkali, &c. Works (1948): Scheduled works*

(Note.—The works whose descriptive phrases are in italics have been included in pursuance of the Alkali, &c., Works Order, 1928, those described in small capital letters in pursuance of the Alkali, &c., Works Order, 1935, and those described in spaced letters in pursuance of the Alkali, &c., Works Order, 1950.)

That is to say, the several works mentioned in the first Schedule to the Act, as extended by the Alkali, &c., Works Orders, 1928 to 1939, which is as follows:—

(1) *Sulphuric acid works*, that is to say, works in which the manufacture of sulphuric acid is carried on by the lead chamber process, namely, the process by which sulphurous acid is converted into sulphuric acid by the agency of oxides of nitrogen and by the use of a lead chamber or by any other process involving the use of oxides of nitrogen.

(2) *Sulphuric acid (Class II) works*, that is to say, works in which the manufacture of sulphuric acid is carried on by any process other than the lead chamber process, and works for the concentration or distillation of sulphuric acid.

(3) *Chemical manure works*, that is to say, works in which the manufacture of chemical manure is carried on, and works in which any mineral phosphate is subjected to treatment involving chemical change throughout the application or use of any acid, and works for the granulating of chemical manures involving the evolution of any noxious or offensive gas.

(4) *Gas liquor works*, that is to say, works (not being sulphate of ammonia works or muriate of ammonia works) in which sulphuretted hydrogen or any other noxious or offensive gas is evolved by the use of ammoniacal liquor in any manufacturing process, and works in which any such liquor is desulphurized by the application of heat in any process connected with the purification of gas.

(5) *Nitric acid works*, that is to say, works in which the manufacture of nitric acid is carried on and works in which nitric acid is recovered from oxides of nitrogen and works where in the manufacture of any product any acid-forming oxide of nitrogen is evolved.

(6) *Sulphate of ammonia works*, and muriate of ammonia works, that is to say, works in which the manufacture of sulphate of ammonia or of muriate of ammonia is carried on.

(7) *Chlorine works*, that is to say, works in which chlorine is made or used in any manufacturing process.

(8) *Muriatic acid works*, that is to say—

(a) Muriatic acid works, or works (not being alkali works as defined in this Act) where muriatic acid gas is evolved either during the preparation of liquid muriatic acid or for use in any manufacturing process OR AS THE RESULT OF THE USE OF CHLORIDES IN A CHEMICAL PROCESS;

(b) *Tinplate flux works*, that is to say, works in which any residue or flux from tinplate works is calcined for the utilization of such residue or flux, and in which muriatic acid gas is evolved; and

(c) *Salt works*, that is to say, works (not being works in which salt is produced by refining rock salt, otherwise than by the dissolution of rock salt at the place of deposit) in which the extraction of salt from brine is carried on, and in which muriatic acid gas is evolved.

(9) *Sulphide works*, that is to say, works in which sulphuretted hydrogen is evolved by the decomposition of metallic sulphides, or in which sulphuretted hydrogen is used in the production of such sulphides, OR ANY WORKS IN WHICH SULPHURETTED HYDROGEN IS EVOLVED AS PART OF A CHEMICAL PROCESS.

(10) *Alkali waste works*, that is to say, works in which alkali waste or the drainage therefrom is subjected to any chemical process for the recovery of sulphur or for the utilization of any constituent of such waste or drainage.

(11) *Venetian red works*, that is to say, works for the manufacture of Venetian red, crocus or polishing powder, by heating sulphate or some other salt of iron.

(12) *Lead deposit works*, that is to say, works in which the sulphate of lead deposit from sulphuric acid chambers is dried or smelted.

(13) *Arsenic works*, that is to say, works for the preparation of arsenious acid, or where nitric acid or a nitrate is used in the manufacture of arsenic acid or an arseniate *and works in which any volatile compound of arsenic is evolved in any manufacturing process.*

(14) *Nitrate and chloride of iron works*, that is to say, works in which nitric acid or a nitrate is used in the manufacturing of nitrate or chloride of iron.

(15) *Bisulphide of carbon works*, that is to say, works for the manufacture, USE OR RECOVERY of bisulphide of carbon.

(16) *Sulphocyanide works*, that is to say, works in which the manufacture of any sulphocyanide is carried on by the reaction of bisulphide of carbon upon ammonia or any of its compounds.

(17) *Picric acid works*, that is to say, works in which nitric acid or a nitrate is used in the manufacture of picric acid.

(18) *Paraffin oil works*, that is to say, works in which crude shale oil is refined *and works in which crude petroleum is refined*, AND WORKS IN WHICH ANY PRODUCT OF THE REFINING OF CRUDE SHALE OIL OR CRUDE PETROLEUM IS TREATED SO AS TO CAUSE THE EVOLUTION OF GASES CONTAINING ANY SULPHUR COMPOUND.

(19) *Bisulphite works*, that is to say, works in which sulphurous acid is used in the manufacture of acid sulphites of the alkalis or alkaline earths *and works for the manufacture of liquid sulphur dioxide or of sulphurous acid or of any sulphite*, and works (not being smelting works as defined in section 8, subsection (1) of

the Act of 1906 or other works defined elsewhere in this schedule) in which oxides of sulphur are evolved in any chemical manufacturing process.

(20) *Tar works*, that is to say, works where gas tar or coal tar is distilled or is heated in any manufacturing process and works in which creosote or any other product of the distillation of gas tar or coal tar is distilled or is heated in any manufacturing operation involving the evolution of any noxious or offensive gas.

(21) *Zinc works*, that is to say, works in which by the application of heat, zinc is extracted from the ore, or from any residue containing that metal.

(22) *Benzene works*, that is to say, works (not being tar works as already defined) in which any wash oil used for the scrubbing of coal gas is distilled, or in which any crude benzol is distilled.

(23) *Pyridine works*, that is to say, works in which pyridine is recovered.

(24) *Bromine works*, that is to say, works in which bromine is made or is used in any manufacturing operation.

(25) *Hydrofluoric acid works*, that is to say, works in which hydrofluoric acid is evolved in the manufacture of liquid hydrofluoric acid or its compounds.

(26) *Cement production works*, THAT IS TO SAY, WORKS IN WHICH ARGILLACEOUS AND CALCAREOUS MATERIALS ARE USED IN THE PRODUCTION OF CEMENT CLINKER and works in which cement clinker is ground or cement is packed.

(27) *Lead works*, that is to say, works in which, by the application of heat, lead is extracted from any material containing lead or its compounds, and works in which compounds of lead are manufactured from metallic lead or its compounds by dry processes which give rise to dust or fume.

(28) *Fluorine works*, that is to say, works in which fluorine or its compounds with other halogens are made or used in any manufacturing process.

(29) *Acid sludge works*, that is to say, works in which acid sludge produced in the refining of coal tar, petroleum or other hydrocarbon derivatives is treated in such manner as to cause the evolution of any noxious or offensive gas.

Under Section 47 of the Finance Act, 1922, which amends section 9 (6) of the Alkali, &c., Works Regulation Act, 1906, the Stamp Duty payable in respect of an alkali work (non-scheduled works, No. 1 in this list) is £10 per annum, and the Duty payable in respect of any other work is £6 per annum.

The part of Clause 27 of the Alkali, &c., Works Regulation Act, 1906, which lists the chemicals to be considered reads:



*Noxious or offensive gas*

27.—(1) (in part) The expression "noxious or offensive gas" includes the following gases and fumes: —

- Muriatic acid (hydrochloric acid);
- Sulphuric acid;
- Sulphurous acid, except that arising solely from the combustion of coal;
- Nitric acid and acid-forming oxides of nitrogen;
- Sulphuretted hydrogen;
- Chlorine, and its compounds;
- Fluorine compounds;
- Cyanogen compounds;
- Bisulphide of carbon;
- Chloride of sulphur;
- Fumes from cement works;
- Fumes containing copper, lead, antimony, arsenic, zinc, or their compounds;
- Fumes from tar works;
- Volatile organic sulphur compounds;
- Fluorine.

The above definitions are essential to an understanding of the Alkali, &c. Works Regulation Act, 1906. The following extracts have been selected to indicate how the Act operates (brackets denoting paraphrases of the original wording):

*Condensation of HCl in alkali works*

1. Every alkali work shall be carried on in such manner as to secure the condensation, to the satisfaction of the chief inspector, of the muriatic acid gas evolved in such work, to the extent of ninety-five per centum, and to such an extent that in each cubic foot of air, smoke, or chimney gases, escaping from the works into the atmosphere, there is not contained more than one-fifth part of a grain of muriatic acid. (Fine, first offence, up to fifty pounds, every subsequent offence, up to one hundred pounds).

*Prevention of discharge of noxious or offensive gas in alkali works*

2. In addition to the condensation of muriatic acid gas as aforesaid, the owner of every alkali work shall use the best practicable means for preventing the escape of noxious or offensive gases by the exit flue of any apparatus used in any process carried on in the work, and for preventing the discharge, whether directly or indirectly, of such gases into the atmosphere, and for rendering such gases where discharged harmless and inoffensive (except for emissions of muriatic

acid of less than one-fifth of a grain per cubic foot). (Fine, first offence up to twenty pounds, subsequent offences up to fifty pounds and up to five pounds for every day of subsequent offence.)

*Prevention of nuisance from mixture of which one component is alkali waste, and from alkali waste alone*

3. (Every work of whatever description shall take precautions against the evolution of sulphuretted hydrogen from the mixing of acids or other substances with alkali waste. Fine, first offence up to fifty pounds, subsequent offences up to one hundred pounds and up to five pounds for every day of subsequent offence.)

4. Alkali waste shall not be deposited or discharged without the best practicable means being used for effectually preventing any nuisance arising therefrom. (Fines as in Section 2 above.)

*Condensation of acid gases in sulphuric acid and muriatic acid works*

6. — (1) Every sulphuric acid work (as defined in (1) of the list of scheduled works above) shall be carried on in such manner as to secure the condensation, to the satisfaction of the chief inspector, of the acid gases of sulphur or of sulphur and nitrogen which are evolved in the process of the manufacture of sulphuric acid in that work, to such an extent that the total acidity of those gases in each cubic foot of residual gases after completion of the process, and before admixture with air, smoke, or other gases, does not exceed what is equivalent to four grains of sulphuric anhydride.

(2) Every muriatic acid work (see list of scheduled works) shall be carried on in such manner as to secure the condensation to the satisfaction of the chief inspector of the muriatic acid gas evolved in such work, to such an extent that in each cubic foot of air, smoke, or chimney gases escaping from the work into the atmosphere there is not contained more than one-fifth part of a grain of muriatic acid. (Fines as in Section 1 above.)

*Noxious or offensive gases from scheduled works*

7. (The owner of any scheduled work specified in the list above) shall use the best practicable means for preventing the escape of noxious or offensive gases by the exit flue of any apparatus used in any process carried on in the work, and for preventing the discharge, whether directly or indirectly, of such gases into the atmosphere, and for rendering such gases when discharged harmless and inoffensive, (subject to the qualification that no objection shall be taken by an inspector to one-fifth of a grain or less of muriatic acid per cubic foot, or to acid gases from any process for the concentration or distillation of sulphuric acid where the total acidity of such acid gases, including those from the combustion of coal, does not exceed what is equivalent to one grain and a half of sulphuric anhydride per cubic foot). (Fines as in Section 2 above.)

*Cement and smelting works*

8. (The Minister\* may by order require the owners of cement works and smelting works to adopt the best practicable means for preventing the discharge into the atmosphere of any noxious or offensive gas, including fume, evolved in such works; the order must be ratified by Parliament.)

*Inspectors*

10. (Provides for the appointment by the Minister of Inspectors of Alkali, &c. Works, and a Chief Inspector.)

*Inspection of works*

12.—(1) For the purpose of the execution of this Act, an inspector may at all reasonable times by day and night, without giving previous notice, but so as not to interrupt the process of the manufacture,

(a) enter and inspect any work to which, in the opinion of the Minister, any of the provisions of this Act applies; and

(b) examine any process causing the evolution of any noxious or offensive gas, and any apparatus for condensing any such gas, or otherwise preventing the discharge thereof into the atmosphere, or for rendering any such gas harmless or inoffensive when discharged; and

(c) ascertain the quantity of gas discharged into the atmosphere, condensed or otherwise dealt with; and

(d) enter and inspect any place where alkali waste is treated or deposited, or where any liquid containing either acid or any other substance capable of liberating sulphuretted hydrogen from alkali waste or drainage therefrom is likely to come into contact with alkali waste or drainage therefrom; and

(e) apply any such tests and make any such experiments, and generally make all such enquiries, as seem to him to be necessary or proper for the execution of his duties under this Act.

*Additional inspector*

14. (Provides for the appointment of an additional inspector if any sanitary authority, i.e. local authority, applies to the central authority, i.e. the Minister, and undertakes to pay not less than half the inspector's salary.)

*Complaint by sanitary authority*

22.—(1) Where complaint is made to the central authority by any sanitary authority, on information given by any of their officers, or any ten inhabitants of their district, that any work to which this

\* 1906-1919, President of the Local Government Board; 1919-1951, Minister of Health; Feb.-Nov. 1951, Minister of Local Government and Planning; Nov. 1951, Minister of Housing and Local Government.

Act applies is carried on (either within or without the district) in contravention of this Act, that any alkali waste is deposited or discharged (either within or without the district) in contravention of this Act, and that a nuisance is occasioned thereby to any of the inhabitants of their district, the central authority shall make such inquiry into the matters complained of, and after the inquiry may direct such proceedings to be taken by an inspector as they think fit and just.

*Application to Scotland*

28. (In the application of this Act to Scotland, references to the Secretary for Scotland shall be substituted for references to the Minister. Other provisions in this section relate to legal procedure in Scotland.)

In 1881 when the first Alkali, &c. Works Regulation Act was passed, there was good reason to pick on Alkali Works, as defined above, for special attention. Section 4 deals with this, and it is interesting, too, because it realistically defines a maximum amount of hydrochloric acid which may legally be emitted. Section 6 also puts a limit on emissions from sulphuric acid works of the acid gases of sulphur and nitrogen; no other form of pollution is limited in this way by any English law. Because of the enforcement of the Act, and also because hydrochloric acid is valuable and worth recovering as a by-product, Alkali Works are now, however, less liable to cause a nuisance than some other works, whose "noxious and offensive gases" have to be prevented by the "best practicable means". There are arguments in favour of introducing a new act, defining nuisances in terms of the gases emitted instead of the works emitting them, but with care, the present Act apparently can be made to perform most of the functions needed of it.

It may be asked why advantage has not been taken of Section 8 above, to make an order treating cement works and smelting works in much the same way as alkali works are treated in Section 2. The answer seems to be that the list of scheduled works is so drawn up that, in practice, all cement works and smelting works are included in the schedule and are subject to the provisions of Section 6 and 7. The distinction between scheduled and non-scheduled works has become unimportant.

The Act clearly needs to be administered by specialists, because of the technical knowledge required for understanding chemical processes and measuring quantities and concentrations of chemicals. Actions under the Act are rarely brought to court, but very many causes of complaint are removed without court proceedings, after manufacturers have discussed matters with inspectors and received their advice.

### PUBLIC HEALTH ACT, 1936

Dangers to public and individual health may arise through a great variety of causes, including drains, sanitation, refuse disposal, food, condition of workplaces and dwellings, atmospheric pollution, and the so-called offensive trades. By section 106 of the Local Government Act, 1933, every local authority in Great Britain must appoint one or more sanitary inspectors to administer the Public Health Act under the general direction of the medical officer of health and, if so directed by the Local Authority, perform other duties under the Food and Drugs Act, 1938, the Diseases of Animals Acts, 1894 to 1909, the Rats and Mice (Destruction) Act, 1919, the Housing Act, 1936, and the Shops Act, 1934. In many districts each sanitary inspector is expected to carry out all these duties, besides others set out in the Regulations made by the Minister of Health in 1935. In the larger districts, however, there is a tendency for inspectors to specialize, and smoke inspectors have been appointed in some County Boroughs. The sections of the Public Health Act, 1936, relating to atmospheric pollution are as follows:

#### *Smoke nuisances*

101.—For the purpose of this Part of this Act—

(a) any installation for the combustion of fuel which is used in any manufacturing or trade process, or for working engines by steam, and which does not so far as practicable prevent the emission of smoke to the atmosphere; and

(b) any chimney (not being the chimney of a private house) emitting smoke in such quantity as to be a nuisance, shall be statutory nuisances, and are in this Act referred to as "smoke nuisances".

*Dust; smoke; chimney; best practicable means*

110.—(1) In this Part of this Act—

the expression "dust" does not include dust emitted from a chimney as an ingredient of smoke;

the expression "smoke" includes soot, ash, grit, and gritty particles; and

the expression "chimney" includes structures and openings of any kind through which smoke may be emitted.

(2) In determining for the purpose of this Part of this Act whether the best practicable means have been taken for preventing, or for counteracting the effect of, a nuisance, a court shall have regard to cost and to local conditions and circumstances.

*Duty of local authority*

91.—It shall be the duty of every local authority to cause their district to be inspected from time to time for the detection of matters requiring to be dealt with under the provision of this Part of this Act as being statutory nuisances...

*Power of individuals*

99.—Complaint of the existence of a statutory nuisance under this Act may be made to a justice of the peace by any person aggrieved by the nuisance...

*Byelaws as to smoke*

104.—(1) A local authority may, and if so required by the Minister shall, make byelaws regulating the emission of smoke of such colour, density, or content as may be prescribed by the byelaws.

(2) Building byelaws may require the provision in new buildings, other than private houses, of such arrangements for heating or cooking as are calculated to prevent or reduce the emission of smoke...

*Saving for mines, smelting works, etc*

109.—(1) Nothing in this part of this Act shall be construed as extending to a mine of any description so as to interfere with, or obstruct the efficient working of, the mine, or as extending to the smelting of ores and minerals, to the calcining, puddling and rolling of iron and other metals, to the conversion of pig iron into wrought iron, or to the reheating, annealing, hardening, forging, converting and carburising of iron and other metals, so as to interfere with or obstruct any of those processes...

*Abatement notice*

93.—Where a local authority are satisfied of the existence of a statutory nuisance they shall serve a notice (hereafter in this Act referred to as "an abatement notice") on the person by whose act, default, or sufferance the nuisance arises or continues...

*Nuisance order*

94.—(1) (If the abatement notice is not complied with) the authority shall cause a complaint to be made to a justice of the peace, and the justice shall thereupon issue a summons requiring the person on whom the notice was served to appear before a court of summary jurisdiction.

(2) (If in court it is proved that the alleged nuisance exists) the court shall make an order (hereafter in this Act referred to as "a nuisance order") for either, or both, of the following purposes:—

(a) requiring the defendant to comply with all or any of the requirements of the abatement notice, or otherwise to abate the nuisance, within a time specified in the order, and to execute any works necessary for that purpose;

(b) prohibiting a recurrence of the nuisance, and requiring the defendant, within a time specified in the order, to execute any works necessary to prevent a recurrence;

and may also impose on the defendant a fine not exceeding five pounds . . .

95.—(If the nuisance order is not complied with, fine not exceeding five pounds and further fine not exceeding forty shillings for each day on which the offence continues after conviction therefor) . . .

The importance of section 104, dealing with byelaws as to smoke, is revealed in section 103, which states that it is a defence for the defendant to prove that "the best practicable means" have been taken for abating the nuisance; but where byelaws are in force, this is no defence. Most Local Authorities who need them now have byelaws of this kind. All byelaws prescribe that the emission of black smoke from a chimney of any building, other than a private house, for more than two (or three) minutes in any period of thirty minutes, shall, until the contrary is proved, be deemed to be a statutory nuisance and a smoke nuisance. Other than "black", no criterion of colour, density or content has so far been acceptable, but black smoke, however hard it might be to define to the satisfaction of a physicist, turns out to be an effective description in a court of law.

Section 109, a saving provision for mines, smelting works and the like, is a survival from the Public Health Act, 1875. The local authority is, however, in a better position now than formerly to apply the Act, because research has shown that few, if any, metallurgical processes need be interfered with or

obstructed by practicable methods of preventing smoke. Although it is too technical to be described in detail, part of this research is historically interesting because it was carried out on behalf of a Local Authority under the section (105 in the present Act) permitting investigations and research into problems relating to atmospheric pollution.

The "Local Authority" in this case was the Sheffield, Rotherham and District Smoke Abatement Committee, and this, too, is interesting. At the present time it is the only example of a statutory committee, set up by two or more local authorities under the Public Health (Smoke Abatement) Act, 1926, to carry out their functions in their entire area in respect of smoke abatement. This method of administration has much to commend it, particularly in districts where there is a great variety of industrial fuel-burning equipment.

#### MANCHESTER CORPORATION ACT, 1946

Sections of this Act are now quoted which were the first of their kind in British anti-smoke legislation.

##### *Part VI. Prohibition of smoke in certain areas*

35.—(1) In this section—

"the central area" means (a particular area of 104 acres in Manchester);

"smoke" includes soot, ash, grit and gritty particles.

(2) As from the commencement of this section no smoke shall be emitted from any premises in the central area.

(3) (Penalty up to ten pounds and five pounds per day.)

(4) (Provision for extension of the original central area.)

(5) (Provision for exemption of particular premises and processes from an order made under the foregoing sub-section, if the Minister is satisfied that their inclusion within the operation of the order would obstruct or interfere with the processes.)

(6)—(8) (Provision for commencement of this section not less than six months after an appropriate order has been made by the Corporation and confirmed by the Minister.)

(9) (Agreements between lessee and owner of premises in relation to the works or alterations necessary for the order to be complied with.)

(10) An order under this section may be varied or revoked by another order made by the Corporation and confirmed by the Minister.

(11) Nothing in this section or in any order made thereunder shall apply to smoke emitted from a railway locomotive.



(12) (Costs of local enquiries.)

(13) The Corporation may if they think fit contribute the whole or part of the expense necessarily incurred by any person in executing works or in providing altering or adapting any fixtures fittings or appliances for the purpose of complying with—

(a) the provisions of sub-section (2) of this section; or

(b) the provisions of any order made by the Corporation and confirmed by the Minister under this section.

*Prevention of smoke from industrial furnaces*

36.—(1) No person shall install in any building whether erected before or after the passing of this Act any furnace for steam raising or for any manufacturing or trade purpose unless such furnace is so far as practicable capable of being operated continuously without emitting smoke.

(2) (Penalty up to ten pounds and two pounds per day.)

(3) If a person before installing in a building a furnace to which this section applies submits to the Corporation plans proposals and particulars of the proposed furnace and furnishes them with such other necessary information in regard thereto as they may require the Corporation shall within a period of six weeks from the date upon which such plans proposals particulars and information are received by them serve a notice upon such person stating whether or not they are satisfied that the furnace is so far as practicable capable of being operated continuously without emitting smoke and if they are so satisfied or if they do not serve a notice upon such person before the expiration of the said period of six weeks no proceedings shall be taken against him under this section in respect of the installation of that furnace in accordance with the plans proposals particulars and information so submitted and furnished.

(4) In determining for the purposes of this section whether a furnace is so far as practicable capable of being operated continuously without emitting smoke the Corporation or a court shall if either of the parties so desire have regard to cost and to local conditions and circumstances.

Section 35 of the Manchester Corporation Act, 1946, was the culmination of a determined effort by the National Smoke Abatement Society and other bodies begun in 1936. It was felt that the reduction of smoke by degrees was too slow a process; and that quicker results would be achieved if, in addition, smoke production were altogether abolished in particular areas, and the areas enlarged with all reasonable speed. The experiment will be watched with intense interest, and it is an encouraging sign that similar statutes have been

adopted by other local authorities. (These are, in December 1951, Salford, Coventry, Rochdale, Bradford, Bolton, Urmston, Crewe, Wolverhampton, and Edinburgh.)

Section 36 of the Act has the effect that the Corporation will be able to warn firms beforehand, if they consult it, against the installation of furnaces which are not considered capable of being operated continuously without emitting smoke; it is called the "prior approval" clause. There is no obligation on firms to seek prior approval, but a firm is clearly to blame if it installs an unsuitable furnace without consulting the Corporation or after being notified that the Corporation is not satisfied as to the suitability of the furnace. Similar provisions to those of section 36 have been adopted by all the local authorities listed at the end of the previous paragraph. The following additional authorities have the "prior approval" clause without the "smokeless zone" clause: City of London, Preston, Parsley, Dudley, Darwen, Birmingham, St. Helens, Smethwick, Brighton, Slough, West Bromwich, and Leyton. An up-to-date list is given in the Year Book of the National Smoke Abatement Society.

#### ANTI-SMOKE LAWS IN THE UNITED STATES

It is likely to be some years before the industrial countries on the mainland of Europe are able to revise their laws against smoke, but there has been much anti-smoke legislation in the United States which merits careful consideration. Law-making in the U.S.A is as far as possible left to the individual states and cities, and though the laws in different areas tend to follow a pattern, there is ample opportunity for any new proposal to be tried. In the matter of smoke abatement, St. Louis, Missouri, was the first to introduce severe laws affecting the whole population.

In 1946 St. Louis had a population of over 810 000. It had 150 000 chimney stacks, and used about 4 000 000 tons of coal per year, distributed by 1500 dealers. The staff of the Smoke Commissioner numbered 22. The nearest coalfields, across the river in Illinois, yielded bituminous coals liable to make smoke, but there were low-volatile coals in Arkansas, 250 miles away.

In St. Louis as in other American cities, attempts had been made from time to time to reduce the nuisance of atmospheric pollution by trying to enlist the co-operation of the whole population. In 1925, for example, a Citizens' Smoke Abatement League was founded, and this inaugurated systematic instructions for firemen and publicized the need for smoke abatement; but in 1933 little progress seemed to have been made. High-volatile coals, containing as much as 30 per cent of mineral matter and 5 per cent of sulphur, were still being used indiscriminately.

Then in 1937 an ordinance was enacted which was similar to those of other smoke-conscious cities. It required all coal containing more than 12 per cent of ash or 2 per cent of sulphur, if smaller than 2 inches in diameter, to be washed before delivery to the consumer. All fuel dealers had to obtain a licence and renew it annually. Installations of new equipment having above 1000 sq ft of direct steam radiation or an equivalent load must be notified to the Smoke Commissioner and must use mechanical fuel-burning equipment or smokeless fuel.

In spite of this ordinance, there was a particularly bad smoke pall in 1939, and in 1940 new legislation was made. The provisions of the previous ordinance were retained, but plans for all new appliances and all alterations to existing appliances had to be submitted for approval. Further, (1) anyone who desired to burn high-volatile coal for either domestic or industrial purposes must employ mechanical fuel-burning equipment, and ensure that no smoke was emitted, or (2) those who did not desire to use mechanical fuel-burning equipment must use a smokeless fuel.

Smokeless coal was defined as that having a volatile content of less than 23 per cent, and the city of St. Louis was empowered, in an emergency, to buy and sell smokeless fuel. The annual requirements of smokeless solid fuel in St. Louis were found to be  $1\frac{1}{2}$  million tons, of which only  $\frac{1}{2}$  million tons were available locally. After negotiations by the Smoke Commissioner, the remainder was obtained from Arkansas with a freight charge of two dollars per ton.

It is claimed that there has been a most marked improvement in the air of St. Louis since the ordinance of 1940, though few systematic observations were made with which the claims could be examined. From visual observations by the U.S. Weather Bureau, the average concentration of smoke seems likely to have been reduced by nearly 75 per cent; and it may be stated, by way of confirmation, that a reduction of this magnitude is probably necessary before the general public can be strongly impressed.

Similar ordinances have since been brought into operation in Kansas City (1943), Pittsburgh (1947), and Los Angeles (1947-49). Although no coal is burnt in Los Angeles there is a serious "smog" problem, due partly to the frequency of particular weather conditions in which there is an inversion, accompanied by light winds. In these conditions the smoke (if any), sulphur dioxide, and other gases from oil-burning plants tend to produce an atmosphere irritating to the eyes; and their effect may be increased by gases from chemical and other works, and by smoke from incinerators. The Air Pollution Control District of Los Angeles has based its Rules and Regulations on part of the Health and Safety Code of the State of California. The Rules include:

*Rule 10. Permits Required.* Any person building, erecting, altering, replacing, operating or using on or after February 1, 1948, any article, machine, equipment or other contrivance the use of which may cause the issuance of air contaminants, except an article, machine, equipment or contrivance described in either Section 24251 or 24265 of the Health and Safety Code, shall first obtain a permit for such operation.

(*State of California, Health and Safety Code, Section 24251.* The provisions of Section 24242 do not apply to:

(a) Agricultural operations in the growing of crops, or raising of fowls or animals, or,

(b) The use of an orchard or citrus grove heater which does not produce unconsumed solid carbonaceous matter at a rate in excess of one (1) gram per minute, or,

(c) The use of other equipment in agricultural operations in the growing of crops, or raising of fowls or animals.

*Section 24265.* A permit shall not be required for:

(a) Any mobile equipment.

(b) Any structure designed for and used exclusively as a dwelling for not more than four families.

(c) An incinerator used exclusively in connection with such a structure.

(d) Equipment described in Section 24251.

(f) Repairs or maintenance not involving structural changes to any equipment for which a permit has been granted.)

*Rule 11. Exceptions.* (a) No permit shall be required from any city, county, municipality, district or other political subdivision.

(b) No permit shall be required for building, erection, alteration or replacement costing less than \$300.00.

*Rule 20. Standards for granting permits.* No application shall be approved or permit granted unless it is shown that every article, machine, equipment or other contrivance the use of which may cause the issuance of air contaminants, is so designed or controlled, or equipped with such air pollution control equipment, that with proper supervision and use it may be expected to operate without emitting air contaminants in violation of Sections 24242 or 24243, Health and Safety Code or of the Rules of the Air Pollution Control District.

(Section 24242 and 24243 of the Health and Safety Code are identical in wording with *Rule 50, Ringelmann Chart*, and *Rule 51, Nuisance*, given below.)

*Rule 21. Conditional Approval.* The Air Pollution Control Officer may approve an application subject to conditions which will bring it within the standards of Rule 20, in which case the conditions shall be specified in writing. Commencing work under such a permit shall be deemed acceptance of all the conditions so specified.

*Rule 25. Appeals.* Within 30 days after service of notice of denial of the application, or of conditional approval, . . . applicant may file with the Hearing Board a written demand for a public hearing.

*Rule 26. Public Hearing.* Within 30 days after the applicant has requested a public hearing, the Hearing Board shall hold such a hearing and give notice of the time and place of such hearing to the applicant, to the Air Pollution Control Officer and to such other persons as the Hearing Board deems should be notified, not less than 10 days before the date of the public hearing.

*Rule 50. Ringelmann Chart.* A person shall not discharge into the atmosphere from any single source of emission whatsoever any air contaminant for a period or periods aggregating more than three minutes in any one hour which is:

(a) As dark or darker in shade as that designated as No. 2 on the Ringelmann Chart, as published by the United States Bureau of Mines, or

(b) Of such opacity as to obscure an observer's view to a degree equal to or greater than does smoke described in subsection (a) of this Rule.

*Rule 51. Nuisance.* A person shall not discharge from any source whatsoever such quantities of air contaminants or other material

which cause injury, detriment, nuisance or annoyance to any considerable number of persons or to the public or which endanger the comfort, repose, health or safety of any such persons or the public or which cause or have a natural tendency to cause injury or damage to business or property.

*Rule 52. Particulate Matter.* A person shall not discharge into the atmosphere any dust, ashes, charred paper, soot, grime, carbon, or other particulate matter exceeding 0.40 grains per cubic foot at the point of discharge into the atmosphere.

*Rule 53. Specific Contaminants.* A person shall not discharge into the atmosphere any one or more of the following contaminants, in any state, or in any combination thereof exceeding in concentration at the point of discharge:

Lead . . . . .	0.035 grains per cubic foot
Zinc Oxide . . . . .	0.035 grains per cubic foot
Sulphur Compounds (calculated as SO <sub>2</sub> )	0.2 per cent by volume.

*Rule 3. Standards.* All analyses and tests shall be calculated or reported at the standard gas temperature of 60 degrees Fahrenheit and the standard pressure of 14.7 pounds per square inch.

*Rule 54. Exceptions.* Rules 50 to 53, inclusive, do not apply to:

(a) Fire set by any public officer in the course of his official duty, for the purpose of weed abatement, the prevention of a fire hazard, or the instruction of public employees in the methods of fire fighting, or,

(b) Agricultural operations in the growing of crops or raising of fowls, or animals, or,

(c) The use of an orchard or citrus grove heater which does not produce unconsumed solid carbonaceous matter at a rate in excess of one (1) gram per minute, or,

(d) The use of other equipment in agricultural operations in the growing of crops, or raising of fowls, or animals.

In the above Rules, permits are required by a large proportion of industrial fuel consumers, and for structures used as dwellings for more than four families. It is within the powers of the Air Pollution Control Officer of the Hearing Board to refuse permits for practically all the operations which would not be permitted in St. Louis.

The use of Ringelmann Charts is fairly general through the United States, although Rule 50 allows the possibility of alternative standards. In St. Louis and some other American cities, a total of 9 minutes an hour of Ringelmann No. 2, or 6 minutes greater than No. 2, constitutes the minimum

violation; this is less strict than in Los Angeles. From locomotives, one continuous minute of smoke equal to or denser than No. 2 is a violation.

One effect of the legislation in the U.S.A. has been an increase in the production of smokeless fuels, mechanical stokers, and equipment fired by gas and oil. In such places as St. Louis the average price per B.Th.U. of fuel has increased, but it is to be hoped that there has been a less noticeable increase in the price per *useful* B.Th.U. It was pointed out that if there was a general attempt to make an abrupt change to smokeless combustion, on the lines of St. Louis, it might lead to economic chaos and failure. Indeed, the same difficulty has been raised in Great Britain. So far, however, both countries have made progress without any serious industrial dislocation. May it be hoped that we are at the beginning of the end of atmospheric pollution as a serious social problem, and that historians of the future will point to it as an example of bygone times when neither States nor citizens could live together without causing mutual inconvenience?

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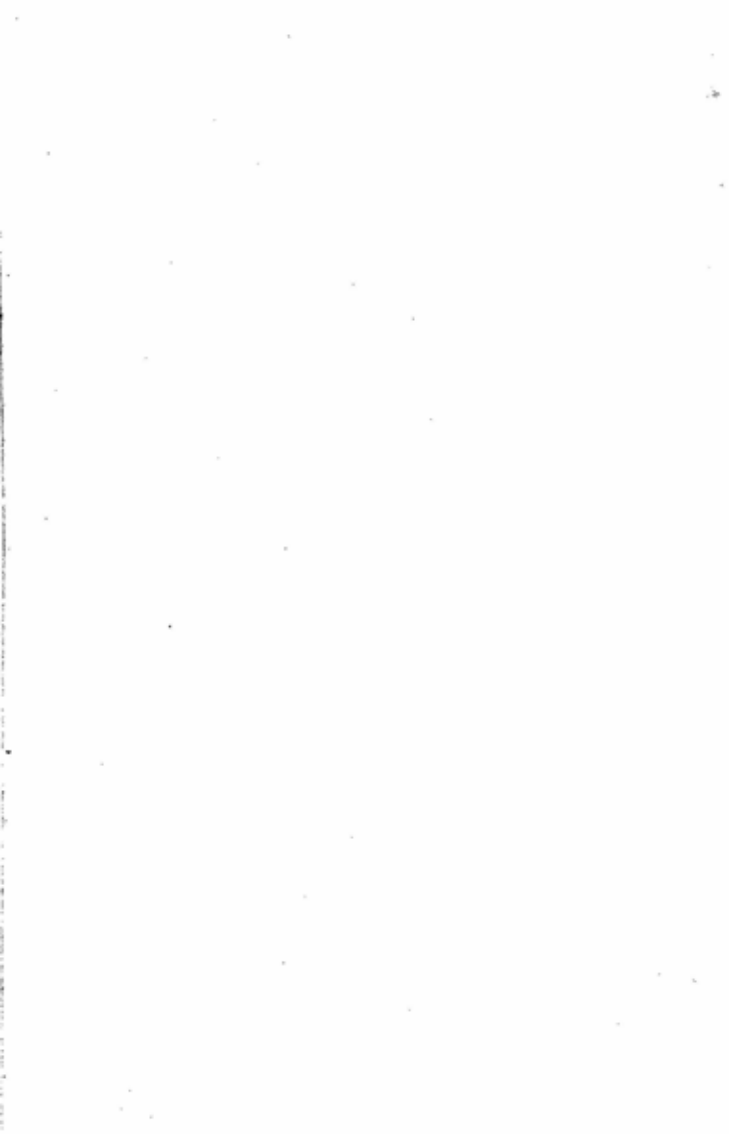
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