INFLUENCES ON ENGINEERING ADVANCEMENT 1856—1956

Part III—The Influence of Engineering Discoveries

A HUNDRED years ago a trained engineer felt himself equipped to make contributions to engineering advance in almost any engineering field. Tunnelling, railway construction, the building of ships and the construction of lighthouses came alike, for example, to Brunel. The need for a marked division between civil and mechanical engineering was only just beginning to be felt (The Institution of Civil Engineers was founded in 1818, The Institution of Mechanical Engineers in 1847), electrical engineering had barely begun, though telegraphy had, and chemical engineers, aeronautical engineers, still less nuclear engineers had not been heard of. To-day it is very different. Now, in engineering " there are many mansions." So far have the bounds of engineering discovery been pressed outwards that a specialist in any one field may be not merely unaware of what goes on elsewhere but barely able to understand the jargon of another specialist. Yet it is very apparent to the Editor of this journal that the essential unity of engineering still exists. In no specialist field are advances made, as it were, *in vacuo*. Workers in each field, consciously or unconsciously, have borrowed ideas and equipment from other fields and in return conveyed ideas or suggested equipment for others. An advance made in one field may trigger off advances who knows where ? In this Part a number of authors, under broadly embracing titles, discuss how work done in the fields thus assigned to them has influenced, or has been influenced by, work carried out elsewhere.

Iron and Steel

By W. F. CARTWRIGHT, D.L., M.I.Mech.E.*

IRON and steel manufacture has stimulated the development of many fields of engineering throughout its history. Some great examples such as the huge reciprocating blowing and mill engines, are now things of the past, but in their day they were among the most powerful machines in use. To-day, the industry still requires larger and more robust machinery than almost any other, but, whereas thirty years ago steel works engineering was already on a large scale, and, above all, robust, it was not precise. To-day, much of it demands as high a degree of accuracy as is used in lighter industry. There has recently been a most noticeable improvement in the standards of engineering design and maintenance and a willingness to adopt ideas from other industries. Three examples of development have been chosen.

Hydraulic Engineering

Before electric motors were used in the industry, steam was the main form of motive power. But for many motions, such as driving capstans, operating blast-furnace bells and tilting converters, hydraulic power was used. Usually, this was drawn from a central system consisting of deadweight accumulators and reciprocating steam pumps. Control valves were of leather and the maintenance engineer's life was made a nightmare by frozen pipes, blown joints and pressure drop caused by the addition of plant to a pipe system already fully loaded. The introduction of electric pumps, usually of centrifugal type, served to emphasise the inefficiency of this system, for it was often seen that the cost of pumping power was twice that which would be required with a more direct system such as electro-mechanical. For a while, there was a tendency to install electro-mechanical drives, or pneumatic operation, wherever possible, instead of hydraulic. Examples are electric winches or pneumatic cylinders instead of hydraulic operation for blast-furnace bells ; rack and pinion drives instead of hydraulic cylinders for furnace pushers, and geared link motion drives for bloom shears instead of steam hydraulic intensifiers. But hydraulic engineering has made rapid strides in recent years and it is being applied in the iron and steel industry to a greater extent than ever before. It is being used in coke-oven machinery, in scrap bundling presses, for special cranes and very extensively in mills.

In days gone by, water, with occasionally the addition of soluble oil, was the universal operating medium. To-day, hydraulic fluid is used for the sake of improved maintenance. But leakage of this fluid is proving very difficult to avoid, particularly in confined spaces. Not only is this expensive, but it is also extremely dangerous. Serious fires have occurred due to burst pipes on bloom shears and due to the ignition of a pool of leakage from a piece of falling hot steel. While obviously the avoidance of leakage by better design and maintenance is the ultimate goal, the production of a cheap, non-inflammable hydraulic fluid is very desirable.

The selection of the correct pressure for each job is very important and the correct pump type for each pressure and quantity. Generally speaking, the pressure of a works system of about thirty years ago was 750 lb per square inch ; to-day, pressures up to 7000 lb per square inch are in use. With higher pressures, pipe diameters, control valves and cylinder diameters become smaller and this assists in good design.

For high pressures of over 5000 lb per square inch, there is still no real alternative to the three-throw ram type of pump. The disadvantages of this type are the space it takes, the difficulty of designing valves which do not wear into their seats and their slow speed. The multi-ram type, which is not usually made for pressures over 5000 lb per square inch, or capacities over 20 g.p.m., is proving most satisfactory and they can be installed in batteries. Their advantages are quite high speed and small space requirement. However, they do demand a very high degree of cleanliness in the fluid and the problem of valve design has not yet been solved satisfactorily. Radial piston, swash plate and vane pumps are all being used now by the industry. For variable volume applications the swash plate pump has much to recommend it. For isolated applications, such as a wagon tippler, the vane type is most satisfactory and cheap in operation and first cost. It operates at about 1000 lb per square inch, with unloading valves and no accumulator.

But in a steel works designed as a whole, it is doubtful whether there is any real reason for employing the multiplicity of pressures, pump types and separate systems now found. There does not seem to be any justification for the perpetuation of the deadweight accumulator. In the future, accumulation and shock absorption should be by a combination of air accumulators, Greer bottles and, for isolated applications, unloading valves. At one time, it was feared that air accumulators were unsuitable for roll balance, but there seems no reason why this should be so. The grouping of all operations in a given area on to one system has proved advantageous, enabling fewer units to be used. But for maintenance purposes, it is wise to separate different processes to allow each to be overhauled in turn.

Leather control valves have passed away unlamented and their place has been taken by either poppet or lapped piston types. The problem of how best to actuate the valves remains in dispute. In practice, hydraulic pilot valves have proved unsatisfactory and either direct operation with a large lever or solenoid operation have proved the best, although pneumatic pilot valves are also used. Some of the difficulties which have arisen with control valves have been caused by bad choice of pipe attachment and by fitting the valves into too small desks. In designing hydraulic control desks, it is essential to have robust pipe connections and easy access to them—this is not usually compatible with a neat and tidy desk.

The thrusts involved in iron and steel works operations are perhaps larger than in other industries, and it is therefore necessary to emphasise the importance of robust equipment. This particularly applies to piping. If flexible hose must be used high pressures and small diameters are better than low pressures and large diameters. A 1½in flexible hose will burst at 3500 lb per square inch, a 1in at 6000 lb per square inch, and a ½in at 17,000 lb per square inch. If flexible hose must be used, it must be very carefully draped. Many commercial pipe fittings are quite unsuitable for steel works use. The best type is one in which a flange suitably proportioned to the thickness of the pipe is screwed on to a taper thread and pulled on to a copper joint ring with four flange bolts. Ring type fittings require an accuracy of pipe diameter and surface which is not always available, but their main drawback is the precision with which they have to be fitted, very often in an inaccessible position. Nor can they withstand vibration.

It seems quite likely that with better appreciation of the engineering principles and problems involved there will be an extension of the use of hydraulics in the industry for intermittently used straight line motions. Often the use of a high-pressure hydraulic system can reduce both weight and complication. Fig. 1 shows the electro-mechanical device used to turn over two 15-ton ingots when they are between the manipulators of a slabbing mill. This device weighs 25 tons and requires a 150 h.p. motor to drive it. Due to mal-operation, occasional overloads occur, fracturing a shear pin, an unreliable method of preventing disaster. Fig. 2 shows the hydraulic actuator to be fitted in substi-

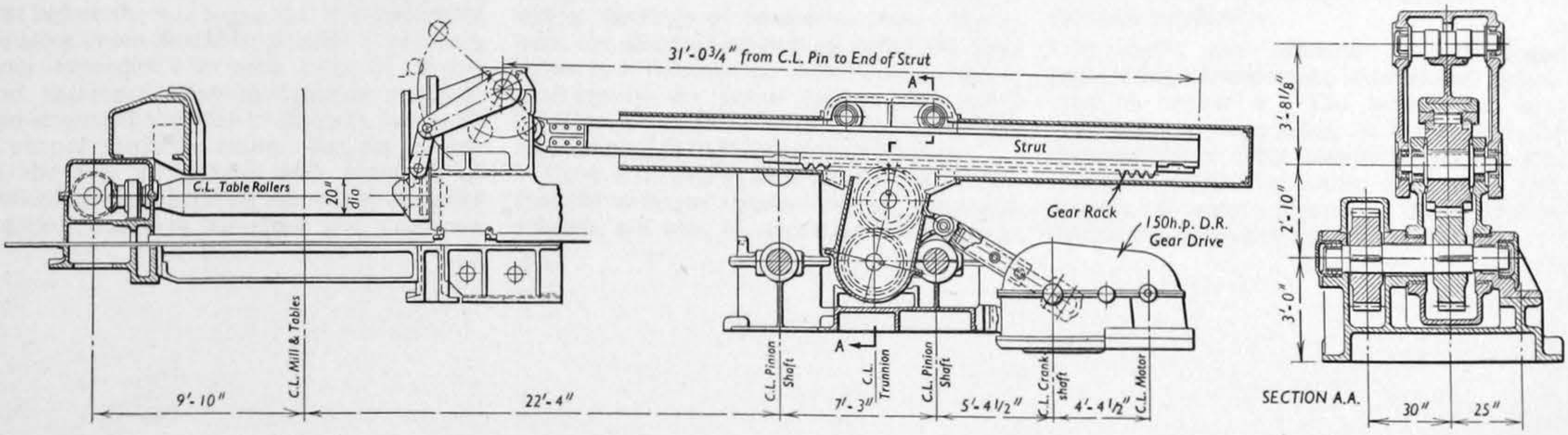


Fig. 1—Arrangement of finger lifting mechanism, rack type manipulator. 45in by 115in slabbing mill

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tution. The weight is 3 tons and the horsepower of the pump 35. Overloads cannot occur, as the mechanism will merely stall. It is this ability to stall which is so simply achieved hydraulically. But a further advantage is that full power is instantly available, whereas in the case of the electro-mechanical system the motor has not time to develop its full horsepower before the current is switched off. In fact, in the case illustrated the current

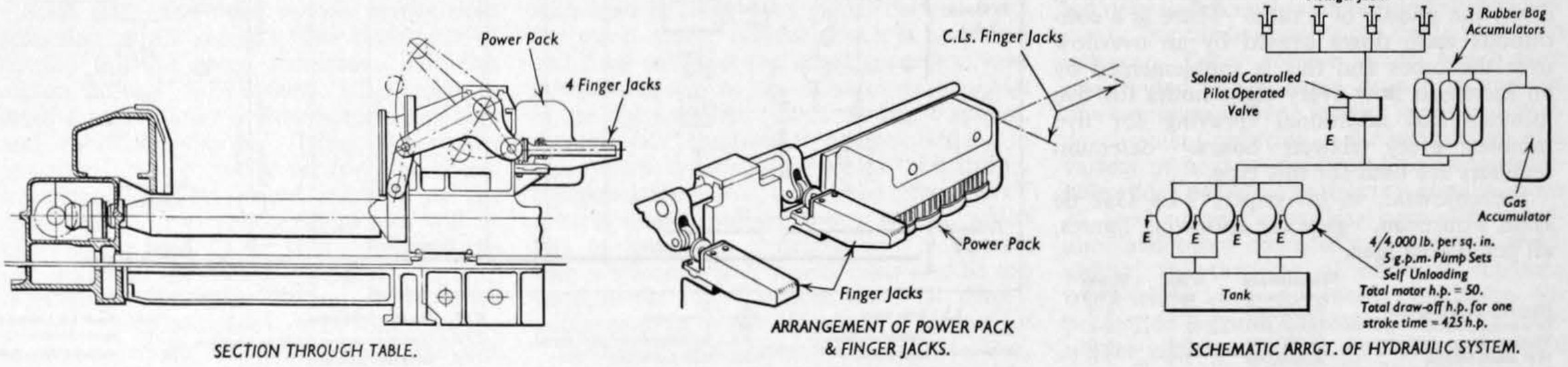


Fig. 2—Arrangement of jack operated finger lift

is switched off at the moment when the motor has completed nine revolutions.

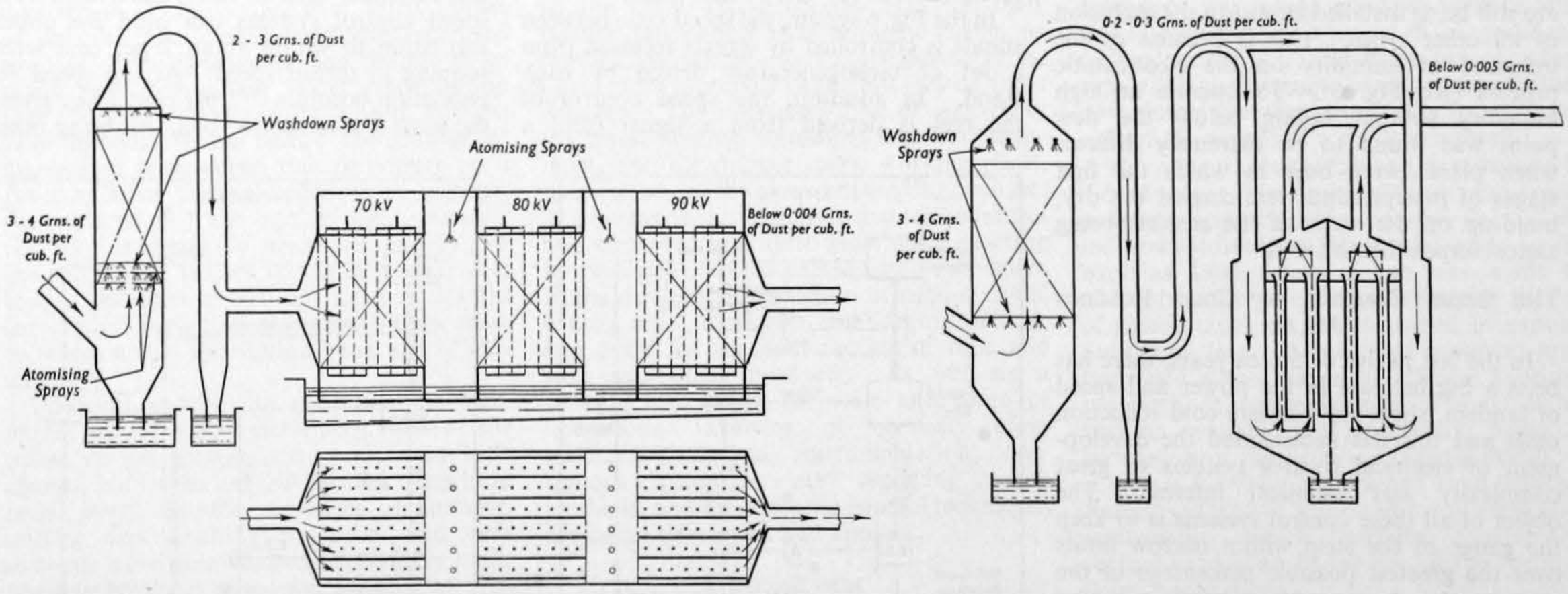
Cleaning of Blast-Furnace Gas

In the early days of iron making all the blast-furnace gas was wasted. But as over 50 per cent of the heat put into the furnace in the form of coke was lost in this way it quickly became obvious that it was desirable to trap and burn it. But as soon as this was done the need for cleaning the gas became apparent. For to use the gas efficiently in stoves, boilers or elsewhere was impossible as long as the heating surfaces became quickly coated with an insulating layer of flue dust. The development of blast-furnace gas cleaning plant has been an interesting one and has done much to assist other industries which have now become involved in similar problems, though not usually with the financial incentive there has been to clean blast-furnace gas. Actually the incentive was greater when blast furnaces were not as efficiently operated as they are to-day. For while, not many years ago, the coke consumption on a foreign ore furnace was about 21 cwt per ton of pig iron and the calorific value of the gas about 105 B.Th.U. per cubic foot, to-day furnaces are operating with coke consumptions of about 14 cwt and gas values of 90 B.Th.U. Also with the advent of sinter plants the flue dust has become of value. Every operator now strives to clean all his gas to about 0·001 grains per cubic foot, so that it can be used for such purposes as heating coke ovens and gas engines, soon perhaps in gas turbines, and also to recover the maximum quantity of flue dust in the form of dry dust and the remainder in a filter cake which can be used in the sinter mixture.

Even in early furnaces the furnace offtake pipe entered a simple box type dust catcher, the drop in velocity causing the deposition of the heavier dust. This idea persists to-day. From this box the gas nowadays enters a cyclone catcher, tall and thin. These were introduced about twenty-five years ago. About 70 per cent of the dust leaving the furnace top will be recovered by these two catchers in dry form, although very often it is pugged with a little water to make it easier to handle. But although simple, the primary dust catcher is by no means free from trouble. The gas, being very full of water vapour, only has to cool a little for dampness to appear and the catcher walls to build up. In a few furnaces this primary box type catcher followed by a cyclone catcher has been replaced by two cyclone catchers, in parallel, which would seem a more logical design and less likely to suffer from build up. The gas leaving the secondary dust catcher or cyclone usually contains from 3 to 4 grains per cubic foot of dust. Three main types of final gas cleaning have been tried. The Halberg-Beth was one of the earliest and, from a gas cleanliness point of view, one of the most successful. The gas passes through fine cotton filter bags which are rapped at intervals to cause the deposited dust to drop. Almost any required degree of cleanliness can be obtained by making the bag mesh small enough. There are three drawbacks to this system. The fine mesh of the bags causes a big back pressure, the bags are liable to catch fire at any temperature above 100 deg. Cent.—particularly are they vulnerable if any pyrophoric zinc is present, which is common in blast furnace dust—and they are very sensitive to any moisture. Usually the gas is cooled first in water cooled heat exchangers, similar to economisers, and then reheated either by steam pipes or by burning air in the gas in order to ensure there shall be no moisture present on the bags. This is still the only workable system which recovers all the dust in a dry state.

Rotary disintegrators are still widely used, but their high power consumption and use of water is against them.

To-day wet electrostatic precipitation is being installed on all new plants. Although two-stage plants with dry and wet recovery have been tried, they were not a success and to-day there are only two kinds in common use. In both the gas is first rough-cleaned in tall wash towers. The gas is then conditioned by high-pressure atomising water sprays, which improve the ionisation. In one type the gas then enters a series of rectangular treaters in parallel, in which there are rows of parallel plates and wires. Fig. 3 shows the way in which these wires and plates are connected. A corona discharge is created around each of the wires, which are negative,



Figs. 3 and 4—(left) Diagram of wash tower and plate type electrostatic precipitator, (right) Diagram of wash tower and tube type electrostatic precipitator

and the dust particles passing through this discharge become negatively charged and attracted to the positively charged plates. At intervals of four hours, the plates are washed down. There are six banks of electrodes in each treater and they are washed down one at a time for about three minutes, during which time the power is switched off that bank. Thus, each filter is operating on five

banks out of six for eighteen minutes every four hours. There are atomising sprays after each bank to ensure high humidity. The direct current is supplied for this type by a mechanical rectifier with a revolving arm in which the current jumps across a gap, the arm being rotated opposite the correct pole by a synchronous motor. This rectifier requires a good deal of space but is extremely reliable and robust. Another type of precipitator is illustrated in Fig. 4. In this the wires giving the corona discharge each hang down the middle of a tube. There is a continuous wash down caused by an overflow over the tubes and this is supplemented by an increased flow every eight hours for five minutes and additional spraying for five minutes every sixteen hours. Selenium rectifiers are used for this type.

Szczeniowski, in his paper, "Le Gaz de Haut Fourneau," gave the following figures, all per 1000m³/gas.

	Installation cost, francs	Water m³	Power kWh
Halberg-Beth bag filter ...	75,000,000	2	3·5
Dry electrostatic	75,000,000	2	2·5
Theisen disintegrator ...	68,000,000	6·1	6·0
Wet electrostatic	70,000,000	5·9	2·0

From this one would expect a strong swing towards dry electrostatic, for the nuisance of the water content in the sludge of the wet electrostatic is considerable. After passing the effluent from the towers and treaters through a thickener, the sludge still contains 60 per cent moisture and even the use of vacuum filters will only reduce the moisture to 30 per cent. So that the development of a dry type precipitator would save not only water but the cost of thickeners, filters and driers. Nevertheless, wet treaters

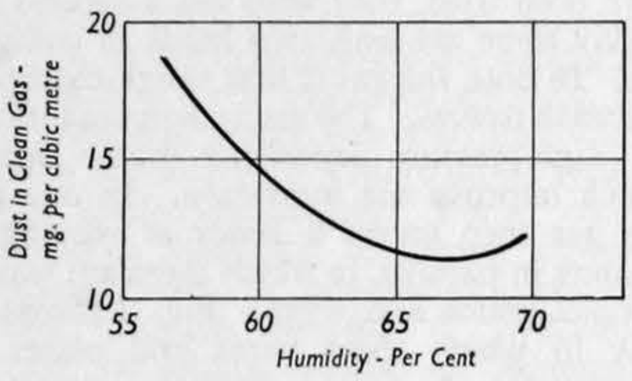


Fig. 5—Influence of humidity on the dry electrostatic process

are still being installed almost to the exclusion of all other types. This is because of the influence of humidity on the electrostatic process (see Fig. 5). To operate at high humidity without falling below the dew point was found to be extremely difficult when plants were built in which the first stages of precipitation were carried out dry, build-up on the walls of the treaters being almost impossible to avoid.

The Speed Control of Cold Rolling Mills

In the last twelve or fifteen years, there has been a big increase in the power and speed of tandem, sheet and tinplate cold reduction mills and this has necessitated the development of electrical control systems of great complexity and technical interest. The object of all these control systems is to keep the gauge of the strip within narrow limits over the greatest possible percentage of the strip length. As a modern tinplate mill may normally run at 4500–5000ft per minute, and the strip may be as thin as 0·008in, the problems of acceleration and deceleration of the reel and the five stands with their massive back-up rolls are great. In order to reduce the frequency of threading and the length of the thread piece, coils are large—up to 70,000 lb in sheet mills and about 40,000 lb in tinplate mills, and the stands are built as close together as possible. To control these

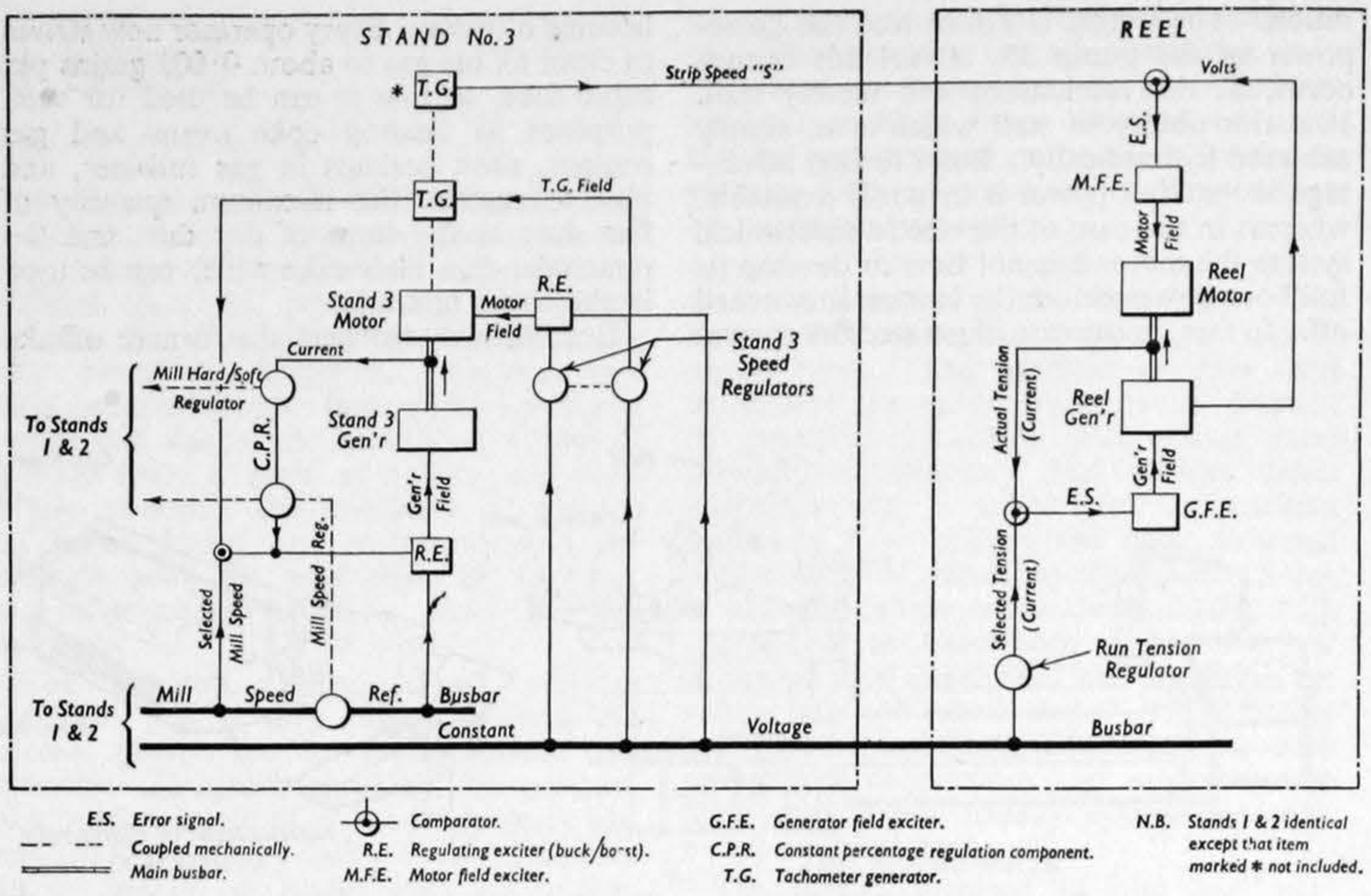


Fig. 6—System of control—3-stand tandem mill

modern high-speed cold mills, it is necessary to have a system of signals which indicate the state of each stand and the reel. These signals, which are derived from various sources, in mills built ten years ago, were almost invariably amplified by one or other of the many forms of cross-flux generator. To-day there is a swing towards magnetic amplifiers which combine the functions of signal amplifier and controller and have a response at least as quick as the rotating cross-flux amplifier and are lower in maintenance cost.

Two main systems of control have been evolved, illustrated diagrammatically in Figs. 6 and 7. The system shown in Fig. 6, which has been in satisfactory operation on three stand mills, has, so far, not been applied very successfully to five stand mills. It may be of some interest to explain the basic differences between the two systems. For it is by no means clear why the system in Fig. 6 cannot be applied equally well to five stand mills as for three stand mills.

In the Fig. 6 system, the speed ratio between stands is controlled by signals received from a set of tachogenerators driven by each stand. In addition, the speed control of the reel is derived from a signal from a separate tachogenerator driven by the last stand. Under this system, with the mill running empty at full speed, the speed of each stand is regulated relative to its neighbours by varying the setting of its stand speed regulator, which varies the voltage on the main motor field of that stand. The setting of this stand speed regulator is ganged with the setting of the stand tachogenerator. Thus, if it was desired to lower the speed on a particular stand to 650 r.p.m. when the stand speed setting was equivalent to 700 r.p.m., this would be achieved by increasing the motor field volts and, at the same time, the tachogenerator output would be appropriately increased so that it would not nullify the speed alteration applied to the motor field. As the mill is loaded, there is a tendency for the speed to drop and the tachogenerator will send out a signal of reduced voltage, thus allowing the regulating exciter to boost the volts applied to the stand generator field. The tachogenerators, are, in effect, used as stand governors. The speed control systems can hold the circuit regulation to within about 2 per cent when running at thread speed. At top speed the regulation becomes 0·2 per cent when giving the same loss in motor volts, this being much

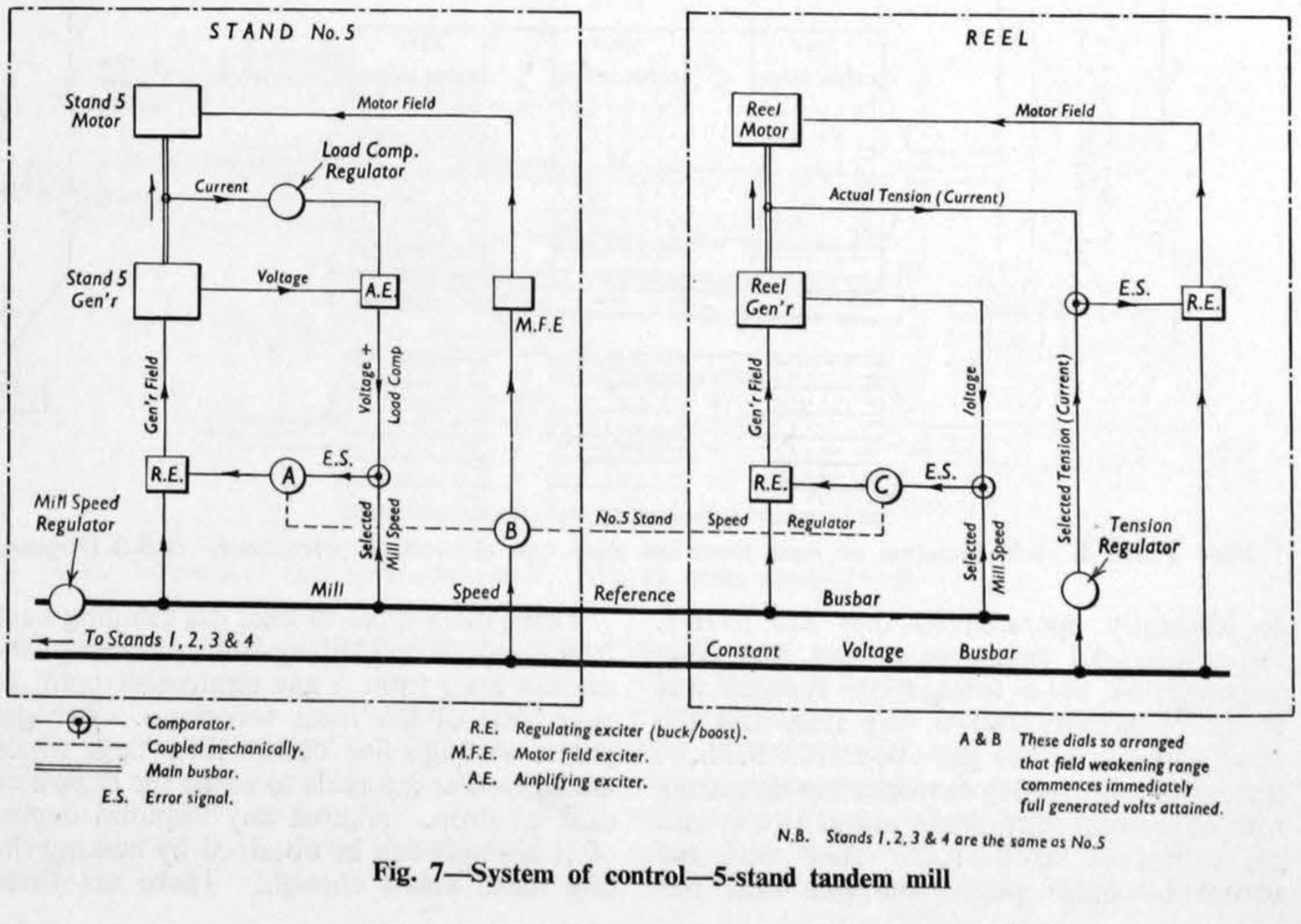


Fig. 7—System of control—5-stand tandem mill

too hard for satisfactory working. As the speed is raised above thread speed the regulation is purposely and progressively spoilt, so that it remains about 2 per cent over the full range. This constant percentage regulation feature is obtained by taking a signal proportional to motor load through two rheostats in series. The one coupled mechanically to the mill speed regulator achieves the spoiling effect, while the other gives the mill operator control of the degree of " softness."

Steel does not flow equally under cold reduction at all speeds. The coefficient of friction falls as speed increases. For this reason among many others, strip tends to leave a mill thicker at low speed than high and, therefore, shorter. Thus, in a rigidly controlled mill correctly set for high-speed, inter-stand tension would increase as the speed fell. To a certain extent this will be offset by the work on the later stands increasing, and also the finished gauge of the strip increasing. In mills rolling fairly thick gauges, the strip is able to take some increase in tension which assists in keeping the mill on gauge. But as the strip becomes thinner, as in the case of a five-stand mill, in the last two or three stands it is unable to bear this tension increase without breaking. To enable each stand to droop with increase in load caused by increase in tension, or thicker strip being fed to it, any variation in stand motor current from that decided upon would cause the regulating exciter to vary the degree of boost of the stand generator volts. This is the " hard-soft " control referred to earlier.

In the Fig. 7 system, the speed ratio of the stands is controlled both by varying the stand generator volts and by varying the motor field. There are no tachogenerators and any tendency for the mill speed to droop with load is offset by a signal derived from the stand motor current which is amplified and used to boost the stand generator volts in the same way as the tachogenerator signal in the Fig. 6 system. As in the Fig. 6 system, there is a " hard-soft " control which, in this system, is usually known as " IR drop " compensation. For, unlike the " hard-soft " control in the tachogenerator system, which has to introduce a degree of " softness " into a system which would otherwise be too hard, in the Fig. 7 system the " IR drop " compensation is to introduce a degree of " hardness " in a system which would otherbe too " soft," particularly at high speeds, and this is done by using a signal derived from the motor current to boost the generator volts.

Non-Ferrous Metals

By MAURICE COOK, D.Sc., Ph.D., F.I.M.*

A HUNDRED years ago there were only four basic non-ferrous metals—copper, lead, tin and zinc. The total world production of these, and the few other metals then available, amounted to no more than a few hundred thousand tons. To-day, this figure exceeds 10,000,000. To these four there have been added in the meantime at least three other high-tonnage metals—aluminium, nickel and magnesium, which form the basis of important alloy groups. But the position over this intervening time has changed not only thus impressively in terms of quantity, but in the variety of metals that are now required in our complex technical civilisation. They number over thirty. Most of this change, particularly the increased production of light metals and the use of so many new metals, has taken place during this century and especially within the last two decades. Even before the output of aluminium approached that of copper on a tonnage basis and exceeded it in volume, the expression " the age of light metals " was not infrequently seen and heard, but the range and variety of the new and rarer metals and their alloys that are now needed for vitally important purposes would seem to warrant the appellation " the age of new metals."

For long centuries the processes and techniques of extractive metallurgy, one of the oldest of the human arts, underwent little change, but in the last few decades there have been many notable advances in mining, milling and smelting practices, and new methods have been devised which have made possible both the economic working of low-grade marginal ores and higher yields of metal content. Furthermore, refining operations have undergone radical alterations, especially in the introduction of electrolytic methods for the production of high-purity metals, now so necessary for many industrial uses. These many discoveries and developments in all phases of metal production have understandably and inevitably been closely linked with corresponding advances in many branches of engineering and the demand for ever-increasing quantities of some of the non-ferrous metals has given rise to many vast engineering projects. To cite but one example, the recent scheme in British Columbia, designed for an ultimate yearly output of 500,000 metric tons of aluminium ingot, involved the driving of a 10-mile tunnel through a mountain to give passage to falling waters, the construction of a power-house inside a mountain, and the erection of the largest overhead transmission cable ever made to carry electric power.

As in the extraction and refining of metals, so the plant and processes used for their further fabrication into wrought forms or finished castings have undergone great change, again more especially in the last two or three decades. The increased use of electricity for metal melting, annealing and heat-treatment, and for driving metal working plant, has been one of the most outstanding changes. The demand for materials in greater quantities and improved quality to meet more exacting specifications has stimulated notable advances in the design and operation of casting units, rolling mills, extrusion and forging presses, and plant for the manufacture of tube and wire and other products. As well as a striking increase in the scale and speed of operations, involving of necessity more mechanisation and instrumentation, continuous processes are replacing batch methods, and more precise control techniques are being developed and applied.

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Aluminium

By far the greatest change in the pattern of non-ferrous metal production and use in recent years is the spectacular advance of aluminium and its alloys which now feature so prominently in, and are markedly influencing developments in, transport, electrical engineering, building and many other applications. At the beginning of this century, fourteen years after Hall and Héroult demonstrated the practicability of an electrolytic process for the production of aluminium, which is used unaltered in principle to-day, the world output of the metal was only a little over 7000 tons. By 1935 it had reached 250,000 tons, and it is now about 3,000,000 tons, an output on a volume basis exceeding that of any other non-ferrous metal.

The discovery by Wilm in 1909 of precipitation hardening in aluminium alloys opened up immense possibilities with far-reaching consequences and led to a whole range of lightweight, high-strength materials which not only significantly affected aircraft developments, but made possible the modern aircraft industry. Other notable factors which have contributed to the rapid growth in the use of aluminium include further successful alloy development resulting in the production of a variety of heat-treatable and non-heat-treatable alloys possessing attractive combinations of mechanical properties, corrosion resistance and other characteristics such as weldability, the devising of effective finishing treatments, such as anodic oxidation for protection against corrosion, cladding techniques and new joining methods exemplified by argon-arc welding, non-metallic bonding and furnace brazing. This expansion has also been facilitated by the introduction in 1936 of continuous casting methods which improved both the quality and uniformity of castings, by developments in extrusion techniques which have made possible the production of large sections and a great variety of shapes, and by mass production methods for the manufacture of strip and sheet.

More than 20 per cent of the aluminium output is consumed in transport in one form or another, and while some of the newer uses in this field are growing rapidly, it is in connection with aircraft construction that aluminium has so far achieved its most notable success. Flight at supersonic speeds is almost commonplace nowadays, but when the Wright brothers launched the first heavier-than-air machine at Kitty Hawk in 1903 it covered a distance of 852ft in fifty-nine seconds. Early aircraft were built of wood and steel with a textile fabric skin and progress was retarded by the lack of light structural materials of adequate strength. This deficiency was made good by Wilm's discovery and the development of alloys of the " Duralumin " type, and thereafter of others with still higher strength/weight ratios, so that now aluminium alloys constitute some 75 per cent of the weight of a modern aircraft.

The advantages accruing from reduction in " deadweight " in both rail and road transport were appreciated in the early days of the industrial history of the metal and, as far back as 1905 extensive use was made of aluminium for panelling and interior fittings of rolling stock on the electrified Liverpool-Southport line. It was not, however, until improved alloys and more efficient fabricating methods and techniques of construction became available that aluminium began to be used to a markedly increasing extent, as it now is for rolling stock and road vehicles. Recent years have witnessed many impressive innovations which indicate considerable further expansion in the use of the metal in these applications.

The first recorded use of aluminium in shipbuilding was in 1891, when the hull of a launch was built of aluminium sheet in Zurich. As in road and rail transport, the appreciable extension of its use came much later and more particularly with the development of the aluminium-magnesium and aluminium-magnesium-silicon groups of alloys and improved welding and riveting techniques. That the merits of aluminium

alloys in shipbuilding are now well recognised is significantly indicated by the incorporation of more than 2000 tons of these materials in the superstructure of the S.S. " United States."

Although there are some noteworthy examples of the use of aluminium in architectural applications and building constructions dating back into the last century, the possibilities of the metal for these and other structural purposes, including bridges, have only been considered seriously in recent years. Because of its advantages of lightness, ease of handling, and durability even in the most aggressive industrial atmospheres, it is now being used increasingly in building, a change in attitude perhaps symbolised in the Dome of Discovery at the South Bank Exhibition.

The established position of copper as a conductor material has tended to overshadow the actual and potential value of aluminium for electrical purposes, but its use in overhead transmission lines and for busbars is growing, and electrical applications alone account for quite an appreciable consumption of the metal.

Magnesium

Although it was first isolated 125 years ago, developments in the other major light metal, magnesium, have not paralleled those of aluminium, largely because of the more limited range of physical and mechanical properties that it is possible to obtain in the alloys so far developed. From an output of about 20,000 tons in 1937 a peak figure of more than a quarter of a million tons was reached in 1943, and although this fell away to between 30,000 and 40,000 tons during the immediate post-war years, there has been a recovery during the past five years to the present figure of about 150,000 tons. As there is an abundance of workable ores of magnesium, such as dolomite and magnesite, and since it is present in sea-water, from which it can be extracted by methods first used in this country in 1938, magnesium is one of those metals, unlike some others so extensively used to-day, for which there need be no anxiety about future availability. Much progress has been made in the last few years in alloy development and production, and with a lower specific gravity than aluminium, magnesium lends itself to applications where maximum weight saving is of paramount importance. This advantage has been utilised particularly in aircraft, where magnesium is a standard material of construction for many components.

Titanium

The newest potentially large tonnage metal is titanium, which, like aluminium and magnesium, occurs abundantly as substantial deposits of workable ores. One of the outstanding attractions of this metal, still in its industrial infancy, is its resistance to corrosion, and some of the alloys so far developed, without appreciable loss of this valuable attribute, have the highest strength/weight ratio of any known metallic materials. The first industrially workable process for extracting titanium was devised in 1940 and the total output of metal in 1954, produced mainly by this method, was about 4000 tons, but much more capacity is being provided against a growing demand. The whole technology of titanium is dominated by the necessity for avoiding contamination by impurities, particularly, but not only, by oxygen and nitrogen, from the earliest stages of reduction and through the subsequent processes of melting, casting and further fabrication. This has occasioned the development of types of plant and equipment and operating techniques new to conventional metallurgy. Most of the titanium now being produced is employed for jet engine and airframe components and the advent of this metal seems likely to contribute much to further aircraft developments. Potentially, titanium has many uses in marine engineering since its resistance to sea-water corrosion is of an exceptionally high order, and, being but half the weight of stainless steel and more corrosion resistant, it has considerable possibilities in the field of chemical engineering.

Copper

At a current figure of more than 3,000,000 tons, the annual output of copper still exceeds that of any other non-ferrous metal. A hundred years ago the world production was about 50,000 tons. This growth in output over that period provided for the needs of the rapidly expanding electrical industry, in which as a conducting material copper was eminently suitable, and this usage accounts for more than half the virgin copper now consumed. Among the many advances that have been made in the extraction and refining of copper, perhaps the most outstanding has been the introduction of electrolytic refining, which was first started at Pembrey in South Wales in 1869, and put into operation a few years later in the United States, where copper production was at that time rapidly developing. To-day more than 80 per cent of the world's production of primary copper is electrolytically refined. To meet new requirements of the past twenty-five years or so several special types of high-conductivity copper have been produced. Thus silver has been added to increase high-temperature strength, tellurium to improve machinability, which it does to a remarkable degree, cadmium and chromium for added strength at room temperature, while oxygen-free high-conductivity copper satisfies particularly stringent needs for ductility. Much of the copper not used for electrical purposes is of the deoxidised variety, a type of copper made by the removal of oxygen from the molten metal by the addition of phosphorus. It was generally introduced about thirty years ago and, being immune to gassing, it made possible and greatly stimulated the use of welding as a technique for the construction of various kinds of vessels and equipment in copper.

Copper alloys, of which a very considerable number have been developed in recent years, both in the form of new alloys and modifications of existing well-known ones, such as the brasses, tin, bronzes and nickel silvers, meet a variety of engineering needs too diverse to itemise. Of these materials, the brasses constitute the most important single group in as much as the tonnage produced exceeds that of all other copper alloys. Apart from many other important uses certain brass alloys are of particular significance as condenser tube materials. The alloys commonly used originally were 70/30 brass and Admiralty brass and because of their inadequate resistance to corrosion by dezincification in sea-water, failures from this cause were frequent until the inhibiting effect of small amounts of arsenic was discovered in 1923. With the use of higher water speeds through the tubes corrosion failure by impingement attack became in its frequency a new serious problem which has been largely overcome by the use of 70/30 cupronickel alloys containing small amounts of iron and manganese, and aluminium brass. With improved production methods, a fuller understanding and knowledge of their properties and behaviour in service, and the use of new welding techniques, corrosion resisting alloys such as the aluminium bronzes, which are amongst the strongest of the copper alloys, and the silicon bronzes are being used increasingly for chemical plant and other constructions. Age-hardenable alloys of copper were first discovered in the early twenties and although it has been shown that there are many systems in which alloys can be substantially hardened and strengthened by solution heat-treatment and subsequent ageing, only limited use has so far been made of these findings, but some alloys of this kind, such as those of copper-beryllium, copper-chromium and copper-nickel-aluminium, have been developed to meet special requirements.

Nickel

From a negligibly small output in 1850, although the metal was discovered in 1751, the annual level of production of nickel has now reached about 200,000 tons. The discovery of the carbonyl process in 1890 for making pure nickel and the development of electrolytic refining processes were most timely, for in 1889 Riley had demonstrated the advantages of nickel additions to steel, since when the metal has found its largest use in the steel industry. In 1914 Brearley introduced the first of the stainless steels, the production of which depends in no small way on the availability of nickel at an economic level and of the required purity, as well as on the silicon reduction process for the manufacture of the necessary low-carbon ferro-chromium. Nickel is also used in producing heat-resisting steels, improved cast irons and many ferro-nickel alloys with special physical and magnetic properties. The merits of the metal do not, however, derive only from its use as an alloying element, for many technological advances have been made with the aid of nickel base alloys. Nickel-copper base alloys of various types and compositions meet important requirements in the electrical, chemical and other industries and nickel-chromium alloys form the basis of an important high temperature group used for resistance elements and in heat-resisting applications. These binary alloys have been modified by the addition of such elements as aluminium, cobalt and titanium and their resistance to scaling, as well as their strength and creep properties at elevated temperatures, thereby so greatly improved that their availability has contributed importantly to the development of gas-turbine engines. Electro-deposited coatings of nickel have been long used for cutlery and other wares and they constitute moreover the basis of many forms of metal finishing treatments.

Zinc

One of the most notable advances in the extraction metallurgy of zinc (the output of which over the century has increased from about 50,000 tons to over 2,000,000 tons, second only to copper of the heavy non-ferrous metals) has been the production of high purity metal required for many modern alloys of which zinc is an ingredient and for zinc-base die casting alloys. In the early part of this century zinc alloys came into use in connection with the newly developed process of die casting for the quantity production of complicated parts. The corrosion troubles and dimensional instability which were associated with them were shown to be due to impurities and with the advent of high purity zinc, alloys free from these crippling limitations have come into extensive use for fittings for motor vehicles, radio and domestic engineering products, and account for about 10 per cent of the zinc consumption. Hot dip galvanising and other zinc coating processes use about one third

of the zinc output and the other major use is in the manufacture of brass.

Lead

In 1850 lead production at a level of about 150,000 tons was by far the highest of all the non-ferrous metals and it has since increased to a figure approaching 2,000,000 tons. Used since ancient times, lead was one of the earliest metals employed in the chemical industry because of its high resistance to corrosion and ease of manipulation. The sulphuric acid industry still depends on it and the provision of high-purity chemical lead, made possible by improvements in refining processes, has contributed to its further use, and so also has the discovery that small additions of various alloying elements appreciably increase the creep strength of the metal without significantly affecting its corrosion resistance. Its other large tonnage uses are for cable sheathing, storage batteries, flashings and piping, type metals and bearing metals.

Tin

The production of tin has increased over the century from about 17,000 tons to about 200,000 tons, about half of which is used in the manufacture of tinplate, a production that has undergone major changes in recent years with the adoption of electro-deposition techniques integrated with the use of large powerful mills for rolling wide strip in coils weighing several tons. Modern production of tinplate, which runs into millions of tons per annum, has, in fact, lead to the development of some of the most impressive plant employed in the metallurgical industry and to continuous processing on a most imposing scale. Another very important use of tin is in making bearing metals which have been so necessary to progress in prime movers and machinery generally. Although many varieties and alternatives have been produced and used, the type of tin-antimony-copper alloy, originally introduced by Babbitt in 1839, still holds pride of place, and it is in manufacturing methods that most advance has been made. More than 20 per cent of the tin production is used for the manufacture of soft solders, essential joining materials for many purposes.

Other Metals

The production of the four metals: copper, aluminium, lead and zinc accounts for more than 90 per cent of the total output of non-ferrous metals and most of the remainder is composed of nickel, tin and magnesium. There are, however, many others which have been vitally necessary to successful developments in alloy steel production. An even greater and growing number of metals, some of which have for long been industrially important, are essential to new technological advances that are now taking place. In addition to nickel, the non-ferrous metals of significance in steel and ferrous alloy production include manganese, chromium, tungsten, molybdenum, cobalt, vanadium, boron and niobium, and this use absorbs most of their output, which in many cases is not for the most part in the form of primary metal and, consequently, not included in non-ferrous metal production.

Manganese is used as an ingredient in many non-ferrous alloy groups, and the availability of pure manganese made possible by the introduction of electrolytic refining techniques some twenty years ago, is of interest in connection with the manufacture of alloys of relatively high manganese contents. The work of Sargent in 1920, which demonstrated the feasibility of chromium plating as an industrial process, was one of the most notable technical contributions that has been made to the metal finishing industry and, also in the electro-deposited form, chromium has an important and extensive use for hard surfacing tools and dies.

Molybdenum, because of its high melting point, is becoming of increasing importance in many new electrical and other applications, and cobalt has been essential to the successful development of magnetic materials and hard alloys. Tantalum is another of the less common or minor metals which, because of its particular properties and characteristics, is being used for a variety of purposes in electrical applications, and for cutting tools and as an acid-resisting material.

The advent of a feasible method for releasing energy from atomic nuclei has posed many difficult problems in the choice of materials for use in the construction and operation of reactors, and apart from fissionable materials, beryllium and zirconium have acquired considerable importance in this connection because of their low neutron absorption.

Many of the precious and rare metals, although understandably used in comparatively small quantities, have advanced in industrial importance in recent years. Of these materials, silver, one of the metals known for thousands of years, is produced in by far the greatest amount, present output being in the region of 200 million fine ounces. Of its many important uses, one of the most essential to our present civilisation is in the photographic industry, which, in its dependence on the metal, consumes many millions of ounces a year. The electroplating industry is also one of the largest consumers of fine silver and its use is also expanding in the chemical and electrical industries and in the production of silver solders. The platinum group of metals, which includes as well as platinum, palladium, rhodium, osmium, ruthenium and iridium, are much newer to industry, their history dating no further back than 150 years. Some of them are being increasingly used, particularly in the electrical and chemical industries, and the importance of platinum and rhodium in the development of pyrometry, now widely used in controlling thermal operations, needs no emphasis.

A class of materials indispensable to several recent developments in the electrical industry are semi-conductors, some of which are metals, and two of these—selenium, discovered in 1817, and germanium, first isolated in 1886—are of particular significance. Exposure to light increases the conductivity of selenium, the characteristic which has led to its use in many types of photo-cell, while a comparatively new and increasingly important use for it is as a rectifier of alternating current. The high-purity germanium required for electronic devices is made by fractional distillation or by the new zone refining method and the use of this metal in transistors is having far-reaching effects in electronic engineering and communication, and must rank as one of the most outstanding recent applications of the newer and less common metals.

Whilst by far the greatest tonnage of wrought non-ferrous products are manufactured from cast ingots and billets by processes that have been briefly mentioned earlier, nevertheless some products, outstanding in the impact they have had on engineering and industrial progress, are made by powder metal techniques. This branch of metallurgy can be regarded as dating back to the time of Wollaston and his work on platinum early in the last century, but it was not until the first decade of the present century that powder metal processing achieved any signal success. Then, in 1909, Coolidge made possible the modern electric lamp by producing ductile tungsten in the form of fine wire for filaments from compacted and sintered tungsten powder. This notable application of powder metallurgy to the electrical side of engineering was followed a few years later by another to the mechanical side with the advent of sintered tungsten carbide tools and all the manifold advantages they have brought to machining operations. In both these uses materials of extremely high melting point and hardness figure prominently, but more recently there have been successful developments in other directions, such as the production of porous bearings from bronze and graphite compacts and further attention is now being given to the possibilities of direct processing of metal powders as an alternative route to existing methods for making wrought products.

The Growth of the Concrete Industry

PROFESSOR A. L. L. BAKER, D.Sc., M.I.C.E., M.I.Struct.E.*

Manufacture of Cement

THE use of hydraulic limes goes back to ancient times. The Egyptians used burnt gypsum mortar in the pyramids of Cheops. Concrete made with hydraulic lime has been found in the joints of the abutments of the Roman bridge built by Hadrian to carry his defence wall over the north Tyne. Many varieties of concrete were used in building his villa near Rome. Hadrian's most extraordinary accomplishment was the roof of the Pantheon, in Rome. This 142ft 6in diameter dome, built 1835 years ago, appears to be in a perfect state of preservation to-day. The inner surface has a skin of light concrete, and it is thought by Robertson that the main core is concrete in accordance with contemporary practice in regard to vaulting, and that the thick jointed brick work which is visible is merely a protective facing.

Various admixtures have been tried with hydraulic lime, particularly in marine works, but no outstanding advance was made until Smeaton undertook research to obtain a mortar which would set under water and which he required for building the Eddystone lighthouse.

In 1756, Smeaton found that hydraulic lime made from limestone which contained clay set in water better than a pure lime, and he used on the lighthouse construction a cement produced from a blue lias lime from Aberthaw, together with pozzolana, obtained from Italy. In 1869, Wilhelm Michaëlis wrote : " A century has elapsed since the famous Smeaton completed the building of the Eddystone lighthouse. Not only for sea faring, but for all humanity this lighthouse stands as a true signal of blessed work, a light in a dark night. From a scientific point of view it illuminated the darkness of nearl 2000 years.

" The errors which came to us from the Romans, and which were shared even by the excellent Belidor, were dispersed.

" The Eddystone lighthouse is the founda-

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tion upon which our knowledge of hydraulic mortars has been built and it is the chief pillar of modern construction. Smeaton freed us from the shackles of tradition by showing that the purest and hardest limestone is not the best, at least for hydraulic purposes, and that the source of the hydraulicity of lime mortar must be sought in the argillaceous admixtures."

In 1817, Vicat tried burning various mixtures of common lime slaked spontaneously by clay, and obtained good results. He was a French Government engineer who devoted much of his life (1786–1861) to research on mortars. He wrote many papers from 1818 onwards and, in 1828, a book which was translated into English in 1837 by Captain J. T. Smith. He concluded that no perfectly hydraulic mortar exists without the incorporation of clay containing silica and alumina. He invented the Vicat needle for testing the setting time of cements.

Joseph Aspdin, a Leeds "bricklayer" or builder, as he would probably be called to-day, had for some years been making a hydraulic cement when, in 1824, he obtained a patent for his material and gave it the name of Portland cement. Joseph Aspdin's specification was not as clear as one granted to Frost, in 1822, for a cement which he called British cement. Frost clearly indicated that he used two parts of chalk to one of clay, produced a slurry in a mill and calcined in a kiln the sludge which had settled in tanks. He used enough heat to drive off carbon dioxide. He then ground the resulting product. Brunel used Aspdin's cement in constructing the Thames tunnel in 1838, and John Grant, engineer to the Metropolitan Board of Works also used it in 1859 in the construction of the London Drainage Canal. In 1866, Grant introduced the tensile briquette test.

In 1827, J. B. White and Co. took over Frost's works at Swanscombe, Kent, a step which later led to the development of the modern cement industry. Aspdin's cement, however, was at that time more popular, and I. C. Johnson, of J. B. White and Co., persistently tried to discover the secret of the better quality of Aspdin's product, but without success. Aspdin guarded his secret with great care. He permitted no one except himself to carry out some of the operations in the manufacturing process. His works was surrounded by a 20ft high wall to keep out the inquisitive and entry could only be made through the office door. Johnson employed a chemist to analyse Aspdin's cement, and the latter reported that, amongst other things, phosphates were present. Johnson immediately assumed that Aspdin used an admixture of ground bones and arranged to buy large quantities in the Thames Estuary area. He found, however, to his disappointment, that the addition of ground bones, if anything, deteriorated the quality of the cement.

In 1848, Johnson, on one occasion, unintentionally raised the temperature of his kilns until the mass nearly vitrified. The resulting clinker he threw away and dumped it where he thought it would be obscure, as he was anxious to safeguard his technical reputation. Some time later, when passing this dump, he noticed that some of the clinker which had become pulverised and damp had set hard. This incident marked the discovery, at least in one important enterprise, of modern Portland cement. From then onwards, Johnson operated his kilns at a much higher temperature until the mass nearly vitrified and ground the clinker thus produced.

In 1858, French Government engineers bought cement manufactured by Johnson for use in constructing Cherbourg harbour and were impressed by its quality. Between 1865 and 1871, it was used on harbour works at Le Havre. Doubtless, these events influenced the beginning of the French development of reinforced concrete, which did not make great headway until strong cement was available. Moreover, it was the success of the French port work which gave Hennebique an opportunity, in 1898, to extend the use of his system to Great Britain. He designed and constructed a wharf near Southampton and set up a branch organisation in London.



Fig. 1—The Pantheon, Rome. Built about A.D. 120 by Hadrian. Diameter, 142ft 6in. Internal finish lightweight concrete core, probably concrete with brick external finish

Many other names could be mentioned as contributors to the growth of the cement industry in the nineteenth century, particularly in France, Germany, Italy and the Scandinavian countries. Le Chatelier (1850–1936), in France, first made real progress in determining the compounds which formed in the burning process. The cost of manufacture of cement, particularly in U.S.A., was reduced by the introduction of the rotary kiln. Thomas Crampton, in 1877, secured a British patent, and Frederick Ransome in 1885. In 1893, Davidsen, of Denmark, invented the tube mill, now almost universally used for grinding, and prepared the way for the great development of reinforced concrete engineering which soon followed in all Scandinavian countries. George and Thomas Earle were manufacturing Roman cement at Hull in 1823, and in 1832 it was claimed by them that their product would set hard under water. In 1933, a masonry joint made with Earle's cement in 1818 in Bridlington pier, was found to be in good condition.

Development of Reinforced Concrete

It is curious that, although the first clear conception of the proper function of steel reinforcement embedded in concrete was described by Thaddeus Hyatt in an American patent dated 1878, and Hyatt made many attempts to exploit his invention, the primary impetus to the development of construction on a large scale occurred in France, mainly through the efforts of Monier, Coignet and Hennebique. The earliest record of concrete being reinforced to span a floor has recently been brought to light by Professor Fisher Cassie. W. B. Wilkinson, a Newcastle plasterer, in 1854, took out a patent for reinforcing concrete with flat bars or wire ropes. In his specification he points out that the reinforcement should be inserted where tension is to be expected. Wilkinson used cement from Aspdin's Gateshead factory which was set up in 1852, and built a house in 1865 at Newcastle which has only just been demolished. It was in good condition. Old colliery ropes had been used as reinforcement. In Continental literature, the earliest attempt to combine steel and concrete is generally attributed to Lambot who constructed a boat in 1855. He took out a patent in which he shows that he visualised the possible replacement of wood with reinforced concrete in boat construction. He regarded the reinforcement as an internal skeleton which gave shape to the structure and generally held it together; in making his boat, he plastered concrete over a mesh. Thaddeus Hyatt, however, who surprisingly was a New Jersey lawyer, made and tested reinforced concrete beams, and located and bent bar reinforcement so that it was suitably placed for resisting the tensile stresses. He used turned-up bars and vertical hangers, and appears to have regarded the reinforcement as the tension members of a trussed system, thus anticipating modern standard practice. Hyatt was also impressed by the fire-resisting properties of reinforced concrete and its advantages for constructing floors in buildings. He carried out tests not only in New York, but also in England, and on one occasion built a house which he demonstrated could not be set alight by a fire. From his tests, he reached the following conclusions:

(1) That the coefficients of expansion of concrete and wrought iron are the same.

(2) That the ratio of the moduli of elasticity of concrete to wrought iron is about 1 to 20.

(3) That Portland cement concrete is fireproof.

(4) That bars are more economical than rolled beams as reinforcement.

(5) That high concrete chimneys, reinforced longitudinally, and with wire hoops are better than those without such reinforcement.

He also advocated "the use of a deformed bar with bosses or raised portions formed upon flat surfaces of the metal."

Hyatt did not develop his patents as commercial propositions, nor could he

persuade others to do so. He was a most public spirited individual and, incidentally, an ardent advocate of the abolition of slavery. It is clear that he wished his inventions to be used, but either conditions in U.S.A. and England were against him, or he was unfortunate in not meeting a business man and practical engineer of the calibre of Hennebique who, twenty years later, in a short period spread the use of his reinforcing system around the world.

No advance of importance in concrete construction appears to have been made in France after the production of Lambot's boat until 1867, when Monier patented the use of an iron grillage embedded in concrete for generally holding the material together and providing structural strength as a tough, flexible internal skeleton. Monier was a gardener at Versailles, where no doubt he was concerned, at times, with small structural problems. He first used his system for making plant tubs. Later, he built reservoirs —one of 25,000 litres at Fontenable, and another of 2,000,000 litres at Sèvres. He also constructed a number of foot-bridges. In 1878, Monier took out a patent for reinforced concrete beams and exploited it in a number of European countries. He was particularly fortunate in his commercial contacts in Germany, where rapid development took place. In 1880, earthquakes occurred in the Riviera and Monier commenced building concrete structures using steel as a general reinforcement. He had no idea of stress calculation, but achieved success through an innate structural sense and practical experience of the behaviour of structural members.

In 1880, Hennebique took out a patent, in France, for floor slabs reinforced with round bars, and in 1892 for beams with main longitudinal tension steel and vertical wire stirrups. Hennebique must have been a man of great energy and force of character, as he immediately proceeded to undertake designs and construction of all kinds of structures in many parts of the world and built up a very large organisation in the following twenty years.

In 1886, Monier's patents in Germany were taken over by Gustave Adolf Wayss, who started an organisation to exploit them, in Berlin. He carried out test loading on beams and floors, and the Prussian Board of Works sent Mathias Koenen to inspect them and report. Koenen pointed out that the concrete had no tensile strength and formulated basic assumptions for beam design and produced a set of rules for calculating beam sections. At this stage he assumed the neutral axis position always to be at mid-depth of the section. In 1887 Koenen, with the help of Wayss and the results of his experiments, produced a brochure which described methods of design based on the assumption that all tension was taken by the reinforcement and compression by the concrete. Wayss deserves credit for taking up and developing Monier's ideas and for carrying out much of the earlier construction in reinforced concrete in Germany. It is interesting to note that Portland cement was available both in England and U.S.A. at that time, but the advances in reinforced concrete design and construction were being made in Germany and France. This no doubt was partly due to the persistence and energy of those who were exploiting the various patents and partly to lack of guidance in building regulations in England and U.S.A., and to economic conditions. Iron and structural steel were strong competitors in U.S.A. and Great Britain.

Hennebique, who was born in 1843, was a stone mason and builder. He showed his faith in the new material of construction by building a large reinforced concrete house for his family, in which was embodied many structural features which clearly demonstrated the structural characteristics of the material. Monsieur Coignet, who was a Parisian contractor and whose father had taken out a reinforced concrete patent in 1861, also carried out much reinforced concrete construction in France. In 1894, together with N. de Tedesco, he published an important paper on strength calculations for reinforced concrete buildings. In 1892, together with Hennebique, he took out a patent for continuous beams and at about this time Hennebique introduced the use of " T "-beams for floors. In 1894, Hennebique built the first reinforced concrete railway bridge at Viggen, in Switzerland. Since then many reinforced concrete railway bridges have been built on the Continent. It is interesting to note that, in Great Britain, reinforced concrete as a material for railway bridges has scarcely been used at all. In 1947, partly owing to the steel shortage caused by World War II, the Adam Viaduct at Wigan was built with beams of prestressed concrete, which had been prepared for emergency use in the war

In 1899, Hennebique designed and built a wharf at Woolston, near Southampton. He used a well-graded dry concrete mix and the wharf remains in good condition to-day. Other work built since in the neighbourhood by other contractors, but with wet concrete, has not lasted. Had Hennebique's standards been maintained, reinforced concrete might have made a much better impression in Great Britain. Following this work at Woolston, Hennebique set up a London branch under L. G. Mouchel, which has continued ever since to take a leading part in design and consulting work.

In 1896, Considère carried out research in France on reinforced concrete and introduced the conception of beams as composite elastic members. It was due probably mostly to Considère that reinforced concrete frameworks came to be treated as continuous elastic systems and various methods of analysis, based on this assumption, were developed in France, Germany and the Scandinavian countries. These new theories, produced mainly by professors of the Continental technical colleges, are a most important contribution to civil engineering advance. In 1897, the first reinforced concrete course was instituted by Rabut, at the Ecole des Ponts and Chaussées, in Paris. It is interesting to note that later Freyssinet attended this institution and learnt from Rabut, who must have greatly influenced his career. In 1903, the Chambre Syndicale for French reinforced concrete contractors was established, and the French Military Public Works Department issued a Code of Practice. The French Design Regulations were issued in 1906.

During this period, rapid development was also going on in other countries. In 1891, a branch of Monier's organisation was set up in Copenhagen. Denmark, not having a steel industry and possessing good supplies of the essential raw materials for concrete, advanced very rapidly. In 1904, the designing and contracting firm of Christiani and Nielsen was established in Copenhagen. The firm now has twenty-four offices in five continents, and has done much to spread the practice of good reinforced concrete design throughout the world, particularly in marine structures. They have been continually advised by men such as Professor Ostenfeld, who contributed much to the elastic theory of frameworks, and other engineering professors and graduates of the famous Technische Hochschulen, of Copenhagen. The four to five years' civil engineering courses at the Swiss, German and Scandinavian technical universities have undoubtedly contributed much to the advance of concrete engineering. A branch office of Christiani and Nielsen's was opened in London in 1913. A number of well-known concrete contractors and consultants now practising in London are offshoots of this organisation. Great Britain and the world have certainly received a wealth of talent from this source.

Between 1880 and 1890, through the Monier organisation, development spread in Switzerland and Russia, and in Austria through the Berlin Wayss company. Professor Ritter, of Zürich, later contributed much to theory, and Maillard designed and built many elegant bridges. In Czechoslovakia, Professor Melan also designed many famous bridges, and was followed by Emperger in Austria, who later extended his work to U.S.A. There, Julius Kahn had introduced, in 1903, a trussed type of reinforcement in building work.

It was, however, after the arrival of Emperger that expansion began. In 1905, Edwin Thatcher built an arched bridge over the Kansas River at Topica, and this was the first large reinforced concrete bridge in U.S.A. Since that time, much research has been done in U.S.A., particularly at the Portland Cement Association Laboratories at Chicago, and at Illinois University. The first standard building regulations were adopted in 1910. In 1914, J. R. Nichols produced a formula for the design of flat slab or mushroom construction which was originally patented by Turner. Many buildings having floors of that kind were tested



Fig. 2—Bridge over Varmskogssundet. Example of early Scandinavian slender reinforced concrete bridge construction

about this time, and the U.S.A. developed widely the use of this type of construction. In the architectural world, Lloyd Wright threw off the shackles of tradition and demonstrated the great design possibilities of reinforced concrete. In the inter-war period, Professor Hardy-Cross published his moment distribution method, which has since been universally accepted as a most welcome advance in structural theory by virtue of its power and simplicity.

While the turn of the century marked a period of great pioneer activity on the Continent, advance in Great Britain was slow. In Germany and Austria much structural testing was done, and design theory propounded, and textbooks written. In 1902, Professor Mörsch published the first edition of *Eisenbeton-Bau*. The first British textbook by Marsh and Dunne, entitled *Reinforced Concrete*, was published in 1904. Faber and Bowie's book was published about six years later. Until work was started at the Building Research Station in 1921, Faber's beam tests and investigations in regard to shear strength represented the only significant structural research in reinforced concrete done in Great Britain. The Scandinavian countries enthusiastically followed the Germans, and designers showed in practice that in reinforced



Fig. 4—Double curvature shell roof, 83ft span, at Brynmawr rubber factory. Architects, Architects Co-partnership ; engineers, Ove Arup and Partners ; contractors, Holland and Hannen and Cubitts, Ltd., and Gee, Walker and Slater, Ltd.

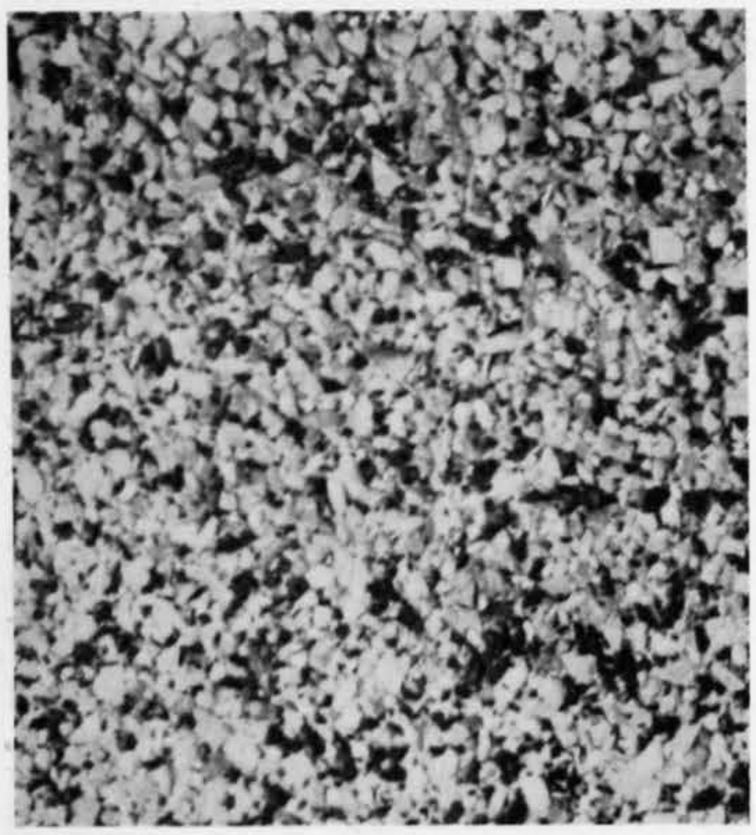


Fig. 3—" Mineralite " finish

concrete structures, art and engineering need not be divorced (Fig. 2). The Scandinavians extended its use to buildings successfully, employing the new material not just as a framework to be covered by brick masonry, but to be the whole structure, taking great care to produce surfaces which would weather well and remain pleasing in appearance. P. A. Bech, of Oslo, has spent most of his life studying this problem. Many Scandinavian buildings owe the quality of their weathering surfaces to his research. The writer brought to London some samples of his " Mineralite " slabs in 1946, and British architects are now beginning to use them in London. An example of a finish is shown in Fig. 3.

To the Scandinavian designers must be given much of the credit for introducing a new elegance in architecture through the skilful structural and artistic use of concrete. Walter Gropius, in Germany, and Le Corbusier, in Switzerland and France, led the revolution in the architectural world. It was not until the inter-war period, however, that " functionalism " began to influence British architects, when Maxwell Fry, Wells-Coates, Lubetkin and others began to use reinforced concrete as their medium and to recognise the advantages and its flexibility of form. By that time, the Scandinavians had completely adopted reinforced concrete as the best and cheapest material for the frameworks of buildings. To-day, Great Britain is probably the last country in the world to embed large quantities of structural steel in concrete cladding for the support of tall buildings. In recent post-war years, particularly during the national steel shortage, engineers returning from such countries as South Africa and South America, where reinforced concrete framed buildings rise to twenty-five and thirty stories, were surprised to see heavy steel grillage foundations still being used for important new post-war buildings in London. Reinforced concrete frameworks are now, however, largely used for flat construction with brick cladding. The insulation value of brickwork and its well-tried weathering qualities give it, in some respects, an advantage over concrete, but there is no reason why British buildings should not have concrete surfaces as pleasing as those of the Scandinavian countries. Great Britain can be proud of her leading position in regard to atomic factories in which reinforced concrete has been greatly used because of its resistance to gamma rays and neutron bombardment.

In the inter-war period, Dischinger and Finsterwalder produced in Germany the first " shell " calculations. The Market Hall at Budapest, built in 1930, is an early notable example of this new form of construction, which has been taken up fairly enthusiastically in Great Britain since World War II. The elastic theory has been greatly advanced by Jenkins. Applications of shell designs are shown in Figs. 4 and 5.

Development of Prestressed Concrete

The credit for the special method of reinforcing, now universally known as prestressed concrete, must go to Monsieur Freyssinet. He has recently given an account of his life in an address, entitled " The Birth of Prestressing," presented on the occasion of centenary celebrations in Paris, in regard to the birth of reinforced concrete. It is interesting to find that this most famous of modern bridge engineers attributes the success of his designs mainly to intuition, though his education must have included structural theory to a high standard. He says : " I am by nature intuitive, much less subject to

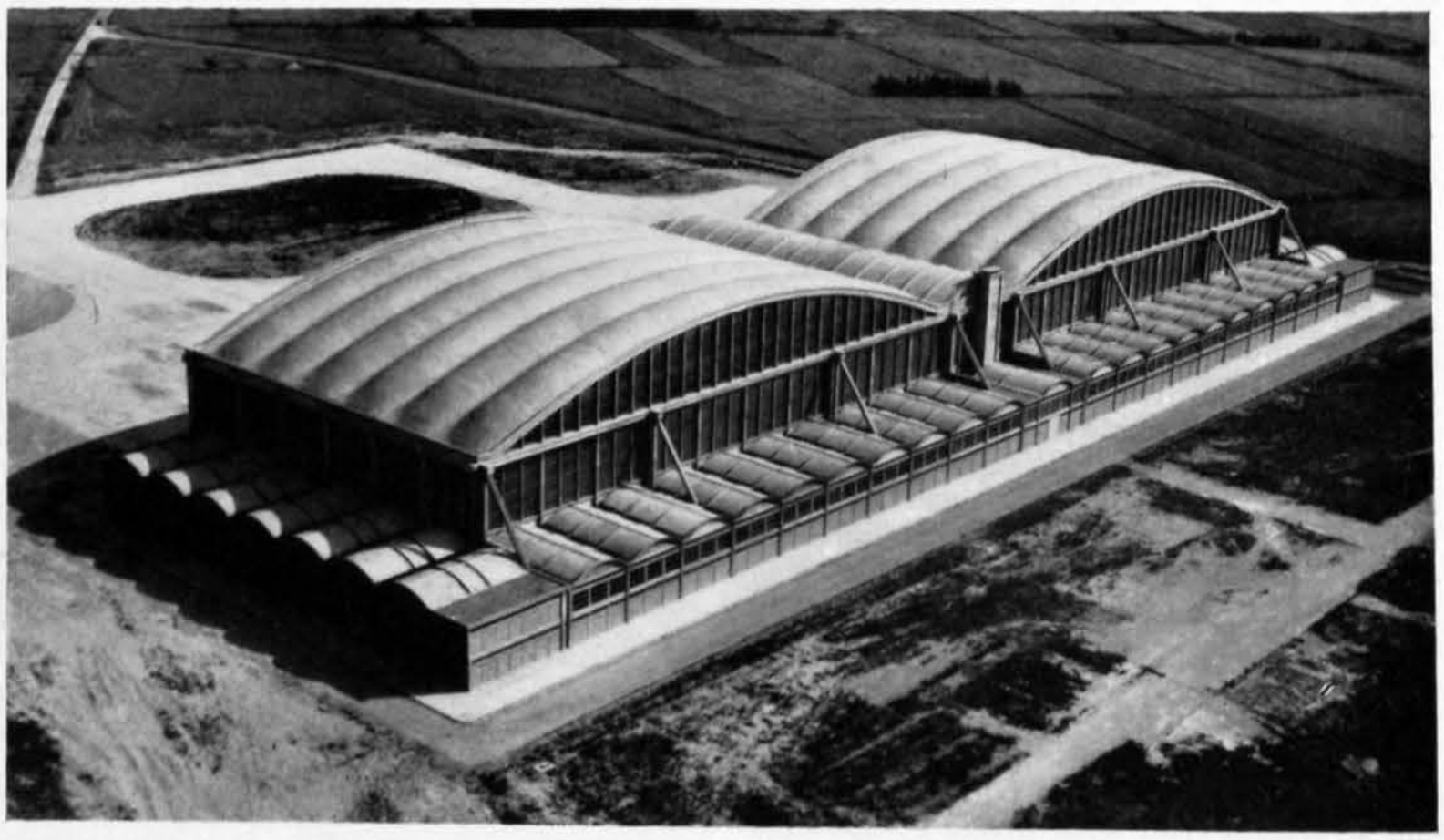


Fig. 5—Hangars at Marignane Airport, France, 340ft shells cast at ground level and hoisted into position

reason than to the impulses of the subconscious. A survivor of a race of artisans with construction in their bones, formed by thousands of years of isolation under particularly hard conditions of life." Freyssinet says his ancestors lived on the plateau Corrize, a country of impenetrable forests and rocky wastes, with a hard climate and poor soil. His parents brought him to Paris at the age of six. He was admitted, in 1899, to the Polytechnic, where, he states, his comrades pleased him by their seriousness, their probity, and their taste for hard work. Later, at the Ecole des Ponts and Chaussées, he studied under Rabut, who introduced to him the merits and defects of reinforced concrete. Freyssinet says even at that time he was dissatisfied with "the discordance of the strains of steel and concrete," and sought a remedy by producing "permanently active forces in the reinforcement." This thought appears to have remained with Freyssinet during many years of fascinating experience of bridge construction. Many of the bridges he designed are famous for their height and span—for instance, Plougastel (span 612ft). In about the year 1926, he investigated a serious case of cracking in the main beams of the Caen steel works, due to high shear stresses. This appears to have influenced his determination to research, and from 1926–30 he carried out various tests which resulted in his taking out a patent. He parted company professionally with his colleague Limousin and recommenced life at the age of fifty as a prestressed concrete engineer.

Freyssinet's early conception of the purpose of prestressing seems to have been to precompress concrete in the tension areas to prevent cracking. Many other advantages have followed. For instance, the ability to precast in segments structures such as bridges and build them by joining them together with stretched prestressed cables. Such a technique was employed in many of the post-war French bridges and in the bridge at Worms, shown in Fig. 7. The publication of *Béton Précontraint* by Guyon in 1951 should be mentioned. It revealed that he must have contributed much in research and analytical work towards the success of Freyssinet's structures.

Other systems of prestressing have followed Freyssinet's. Professor Magnel, in Belgium, has produced his own particular system of anchoring the high tensile steel wires and written a much-used textbook. Hoyer, developing Freyssinet's early work in Germany between the wars, stretched wires between anchorages about 200ft apart and cast concrete beams around them so that the wires, through bond, induced compression stresses in the beams. Hoyer's work was followed by Erikson and Bjuggren in Sweden. During World War II Mautner followed Freyssinet's work and designed a factory for manufacturing railway sleepers at Tallington. In 1949, following visits by F. Wells and E. R. Hole to the Swedish works, a factory was built at Iver and opened by the Minister of Works and used for the manufacture of all kinds of Hoyer units, including long piles. More recently the Lee McCall system of prestressing has been introduced in Great Britain.

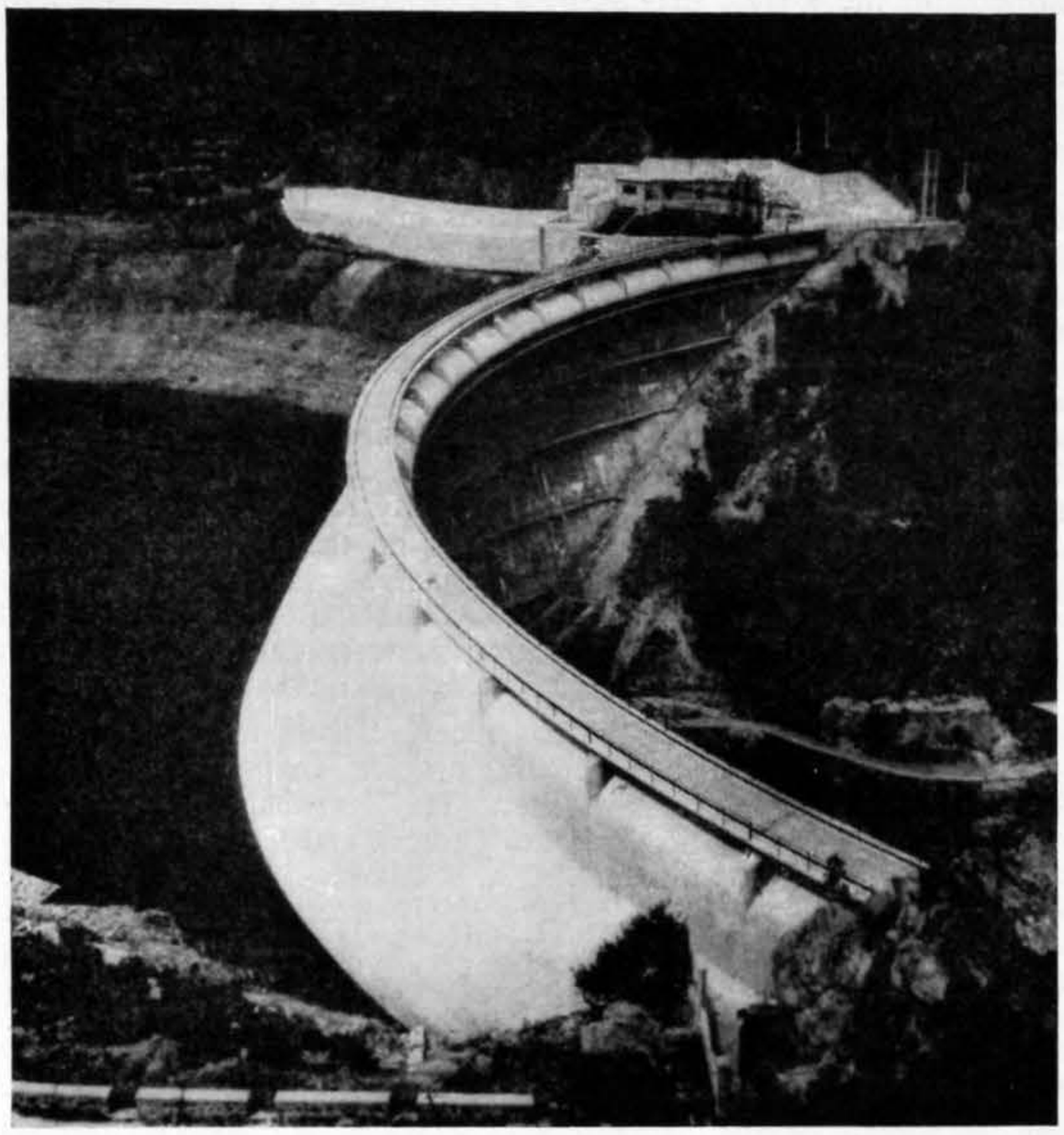


Fig. 6—Double curvature shell dam at Osiglia, Italy, 250ft high, 720ft long at crest. Engineer and contractor, Dott-ing G. Torno

Some General Observations

It may be of interest to consider some of the factors which have influenced the course of the developments which have been described. It is curious that Thaddeus Hyatt failed to exploit his patents either in U.S.A. or in Great Britain, whereas, twenty years later, Monier, whose ideas were less advanced, was able to set up successful business organisations in several of the Continental countries. Would Hyatt have succeeded had he gone on to Paris, Berlin or Copenhagen ? Was it the particular local conditions which were against him, or did he lack the business ability which men like Monier and Hennebique must have possessed ? The principal discoveries in regard to cement, for instance, in the case of Aspdin and I. C. Johnson, were both well-exploited in Great Britain. The production and sale of cement was, however, open to normal industrial enterprise. The right conditions existed for manufacture and the expansion of internal and export trade. The men who took charge took full advantage of the nineteenth century expansion in building. But in regard to reinforced concrete, standards of safety in design were involved. Local authorities and building regulations had to be satisfied and no suitable regulations existed for guidance.

On the Continent, design was usually competitive and carried out under the auspices of contractors who were prepared to take the responsibility and regarded taking risks as part of their business and sought to secure contracts by tendering on cheaper designs. In Great Britain, consulting engineers or architects generally undertook the responsibility of design and, therefore, neither they nor the contractors had anything to gain by using new and untried materials for permanent structures for which the use of brick and stone had set a high standard of durability. The products and services of a rapidly growing structural steel industry, too, provided the most powerful competition. It is interesting to note that British engineers were not lacking in enterprise, when the conditions for using the new material were favourable, for instance, in the Colonies and, in particular, in India and South Africa. Progress in the use of reinforced concrete in building frames was much more rapid in the latter country than in Great Britain, due partly to climatic conditions suiting the material, but more particularly on account of the higher cost of structural steel.

While advance was slow in Great Britain, Hennebique and Monier expanded their businesses at a phenomenal rate throughout the Continental countries. Improvements in the details of reinforcement, in the quality of the concrete and in the design methods used, went forward simultaneously. The Continental technical colleges took a leading part in this work. Professors, such as Mörsch, Ritter, Melan and Ostenfeld, in Germany, Switzerland, Czechoslovakia and Denmark, all developed design theories for the new material and monolithic-framed structures. Moreover, in accordance with common Continental practice, they worked in close conjunction with industry, taking a leading part in the design of important structures and

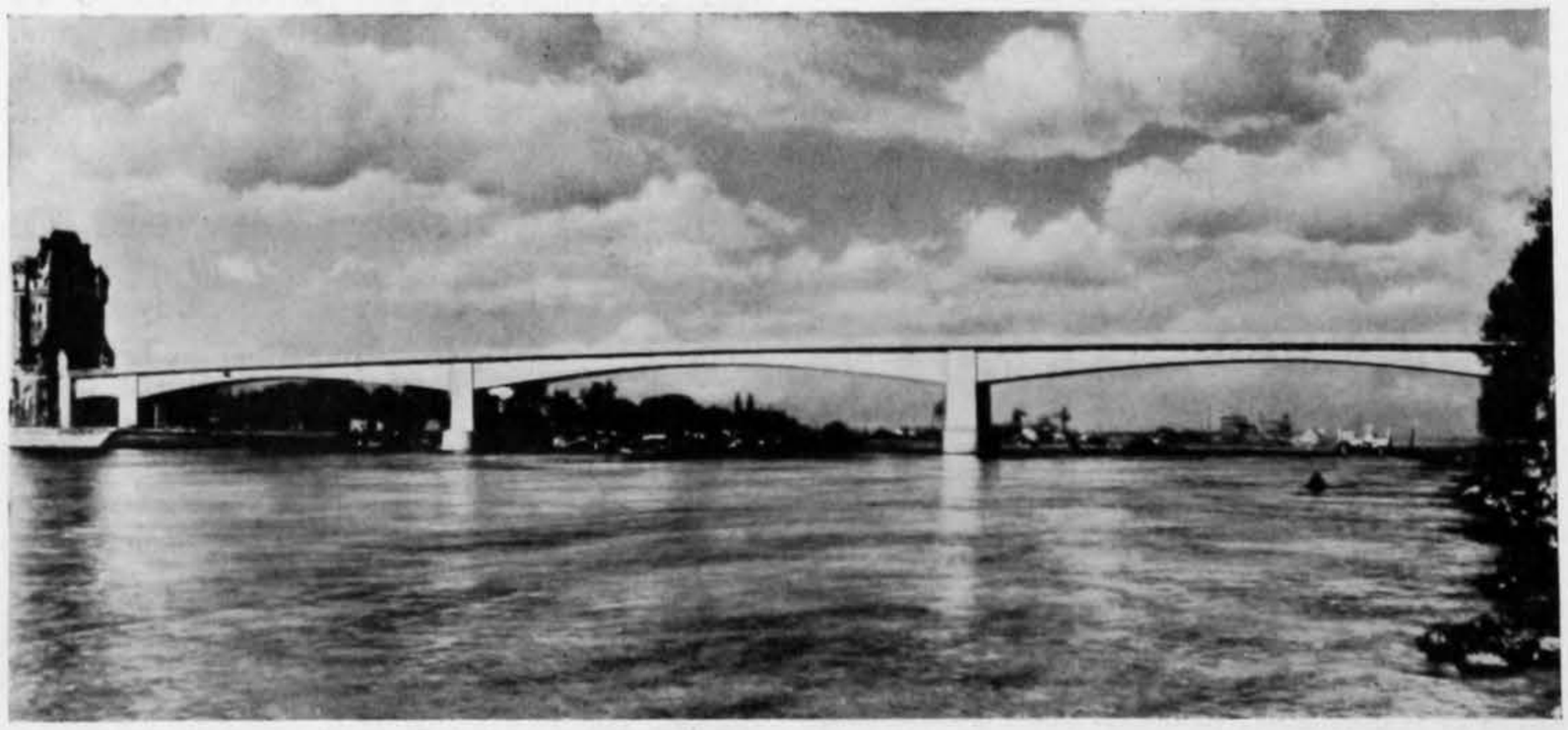


Fig. 7—Prestressed concrete bridge, Worms, Germany. Architect, G. Lohmer ; engineers and contractors, Dyckerhoff and Widmann A.G.

carrying out research in their laboratories. In Great Britain the teaching of the new subject in the engineering schools advanced more slowly. The theory of reinforced concrete as taught, for some time, was limited to a brief chapter on composite sections in the textbooks on strength of materials. H. Kempton Dyson gave lectures on reinforced concrete in 1911 at the Brixton School of Building, and F. W. Drury at Manchester College of Technology in 1923. It is only in the past twenty years that civil engineering professors, such as R. H. Evans, of Leeds, and D. H. Ross, of King's College, London, have taken especial interest in fundamental research. It was not until 1945 that the Chair of Concrete Technology was established at Imperial College through the financial support of the Cement Makers' Federation, and the research laboratory set up at Wexham Springs by the Cement and Concrete Association. Between the wars valuable fundamental research was done at the Building Research Station under the direction of Sir Reginald Stradling, by Glanville and Thomas, in regard to the stress-strain properties of concrete. At the Road Research Station, too, Sparkes and Collins, following up the early work of Feret in France and Fuller and Abrams in U.S.A., have contributed much to the problem of mix design.

Further evidence of the isolation in technological advance of Great Britain from the Continent is provided by the late arrival of efficient methods of analysing statically indeterminate structures. For the past forty years, nearly all Continental engineers have used one set of general elastic equations with a standard notation for all statically indeterminate structures. Professor Müller-Breslau, of Berlin, first introduced them and they have become the classical method. The derivation and application of these equations was not published in a British textbook until 1947, when *Statically Indeterminate Structures*, by Dr. Ing. R. Gartner, was published by Concrete Publications, Ltd. It is interesting, perhaps, to relate that this occurred through Dr. Gartner leaving Germany for South Africa in 1935, because of the Nazi régime, while the writer left England for South Africa at about the same time due to the depression in civil engineering in Great Britain. Dr. Gartner had no idea at that time that the standard Continental methods were almost unknown and unused by British engineers, and the writer was able to persuade him to produce his book. Moreover, these methods of analysis, together with further extensions which have been produced by Jenkins and Henderson, are now being taught to post-graduate students at Imperial College. It would be wrong, of course, to suggest that the Continental countries mostly take the lead in the production of theory. Clerk Maxwell's work preceded Müller-Breslau's. Frequently new fundamental conceptions are introduced by British engineers and mathematicians, and then perfected in their practical application by Continental men. In general structural theory of the last thirty years, the relaxation process has been produced by Sir Richard Southwell, and Professor J. F. Baker, of Cambridge, has developed the plastic hinge theory of structural steel frameworks. Nevertheless, the disregard in Great Britain and ignorance of Müller-Breslau's efficient notation and treatment of statically indeterminate structures is regrettable, and has been a handicap to British reinforced concrete engineers working alongside Continental colleagues.

There has then been a lag in the use of reinforced concrete and its associated design theory in Great Britain as compared with the Continent, although modern Portland cement was first produced here. This perhaps applies mainly to Government and local authority work. Industry and, in particular, the oil companies making use of competitive designs, mainly prepared by Continental engineers practising in London in the early days made considerable use of the material and more gradually Government departments and local authorities have come to rely on it.

A similar process of development has taken place in regard to the use of prestressed concrete, but the lag behind the Continent has not been so long. This was probably due to the shortage of steel after World War II which encouraged the use of prestressed concrete in the same way as World War I did the use of reinforced concrete. In the U.S.A., progress was slow until the price of cement was brought down by the introduction of the rotary kiln, and cements became more reliable in strength.

The main world expansion in the use of reinforced concrete took place in the early twentieth century. The Paris World Exhibition of 1900 may have helped Monier and Hennebique to expand their organisations at a time when world trade conditions were favourable. Communications had been opened up in U.S.A., Africa and India, and these countries were ready for expansion in building and industrial structures. Hennebique in particular must have been a man of great enterprise and energy who was able to take full advantage of this situation. Throughout the growth of the industry, the genius of the French for producing and enthusiastically following up new ideas stands out. The Scandinavians and Germans have contributed much in systematisation of method, both in construction and design. The British can claim full credit for the important advances in the production of Portland cement.

There can be few other industries made up of such a large number of small independent organisations which have grown through such a variety of people and circumstances in all parts of the world. A new material has been created and a new method of building linking together across national frontiers, inventor, scientist, engineer, business man and craftsman. Each handles only a part of the work of building a single structure. Some may never see the final result which may surpass in elegance and beauty some of the architecture of traditional masonry construction. The good craftsman loves his material, and so must the concrete designer and all his associates, for on them lies a great deal of the responsibility of ensuring that the 100 million tons or so of cement now used annually do not deface the earth with a material which it is difficult to erase. Good designs stimulate enthusiasm for good workmanship and encourage contractors to take a pride in their execution. Research and technological education can help to provide a better knowledge of the material and so avoid the unsightly cracked and stained structures which in the past have given concrete a bad name.

Acknowledgments

The author gratefully acknowledges the help he has received from many friends in preparing this article. In particular should be mentioned: The Cement Makers' Federation and the Cement and Concrete Association; Mr. A. J. Harris, Mr. A. Kirkwood Dodds, Mr. P. Uttenthal, Professor A. W. Skempton, Mr. P. Ahm, Dr. Ing. R. Gartner, Mr. F. E. Wentworth-Shields, Mr. D. H. New, Mr. W. Hunter Rose, Mr. C. J. Inglis.

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Plastics

By R. H. DIBB, M.Sc., M.I.Mech.E.*

THE plastics in use one hundred years ago were natural materials such as gutta percha, shellac, horn and ivory. The foundations of the modern plastics industry were, however, already being laid. The atomic theory of John Dalton was well established and synthetic organic chemistry was attracting the chemical experimenter. Polystyrene had already been made in the laboratory and polyvinyl chloride (p.v.c.) was to be made within the next twenty-five years. These, however, were not the result of a deliberate search for materials to augment natural sources and both these plastics, now made in such large quantities, had to wait until World War II for serious industrial exploitation. More utilitarian in its objectives was the work which had already started on materials derived from cellulose, a natural polymer. The manufacture of celluloid marked the foundation of the plastics industry in England and later in America. In 1900 partially synthetic plastics based on the natural polymers, cellulose and casein, were all we had available. The next quarter of a century saw the establishment commercially of the important thermosetting plastics†—phenol formaldehyde and urea formaldehyde. These were completely synthetic and not, of course, based upon natural polymers. The impact on the electrical industry, particularly of the phenol formaldehyde resins and moulding powders, has been most important. Plastics mouldings have gradually displaced metal, wood and porcelain throughout the sphere of the smaller electrical appliances and in radio have played a vital part since the industry's birth.

It has been in the last twenty-five years, however, that there has been an enormous growth in the range and outputs of commercially produced synthetic plastics. Today such plastics as polyvinyl chloride, polythene, polystyrene, and the acrylics, in addition to the thermosetting plastics, are produced in yearly tonnages which in the U.K. are measured in tens of thousands of tons. The completely synthetic fibres are, of course, plastics—Nylon is already established and growing apace and there is every reason to expect that "Terylene" will have a similar success. The large scale production of synthetic rubbers, based on the petroleum industry, was a striking war effort in the U.S.A. Subsequently this range of products has been extended and has found many applications other than that of rubber substitution or reinforcement. The

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† Most synthetic plastics are thermoplastic, that is, they soften when heated; the thermosetting type when heated in a mould under pressure undergo a chemical reaction (known as "cure" or, more scientifically, as cross-linking) producing a rigid moulding which does not subsequently soften perceptibly when heated.

continuing development of the petroleum chemical industry in the U.K. will soon enable these materials to be produced here. Much more restricted in quantity, but of great technical interest and importance, are the fluorine polymers, such as polytetrafluoroethylene, and the silicones. Potentially of growing importance to engineering are the laminating resins on which the frequently heralded plastic car and plastic boat depend. As adhesives synthetic plastics are established in the aircraft and wood-working industries.

The success of a plastic depends upon its possessing a useful, and preferably a uniquely useful, combination of physical properties. Plastics are apt, by their nature, to be complex. They are polymers, which means materials of very high molecular weight formed by the combination into a chainlike form of a large number of single molecules. Their properties depend not only on the chemical composition of their simple basic molecule but on the size of the macromolecule ; that is to say, on the degree of polymerisation. The properties are also affected by how the chainlike molecules are arranged relative to one another, whether completely at random or to some degree

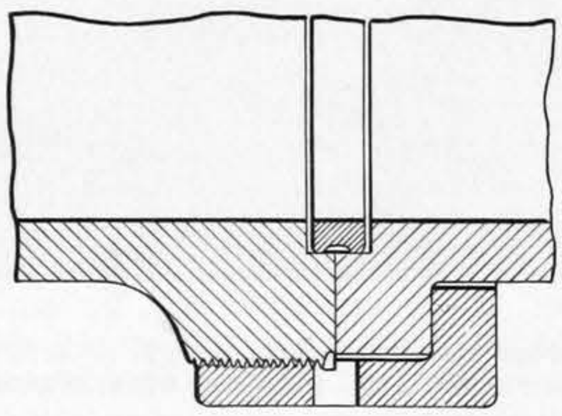


Fig. 1—Wave ring joint as used for pressures of 1500 atmospheres

orientated, on whether the chains are separate or to some degree interlinked, on whether they are straight or branched. There is the further complication of crystalline or amorphous form. The physical treatments to which a polymer has been subjected—the conditions under which it was synthesised, the work which has been done to it and the temperature conditions which it has experienced—influence these characteristics and affect its properties profoundly. As an extreme example, one sample of polythene may remain flexible at —70 deg. Cent, whilst another, equally pure, is brittle at normal temperatures. The range of materials which can be made available is thus greatly enlarged and, since the chemist has at least a general idea of what properties result from which structures, the tailoring of materials to end uses becomes a possibility. On the other hand, this difficulty of characterising polymers poses problems for the chemical engineer, for the designer of the manufacturing plant, and for the fabricator and the designer of his machinery. Not only must purity, in the usual sense, be ensured but the physical history of the polymers must also be such as to maintain with certainty the desired properties in the finished article.

The impact of plastics on engineering takes place in three ways. First, for all new synthetic materials a manufacturing process has to be established. It must be possible to transfer the laboratory synthesis to large-scale commercial manufacture. This may involve major advances in engineering techniques. Secondly, the materials have to be fabricated for the various end uses for which they are required. Requirements here also necessitate developments in engineering design and techniques. Thirdly, there are the engineering uses to which the new materials can be put. Though they often start as substitutes for some existing material, their properties, being so amenable to deliberate modification, will often permit developments which, with the unsurmountable limitations of a natural substance, might be quite impracticable. Alternatively, plastics may from the start be used in a way for which no natural material would be suitable. The subject is now too big for any exhaustive treatment in the space available. An attempt to cover the field would produce a catalogue of facts rather lacking technical interest. One or two examples will therefore be taken under each of the above three headings, and, since the thermosetting types have been longest in the field and are the more firmly established in engineering practice, the examples will be taken from the thermoplastic materials, which have recently expanded so rapidly.

Polythene was discovered in 1933, when, in the I.C.I. research laboratories at Winnington, it was observed that ethylene, contained in a small vessel which had been raised to a pressure of 1400 atmospheres, had coated the inside with a thin layer of " white, waxy solid." Much work was necessary before it was established that a new plastic worthy of commercial exploitation had been found. In the course of this work it was necessary to establish a technique capable of handling gases at pressures up to 3000 atmospheres and suitable, on an industrial scale, for a working pressure of the order of 1500 atmospheres. The synthetic ammonia process had already been in operation since World War I at pressures of the order of 250 atmospheres, but there was no industrial experience in these higher ranges. Heavy cylindrical steel forgings had been used as converters, but with increasing pressures and sizes the point was reached where the problem of their design became insoluble on the basis of the accepted thick cylinder formulæ and of a safety factor applied to the elastic limit. The two alternative methods of arriving at a solution are either to prestress in the opposite sense or to permit straining beyond the elastic limit in part of the vessel's walls. Building a vessel from concentric shells and winding externally with wire or strip under tension, are examples of the first approach, whilst " autofrettage " utilises the second. Both have been successfully used. Gas compressors were also required. Nowadays, " high-pressure " compressors are a standard line with some firms in Europe and in the U.S.A. For the first production units in this country, however, compressors had to be specially designed which could deliver at 1500 atmospheres. In these ranges

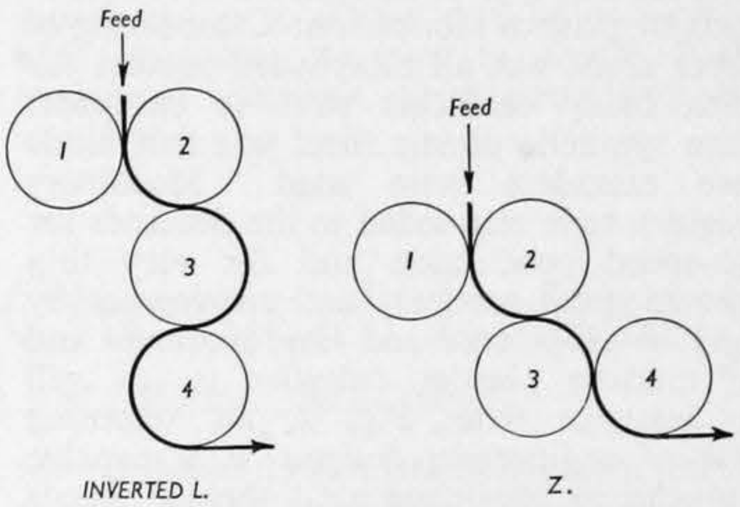


Fig. 3—Calender roll formations

ethylene is far from the " perfect " gas of classical physics being at first much more compressible than towards the top of the range. Consequently, much more heat has to be removed at first. The usual practice is to divide compression into a number of stages in each of which the ratio of final to initial pressure is kept below 4 to 1, and to provide external cooling between stages. Packing glands have to be long and depend on metallic contact, with special lubrication to prevent seizing, whilst contamination of the gases with oil has to be kept extremely small. The metal-to-metal lens ring joint had been used on vessels and pipelines at 250 atmospheres ; the wave ring joint, Fig. 1, was developed for the polythene process. This joint carries the self-tightening principle to its logical conclusion and its success was a major contribution to the project. Some low-pressure polythenes have recently been made by catalytic processes. From what has previously been said on the subject of

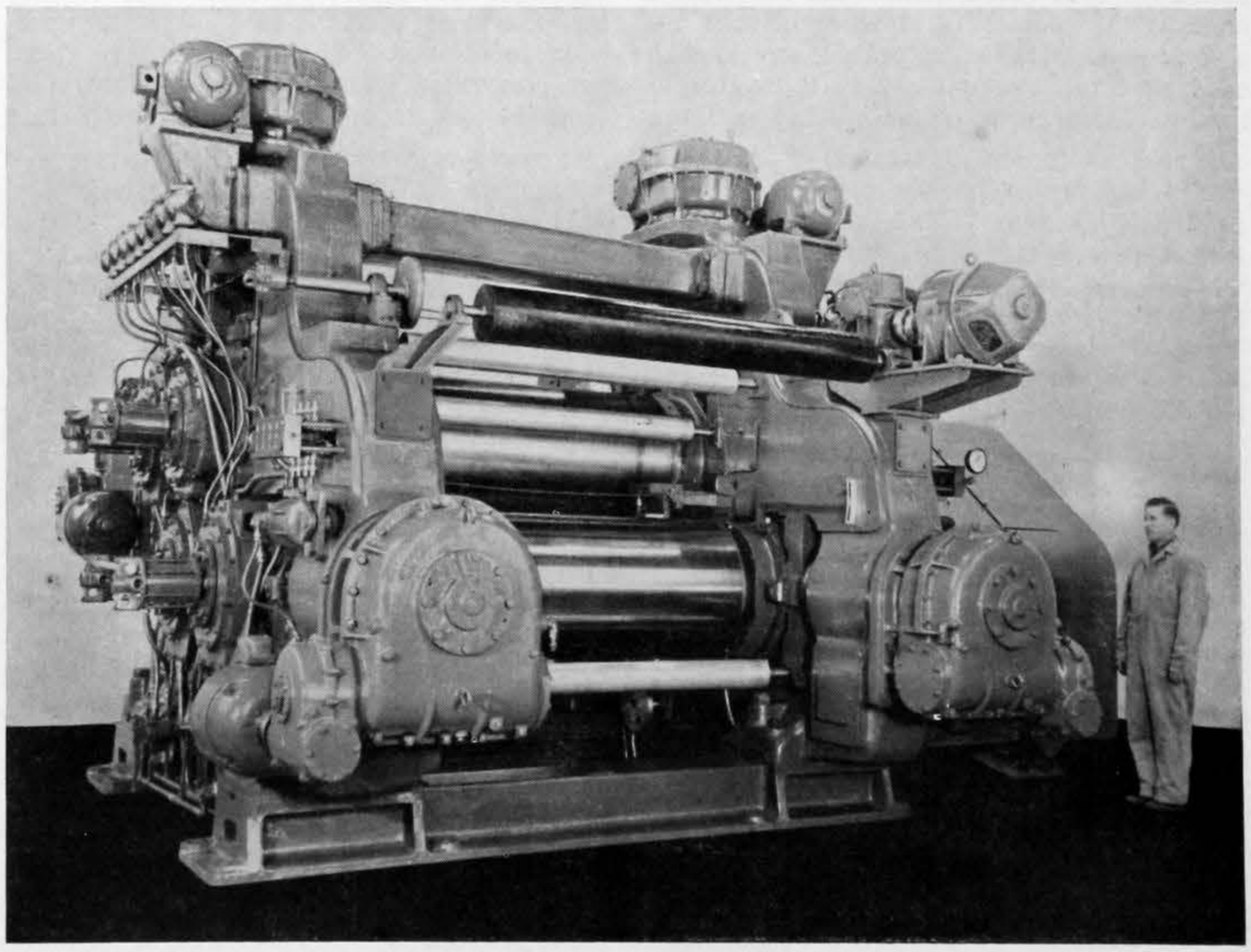


Fig. 2—28in by 72in four-roll " Z " high-speed calender for plastic sheeting with cross-axis alignment mechanism, flood lubrication and hydraulic pull-backs for pre-loading bearings. (Messrs. Farrel-Birmingham, U.S.A., and Messrs. David Bridge, Rochdale)

characterisation, it will be understood that these are not identical materials and what exactly their effect will be is difficult to predict. It is very probable, however, that the high-pressure process which was essential to the industrialisation of the original discovery, will remain the source of large quantities of polythene.

The development of calenders for the production of thin polyvinyl chloride sheet can be taken as an example of the adaptation of an existing type of machine to the requirements of plastics fabrication. Calendering of rubber sheet was an established process for which many calenders were in existence. When synthetic plastic sheet was first made these calenders were used. Machinery designers have responded to the demands for high-speed production and for very thin sheet of great accuracy and consistency by many developments and improvements and the modern plastics calender is, as will be apparent from Fig. 2, an imposing piece of engineering design. It is capable of producing plasticised p.v.c. sheet at speeds up to 100 yards per minute, with a thickness of 0·00175in and a tolerance of ±0·00010in. Twenty-five years ago good conditions for rubber sheet would have been of the order of 30 yards per minute, with a thickness of 0·008/0·010in and a tolerance of perhaps ±0·0005in. With the demand for thinner sheet and higher calendering pressures the diameter of the chilled steel rolls has increased relatively to the working length. The rolls are cored for heating, which is normally by steam or high-pressure hot water. More even temperature control across the face of the roll has been demanded, whilst the increase in bowl dimensions and the use of flood lubrication on the bearings has tended to increase the cooling effect which naturally takes place at the ends. Drilling of passages for the heating medium parallel to the central cored chamber, but much nearer the surface, has improved heating, but sometimes radiant heaters have been added to ensure that the material at the edges could be brought to the same temperature as that in the centre. Internal electrical heating has also been used on calender rolls, zoned so that more heat could be applied towards the ends. The stressing of rolls has to be considered, as temperature stresses can easily become as important as those due to the internal pressure of the heating medium. Cambering of calender rolls had long been carried out to counteract both natural deflection and deflection under the pressures of working conditions. To judge the best camber on each of a series of three or four superimposed rolls, reacting upon one another through the material being calendered, was an art which only experience could teach. Any camber was really only ideal for one set of conditions and changing the camber was a major operation which required production to be shut down. Hence the principle of cross-axis alignment was introduced. A slight skewing of the axis of one roll relative to its neighbour had a similar effect to that of a slight change in camber. This is done by moving the bearings, which are in spherical seatings. In one recent form this is applied to the last roll of a calender with a Z formation of rolls, Fig. 3, as then the final nip can be controlled, with the calender in operation, without influencing the conditions in the earlier nips. On another design with rolls in inverted L formation the third roll is skewed whilst the fourth roll has a further refinement of counter-bending by hydraulic pressure applied through small bearings on extensions of the roll necks outside the bearings. With the demand for great dimensional accuracy the clearance in the bearings became important. In the older types of calender the material in the nips really takes control and clearance in the bearings permits slight movements of the axis of the rolls as the calender takes up load and attains working conditions. Surprising accuracy can, in fact, be obtained under these conditions, but it is an art dependent upon a very careful control of the feed and of the other variables. Preloaded and zero-clearance calender bearings have been introduced so that the accurate presetting of the rolls can be done on a scientific basis. In the preloaded bearing the roller neck is in contact with the same segment of bearing when light and under various conditions on loading. This is achieved by providing an auxiliary bearing under the control of a hydraulic pull-back cylinder and, preferably, each bearing is controlled by independently adjustable hydraulic pressure. A zero-clearance type of tapered roller bearing has also been used. Flood lubrication has been mentioned. Oil is supplied in large but controlled quantities and at controlled temperatures from an external circulating system. There is now a trend towards removing the gearing previously mounted on the ends of the calender rolls and housing all gearing in a unit gearbox separate from the calender. Each output shaft from the gearbox then drives its corresponding roll through a universal coupling. The removal of stresses from the rolls is advantageous and again helps accuracy, and maintenance operations are made easier. There are also installations in which each roll has its own motor and in which the frictional ratios of the rolls can be varied by altering the motor speeds separately.

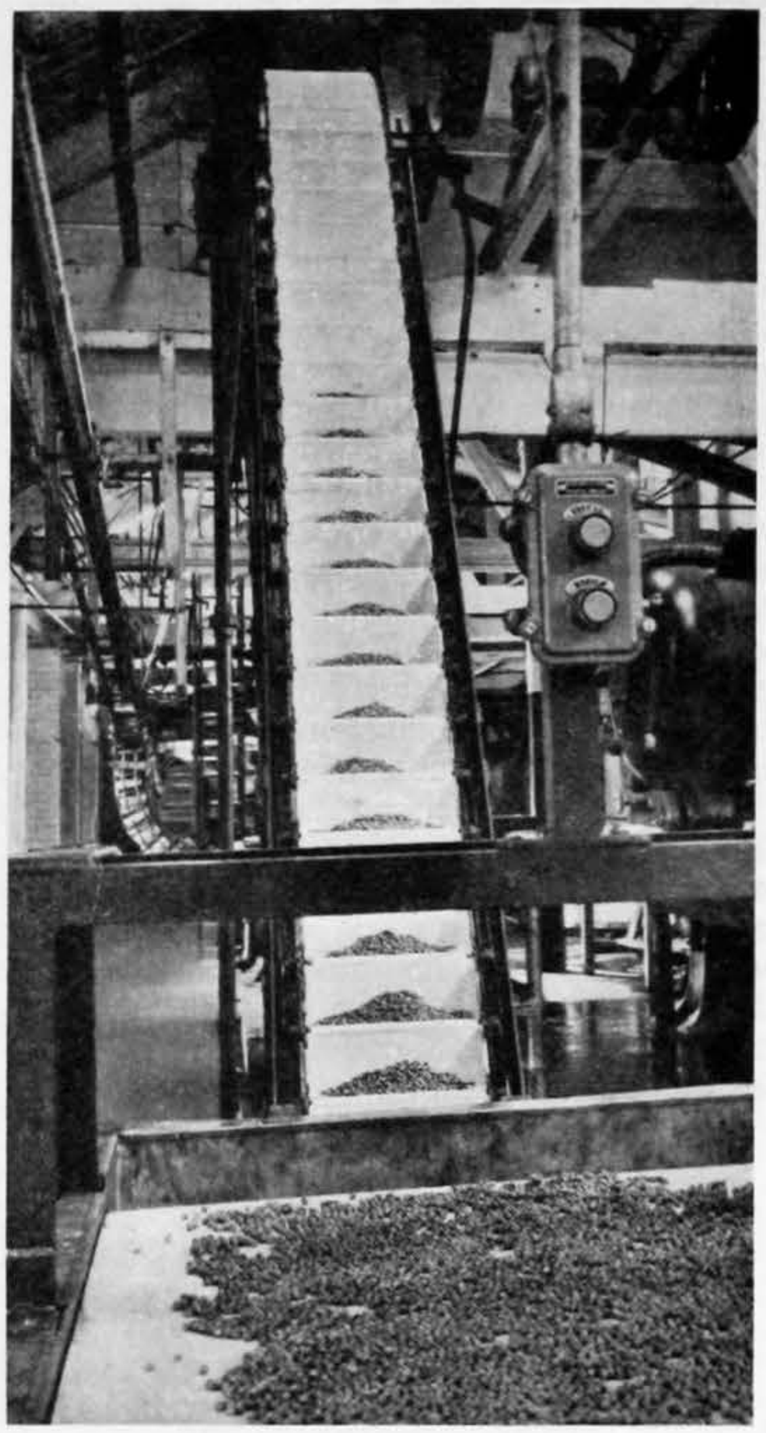


Fig. 5—Food elevator buckets of rigid p.v.c. in works of Joseph Farrow, Ltd. (Messrs. Orbex, Manchester

Presses for the injection moulding of thermoplastics provide another excellent example of a development from simple machinery to large and more elaborate machines with very high rates of production, Fig. 4. The process is analogous to the pressure die casting of metals. A metered charge of granular material is melted or softened in a heated cylinder and injected by the movement of a plunger into a split mould. For gutta percha a stuffing machine injecting the material into a split mould clamped in a simple hydraulic press had been used. Later, as the new synthetic thermoplastics were introduced, existing presses, such as those used for the die casting of metals, were used with comparatively slight modification. The machines now in commercial use are impressive. The majority have a capacity of between 2 and 20 cubic inches per injection, though machines up to 400 cubic inches capacity are manufactured. Accurate metering of the charge, precise temperature control, and rapid operating cycles are the requisites. In the early machines, the injection plunger in moving forward engaged the correct amount of material from a gravity hopper. Now an additional feed plunger supplies the measured charge, which may even be automatically weighed. A recent development is to pump presoftened material into the injection

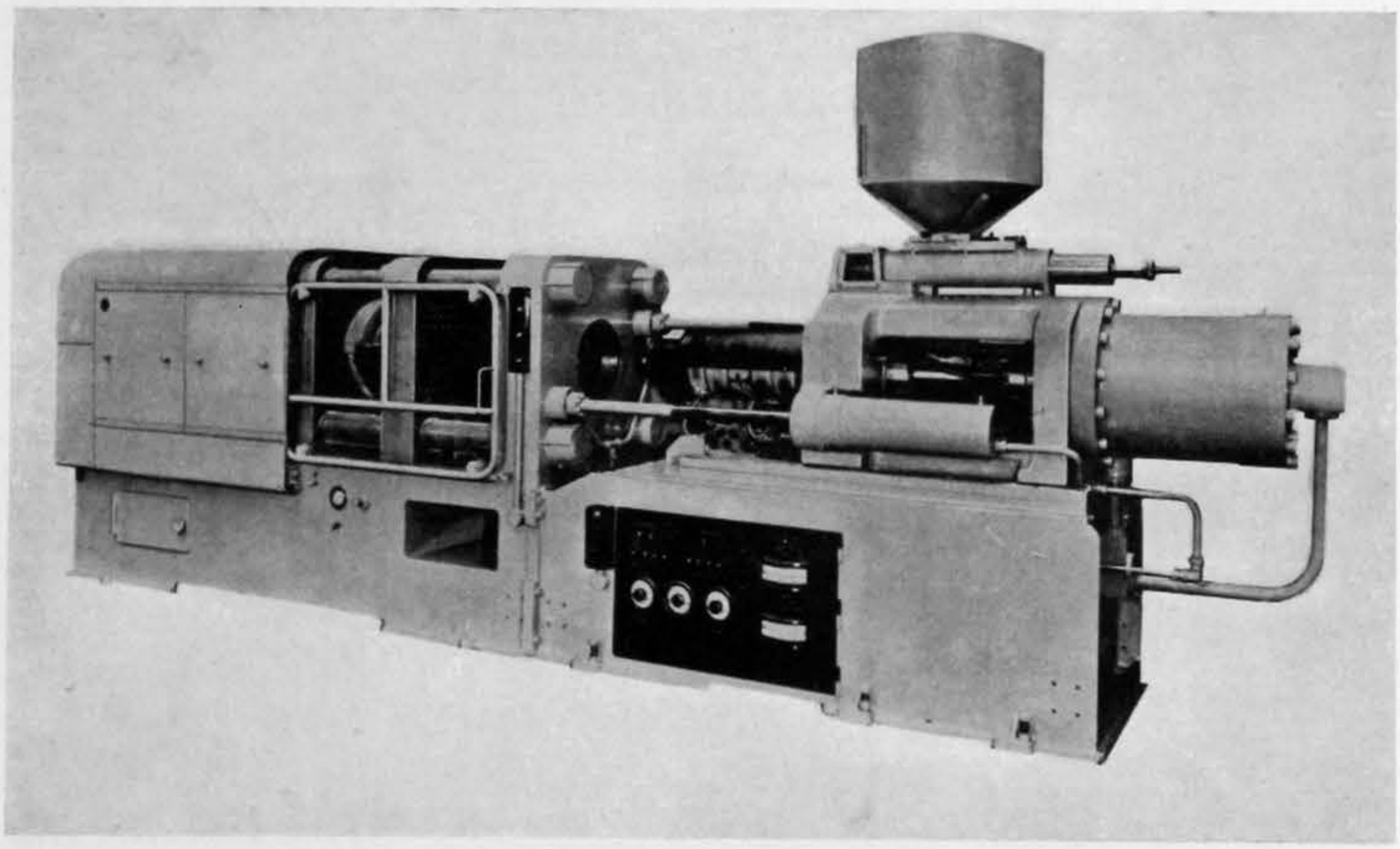


Fig. 4—Injection moulding press for thermoplastics. Overall length of bedplate, 16ft 11in ; height of centre line of plunger, 3ft 11in ; volume per injection, 52·7 cubic inches ; rate of injection, 28·9 cubic inches per second ; pressure on material, 17,640 lb per square inch ; mould locking force, 500 tons. (The Projectile and Engineering Company, London)

cylinder. Mould temperatures can be very important and the two halves of a mould may have to be kept at different temperatures for good results. Electronic temperature controllers of the proportioning type are often used. The softened plastic may still have a high viscosity and to produce a complicated pattern accurately injection pressure up to 10 tons per square inch may be required. Very robust locking systems are necessary to lock split moulds in large machines and on the largest machines this holding force may reach 2000 tons. Locking may be by hydraulic rams or hydraulically operated mechanical toggles. With hydraulic locking, two-stage pumps combine rapid closure with adequate locking. Automatic ejection plungers remove the moulded article. All the various motions in the cycle may be automatically time controlled. The cycle depends on the plastic and the volume and shape of the article, but rates of 300 cycles per hour are not uncommon. This is not high compared with die casting of metals, but the high specific heat and low thermal conductivity of the plastic are limiting factors. Multi-cavity moulds may produce fifty similar units per injection, or produce all the different units required for one assembly.

Certain engineering uses of plastics have been touched upon in earlier paragraphs. The uses of thermosetting mouldings in electrical work and of thermosetting laminates for gears and for bearings, operating at loads up to 5000 lb per square inch as in steel rolling mills, are already well known. The use of thermosetting resins in shell moulding is much more recent. The thermoplastics, though now made in such large and constantly increasing quantities, are still often thought of in terms of the consumer goods market. One or two examples will show how misleading this is.

A major use for both polythene and polyvinyl chloride is in electric cables. The first use suggested for polythene was the insulation of submarine telephone and telegraph cables. Its mechanical similarity to gutta percha with its better and more uniform electrical properties assured its success in this field after World War II, but meantime, during the war, the very low power factor of polythene, which remains constant over a wide range of frequencies, had made it the ideal material for radar cables. Polythene is being used as the dielectric in the new transatlantic telephone cable, which will provide thirty-five high-grade telephone circuits between the United Kingdom, Canada and the United States ; 1400 tons of polythene will be required. For general industrial and house wiring a range of polythene-insulated, p.v.c.-sheathed cables have been developed and are covered by B.S.S. 1557. In many wiring applications the non-inflammability and the oil, chemical and ageing resistance of p.v.c. are valuable. For certain service uses, the extruded polythene dielectric is protected by a Nylon sheath.

The chemical resistance of many plastics is a valuable property in a variety of industrial uses. Both p.v.c. and polythene sheet are used as chemically resistant linings in chemical plant. Buried drains made of polythene resist both internal and external corrosion. Effluent drains can be of considerable size ; a 36in diameter drain, with all-welded joints and embedded in concrete, is a feature of a recent sulphuric acid plant. Small-bore polythene pipe has the virtues of flexibility and, if required, of very long lengths without joints. It is very easily laid for agricultural work and its popularity for household plumbing is growing. Polythene foil can be lap welded to provide a continuous liquid-proof membrane in building construction. In chemical works or any works where corrosive liquids are handled, damage to structures, floors and foundations by spillage or seepage can be prevented with a certainty that was never attainable with the traditional materials which necessarily used cemented joints. The resistance to erosion of polythene has been utilised in protective sleeves inserted into the ends of the cooling water tubes of steam condensers.

P.v.c., if unplasticised, is heat resistant and non-inflammable as well as corrosion resistant. Fans and ducts for handling corrosive vapours can be fabricated and pipes made from rigid (i.e. unplasticised) p.v.c. are in the early stages of what may be a very large development. P.v.c. conveyor belting for mines and other heavy duties has already received a good deal of publicity. Foamed p.v.c. is still in its infancy, but with its inertness and non-inflammability many uses will undoubtedly be found.

In these and very many other engineering applications, Fig. 5, plastics are finding a place, not as substitutes, which are cheaper or more readily available, but as substances with properties superior to those of the traditional materials which previously had to suffice.

Engineering in the Chemical Industry

By SIR EWART SMITH, M.A., M.I.Mech.E., M.I.Chem.E.*

THE production of chemicals has been carried out from the dawn of civilisation, but the chemical industry was only beginning to take its present form when THE ENGINEER was born a hundred years ago. Until the beginning of this century the industry was concerned primarily with inorganic materials or those which could be easily derived from animal or vegetable sources, or from the by-products of coal distillation. It is only in recent years that there has been the vast upsurge of organic processes, based mainly on petroleum, which has given birth to numerous materials hitherto unknown to man. There is no reason to foresee any slackening of the industry's present spectacular rate of development. In these developments, which call for the highest standards of mechanical, electrical and civil engineering, and for the most advanced techniques of instrumentation and control, the engineer has a role of increasing significance. The advance of scientific knowledge year by year shows with increasing clarity that engineering and chemistry are closely linked through the basic science of physics. In spite of growing complexity, their essential unity and interdependence stands out more boldly, and the rapid rise of chemical engineering as an important branch of technology is a recognition of this fact. It would be impossible to discuss here the manifold ways in which engineering is applied to chemical processes, or to attempt a comprehensive account of the use of chemical products in the engineering industry. A few examples will, however, be given, with particular reference to the effects of cross fertilisation of ideas and to the directions in which technical development seems likely to open up new and productive fields.

CONTINUITY AND GROWTH

The chemical industry has long appreciated that three basic principles of good engineering—symmetry, simplicity and continuity—have implications in a much wider field ; in particular continuity is of far-reaching importance. On the chemical side this was illustrated by the rise during the latter half of the nineteenth century of certain large-scale continuous processes, such as that for the manufacture of soda ash, and by the more recent change-over from batch working to continuous production of most of the important chemicals. In engineering the development of turbo-machinery of every kind—as opposed to reciprocating machinery—and of flow production methods are evidence of the same trend. Many reasons lead the chemical industry to search for continuity in fundamental design and in manufacturing operations. Some of these are peculiar to the industry. Thus certain processes, such as the fixation of atmospheric nitrogen to form ammonia, would not be technically or economically possible on a batch system. Many processes could not be operated for one or two shifts a day, as it would be impossible to reach steady operating conditions of temperature, pressure or chemical reaction in the time available. It is, indeed, common for many processes to operate continuously, at approximately full output, for twelve months or more.

But there are other important factors which lead to continuity of operation and which may well apply in many other industries. For example, the rapid growth of demand associated with the continuous rise in standards of living calls for high production and a minimum of operating staff. This involves large unit size and very high capital costs per employee ; it is now common for the latter figure in the chemical industry to reach £10,000 or even more for the most modern plants. The creation of production facilities to this value represents a " rolled up " human effort of some twenty man-years, but new plants may well be obsolete in ten years or less. It is therefore uneconomic in the social, no less than in the financial, sense, if such equipment is not put to continuous use throughout its life. Both quality of product and the efficient use of materials are greatly aided by continuous running with control to close limits. This demands a high level of instrumentation, and it is now generally accepted that what can be measured can be controlled far more steadily and exactly by automatic means than by direct human agency. The development of " automation " methods, which are now so much in the public eye, is merely an extension of this trend which has been apparent in the chemical industry for a long time.

The breadth and scope of this approach is illustrated by considering the manufacture of explosives, which is a part of the chemical industry where the hazardous nature of the processes inevitably induces a conservative attitude. Despite this, the production of industrial explosives is already being mechanised for continuous output to increase productivity without detriment to safety. In fact, the actual quantity of explosive in process at any time is decreased, the number of operators exposed to hazard is reduced or, with automatic and remote control, eliminated completely.

It is appropriate to mention here two applications of explosives in which blasting has been modified to overcome

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disadvantages resulting from sharp discontinuity of action. The first is a new technique for coal getting known as " pulsed infusion shotfiring." New explosives have been developed which can be fired in a sealed bore-hole filled with water under pressure to produce a high pressure impulse. This is very effective in breaking out the coal with little dust formation, and a consequent reduction of explosion and health hazards. Secondly, the mining of ores, quarrying, and production of opencast coal have been influenced by the introduction of short delay detonators for firing a sequence of charges



Fig. 1—Handling nitric acid for explosives manufacture at the end of the 19th century

at intervals as small as 0·02 seconds. This extends the ripping action of the explosive in a progressive and effective manner.

Because of its scientific basis, the chemical industry has been pre-eminent in the use of research. This applies not only in the systematic search for new materials and new processes, but in the application of the scientific method to every aspect of technical work, to commercial operations, and to management in general. This in turn has led to the widespread employment of scientifically trained personnel in every phase of activity. In the larger organisations, it is common to find that 5 per cent or more of the total employees have had training of university degree standard in pure or applied science. Because the emphasis is on brains rather than human physical effort, the ratio of staff to production operatives is increasing and may reach 1 to 3, or even 1 to 2 in advanced organisations. This trend is by no means confined to the chemical industry, but it is doubtful if the implications of this movement, and particularly of " the high cost of low overheads " are yet fully appreciated in this country by the community at large.

The present shortage of scientific and technological manpower is a result of the failure to adjust our educational system quickly enough to keep pace with the changing pattern of demand. The serious consequences of this are already recognised in the chemical industry, where the most urgent need is for more engineers with a sound education in basic science, in addition to training in their particular field of specialisation. The demand for men of this type must continue to grow in step with the widening application of scientific knowledge in manufacturing processes of every kind and in the service industries. In fact, this shortage of technologists may well prove to be the Achilles heel of our industrial economy, unless prompt and energetic action is taken to keep Britain in line with other countries in this vital matter.

Rationalisation, and the integration of complementary processes has been an outstanding feature of the chemical industry in modern times. The almost numberless possibilities of chemical reaction make it advantageous to have a wide range of processes on the same or on contiguous sites, so that the products or by-products of one process may provide, under balanced control with a minimum of storage and transport, the raw materials of another. Here again, there is a close parallel with the engineering industry as, for example, in the large-scale integrated production of motor vehicles. There is no doubt that under effective management and with proper control this movement towards rationalisation can lead to higher overall efficiency in the widest sense of the term.

As a result of all these developments and the attitude of mind which they induce, the advance in productivity in the chemical industry, particularly in the post-war years, has been outstanding. This is illustrated by some comparisons which were recently published by the Treasury. It is estimated that productivity in the post-war period for industry as a whole has increased at the rate of about 3 per cent per annum, or double the pre-war average rate of increase. The chemical industry has shown the highest average percentage increase in yearly output per man during the period 1948/1954, the figures being : 8 per cent for the chemical industry, 4 per cent for engineering, shipbuilding, electrical goods, 3½ per cent for iron and steel, 3 per cent for bricks and cement, and 2½ per cent for glass. This achievement by the chemical industry may be ascribed in part at least to the following factors :

(*a*) The large scale of research effort directed to the improvement of existing plants and methods, as well as to the development of entirely new products and processes.

(*b*) The high rate of capital expenditure related to (*a*) and to keep pace with the rapid rise in demand. A study of long term trends, both here and abroad, suggests that the chemical industry expands at about twice the rate of manufacturing industry in general. The new installations incorporate the latest types of plant and controls and as they tend to increase in unit size, it is natural to expect a corresponding rise in productive efficiency.

(*c*) The high level of technical effort already referred to is also a major factor in this advance. The scientific training and attitude of the staff affects not only the technical sphere, but inevitably influences the approach to organisation and management, including human relations. One result of this has been a rapid extension of training facilities at all levels. Above all, it promotes the desire for evolutionary change and progress as a matter of deliberate policy.

Operating Conditions

The development of more efficient operating conditions poses many problems in chemical engineering. Generally speaking, chemical reaction will proceed most rapidly and effectively when there is the best possible contact between the reactants, and systematic exploration is being directed to this field. Among the more important controlling factors are the degree of mixing and dispersion, the influence of pressure (particularly in fluid reactions) and the effects of temperature. In both gaseous and liquid reactions, catalysts are continually being found which will induce or speed up chemical combinations that are difficult or impossible to effect without such aids. Research effort in this field is intense but still largely empirical ; recent work is beginning to throw light on the mechanism of surface action but full theoretical understanding has yet to be obtained.

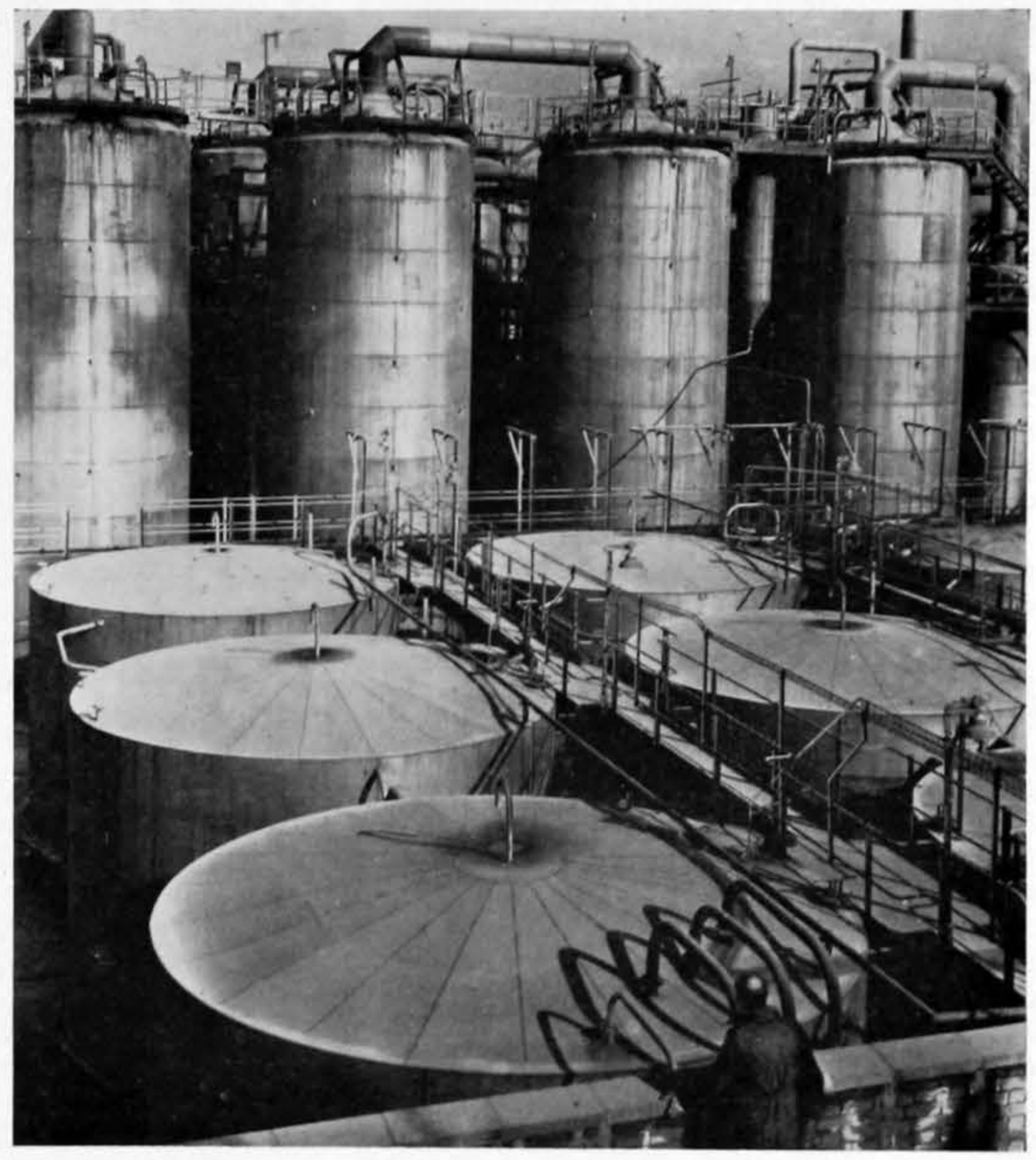


Fig. 2—Absorption towers and storage tanks in a modern nitric acid plant ; a typical use of stainless steel

An important and interesting development has been the application of high pressures to aid chemical reactions. This possibility had scarcely been considered before the beginning of this century, and even in the 1920s, operating pressures of 3/5000 lb per square inch were regarded as high. Now, there are large scale plants operating continuously at pressures of 15,000 lb or more, and experimental work is being directed towards the possibility of industrial operation at pressures of the order of 100,000 lb per square inch. Such developments involve fascinating engineering problems,

particularly where elevated temperatures and corrosive media are also involved. For example, early types of gas compressor for continuous industrial operation at around 15,000 lb per square inch were complex and unreliable, but great improvement has been effected by careful attention to design, including the surface finish of cylinders and plungers, dimensional accuracy, and the choice of the most appropriate materials. Advances of this kind can only be made by very close collaboration between the engineering staff on the chemical side, and the engineering firms responsible for supplying the machines or components in question. Foreign manufacturers now offer, as standard equipment, valves, compressors and pumps for pressures of the order of 15,000 lb per square inch, but in general it is still necessary for such equipment to be specially designed if users wish to purchase it in this country. The extension of operations under the more extreme conditions is likely to continue, and it is to be hoped that British suppliers will appreciate the need for a bolder and more progressive approach.



Fig. 4—The main control room of the Olefine plant shown in Fig. 3

Materials of Construction

New chemical processes are frequently dependent on advance in the available materials of construction. Thus the discovery of austenitic steel revolutionised the manufacture of nitric acid, Figs. 1 and 2, and experience in this work has further advanced the techniques of stainless steel production. Similarly, demands by the chemical industry for very large forged pressure vessels in alloy steel have led to advances in steel making. The rapid expansion of the nitrogen fixation industry after the first world war called for the largest possible pressure vessels for operation at about 4000 lb per square inch. In 1922, the optimum vessel which could be obtained in this country was a mild steel forging with a finished weight of 82 tons and an internal volume of 284 cubic feet. In 1926, it was possible to obtain 329 cubic feet with a valuable increase in diameter from 4ft to 4ft 5in by using nickel-chrome steel for a composite vessel consisting of a body forging of 39 tons end breech ring of 20 tons to hold the end closure. For the development of coal hydrogenation in 1933, it was particularly important to secure still bigger volumes, and by a novel design of the end closure, and with the co-operation of the forgemasters, vessels having a diameter of 4ft 9in, with a volume of 640 cubic feet for work above 4500 lb per square inch were successfully produced in nickel-chrome-molybdenum steel. In this case the body ingot weighed some 250 tons. All these vessels were to work with hydrogen as one of the reactants at temperatures not exceeding about 150 deg. Cent. However, the hydrogenation process demanded that certain items of equipment, in particular pipes and junction boxes, &c., should be capable of standing the full pressure at temperatures of around 500 deg. Cent. Under such conditions mild steel and normal alloy steels could not be used, as they are subject to rapid decarburisation and embrittlement due to the presence of hydrogen. Experiments showed that a low carbon-chrome steel with chromium content of 3 to 6 per cent offered a solution. Although such materials were novel to the forgemasters and tube makers at that time, success was achieved, and an appreciable advance was made in metallurgical technique.

The importance and difficulties of operations at high pressures is paralleled by the problems which the chemical industry presents in its desire to work at very high and very low temperatures or under conditions of high vacuum. There are also frequent problems arising from corrosion by the liquid or gaseous reactants which have to be handled. Any advance which would widen the practicability of operations at temperatures in the range 500 deg. to 1000 deg. Cent. would be particularly valuable.

In general, the limitations of known materials of construction are a major check on further progress ; the continuous improvement in the properties of such materials, and a thorough understanding of their fundamental nature, is thus of special concern. The chemical industry itself makes a very real contribution to this work. A considerable part of the £13,000,000 a year which it currently spends on research, and of the support which it gives to research associations and work in the universities, is applied in the engineering field to work on metallic and non-metallic materials. The industry is particularly concerned with problems of creep, fatigue and corrosion under operating conditions that are often critical ; even minor deviations from the specified constitution or physical properties of materials may lead to very costly or even dangerous failures. In view of these circumstances—which also affect other major industries, such as those engaged in aero-engine production, nuclear energy and petroleum technology—it is to be regretted that bolder steps have not yet been taken to provide more comprehensive and advanced schools in the universities or elsewhere for teaching and research in the wide field of metallurgy and non-metallic materials.

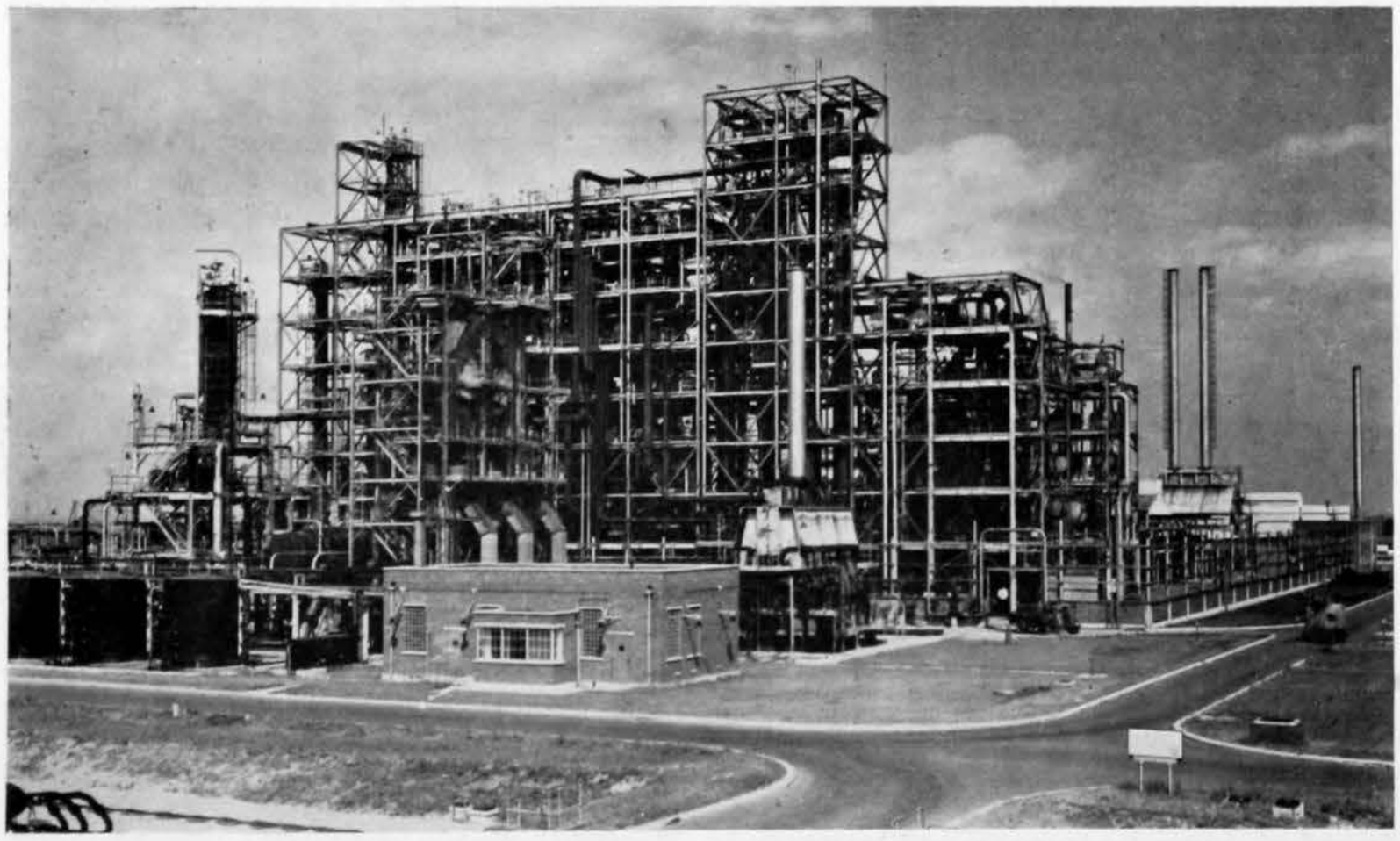


Fig. 3—The Olefine plant at Imperial Chemical Industries, Ltd. Wilton works from which ethylene is the main product. The control room is seen in the foreground

Chemistry and Other Industries

Industrial developments generally and the ever-widening scope of the chemical industry have led to a condition where there are no clear boundaries between this and several other industries. We thus find close and often overlapping connections between the chemical industry and others, such as those producing steel, non-ferrous metals, plastics, oil, and nuclear power, which are dealt with elsewhere in this Centenary Number of The Engineer. The gas industry, which has long been an important producer of intermediate and finished chemicals, is now being super-

seded by the petroleum industry as a major source of raw materials for the production of organic chemicals. The oil companies are constantly expanding their chemical manufacturing activity, and this is already important enough to influence the operational design of oil refineries. As a complement to this the chemical industry has shown that economic production is possible by "cracking" selected petroleum fractions for the prime purpose of chemical manufacture, any petrol or heavier oils that result being regarded as by-products. This is illustrated in Fig. 3, which shows an olefine plant for the production of raw materials required in the integrated manufacture of numerous chemical products. As an example of the close interlocking between the two industries, one may quote the production of ethylene from petrochemical plants of this kind. The ethylene may be used for the manufacture of polythene, which is extensively employed in the electrical industry and for an increasing range of other uses. Alternatively, the ethylene may be used for the manufacture of tetraethyl lead, which is supplied back to the oil industry, for making ethylene glycol, and for many other purposes.

The extraction of non-ferrous metals from their ores is traditionally associated with mining engineering enterprises, but many of the processes involved are essentially chemical or electrochemical in their nature. Aluminium, whose century of useful application was celebrated last year, stands as the product of a single great industry requiring abundant electrical energy. This and the electrolytic extraction of zinc are among the outstanding achievements of recent times. The wide use of titanium oxide as a pigment has speeded the availability of the salts from which titanium metal is prepared. The production of this new material of construction is primarily a chemical problem ; the metal is likely to play an increasing part in advanced engineering design of the future, and is of particular interest to the aircraft engineer. The severe conditions necessary for some chemical processes, which have already been referred to, also make titanium of great interest in chemical engineering.

Some Examples of Recent Industrial Chemical Developments

Man-made fibres have become of much importance, but interesting and valuable as these materials may be, there is a danger of seeing them out of perspective. In the United Kingdom, Nylon is being made at the rate of some 30,000,000 pounds a year and Terylene—an entirely British invention—is already in production on a plant designed to make 10,000,000 pounds a year. These are very considerable quantities, but it must be remembered that some 2500 million pounds of natural fibres and some 500 million pounds of rayons are also processed in the United Kingdom each year. The world demand for the older fibres continues to increase in spite of the development of truly synthetic fibres for more specialised purposes.

Nylon and Terylene.—The equipment used in the manufacture of the polymers from which these fibres are made is elaborate and expensive because of the many steps in the process and because the extremely high quality standards required in the final products demand very special attention to the detail of plant design and operation. A typical problem occurs in the polymerisation stage of the manufacture of Terylene, where the speed of reaction depends to a considerable extent on the rate of removal of the gases evolved and where the material changes from quite low to very high viscosity as the polymerisation proceeds. Then again a special machine had to be designed to cut the 18in wide ribbon of tough cooled polymer into $\frac{3}{16}$in cubes with a minimum of fines. Many complicated engineering problems had to be solved in connection with the processes for making yarn from the synthetic polymers by the melt extrusion technique, since there is no counterpart to this in normal textile technology. The polymer is melted, filtered, pumped through spinnerets, and wound on bobbins. Then, in order to develop the valuable properties of these yarns—particularly the high tenacity associated with Nylon and Terylene—the molecules must be orientated along the axis of the fibre by stretching the yarn on drawframes. An

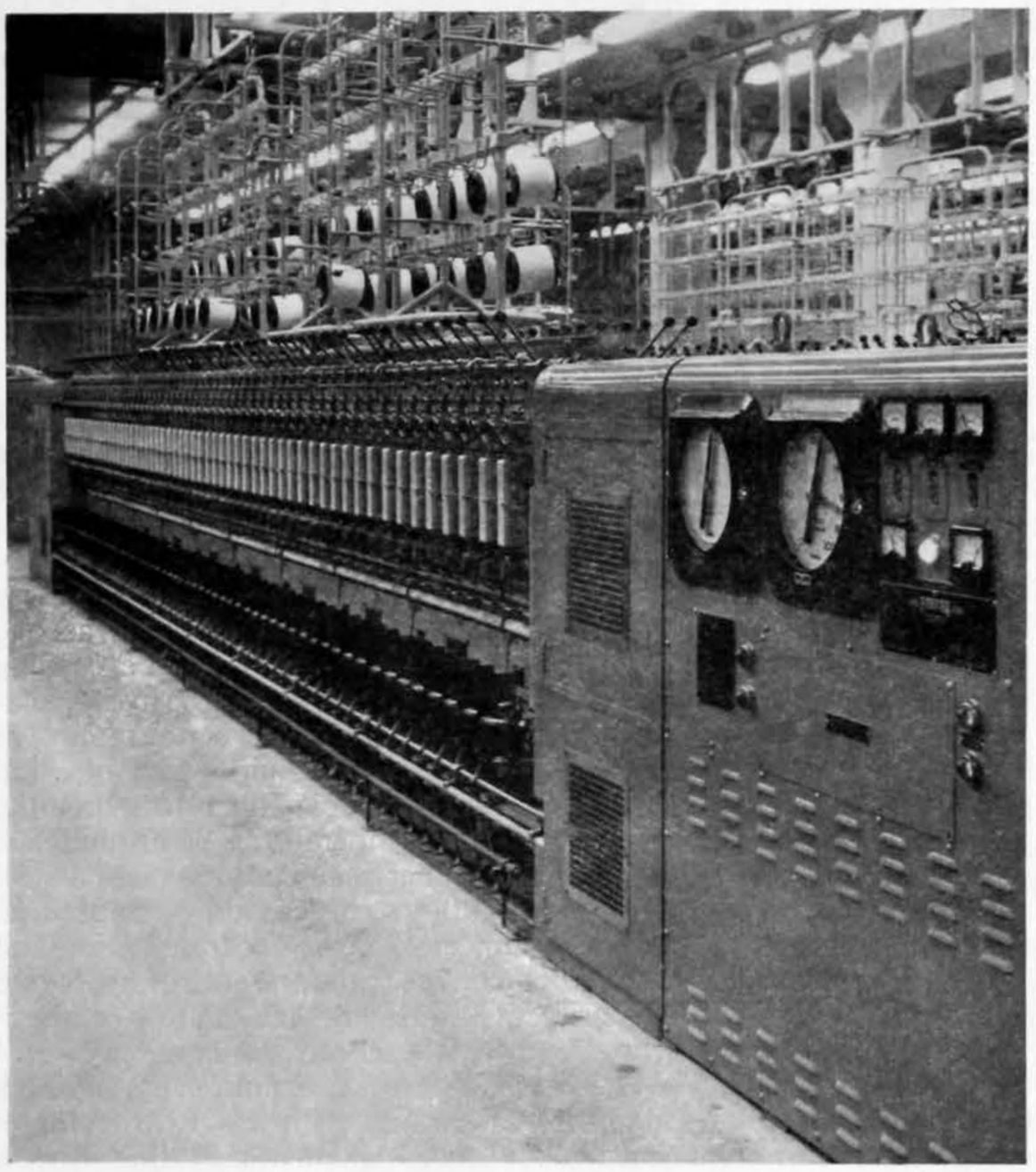


Fig. 5—A section of plant for the drawing of Terylene yarn, involving close temperature control and automatic scanning of threads at high speed

average yarn leaving the drawframe may consist of ten to fifty individual filaments, each of which is about 0·0005in diameter. Any break or other fault in these fine filaments may lead to a stoppage of the textile-processing machinery through which it subsequently passes, and present-day standards, which become progressively more rigorous, demand that no such faults shall be detectable in several miles of yarn.

The drawing of Terylene yarns, Fig. 5, is done at temperatures approaching 200 deg. Cent. This entails a series of difficult heating problems, since the yarn runs at speeds as high as 3000ft a minute, and the temperature must be uniform. A solution is not easy even if expensive equipment is used, but when several thousand running yarns must be heated separately with a high degree of uniformity, it is necessary to have temperature-control equipment which is inexpensive as well as accurate. A good deal of success has been achieved by the development of simple temperature control elements for use on each thread line, together with development of automatic scanners and temperature indicators, each checking groups of about sixty thread lines and indicating any departure from normal. The winding up of the drawn yarn is carried out on equipment which is an adaptation of standard textile spinning equipment, but with bobbin speeds as high as 10,000 r.p.m. very high standards of design and maintenance are required. There is keen and growing international competition in this field, and success demands close co-operation between the chemical and engineering industries, backed by the highest possible level of technological competence.

Electrolytic Processes.—In the heavy chemical field, we find that caustic soda and chlorine are two of the basic materials, the production of which have for years been reliable indices of industrial development. The electrolysis of brine produces both chlorine and caustic soda, and by the electrolysis of sodium chloride in a molten state chlorine and metallic sodium can be produced. These and other similar processes lead to heavy demands for d.c. electricity—the demand in a single factory may be over 200,000A at 250V—and corresponding electrical engineering problems. The older plants used steam-driven d.c. generators to produce the necessary current, but now diesel-driven d.c. generators, and rotary and motor converters are also used extensively. Mercury-arc rectifiers are not very appropriate for this purpose because at the low voltages which are required, the efficiency is low. But the contact rectifier which is now manufactured in this country has an efficiency which may exceed 97 per cent, and it is finding increasing use for heavy loads at direct voltages up to 350V.

The commercial development of large germanium and silicon rectifiers—which itself poses many chemical engineering problems — is awaited with interest.

Protective Coatings.—The prevention of corrosion is a universal industrial problem, for damage due to corrosion is measured in hundreds of millions of pounds annually. Painting is one of the oldest, and still among the most satisfactory, preventive measures. Chemical research has led to a better understanding of the behaviour of paints and to the introduction of new protective coatings. New film-forming materials, such as the alkyd resins, urea and melamine formaldehyde resins, and, more recently, resins of the epoxy type, can provide coating compositions possessing greatly improved durability, flexibility, chemical and heat resistance, as well as being harder and more resistant to abrasion. The traditional method of making paints and varnishes in small batches without scientific control, is giving way to controlled continuous processes ; these call for greater engineering effort in design and manufacture and result in more efficient production.

In addition to improving the durability and covering power of coatings, research has led to better techniques of application that can mater-

ially reduce costs. Modern finishes are capable of being applied and hardened more rapidly than those of yesterday, and the development of hot spraying makes it possible to apply a heavier coat in the same time as a normal one. A recent and promising development involves the simultaneous application of the coating material and a catalyst to promote rapid hardening. These advances are of particular significance in automobile engineering.

Much research is being directed to the production of more efficient types of anti-fouling paints to reduce biological growth on ships' hulls. Although improvements during recent years have had a significant effect on speed and fuel consumption and on the time intervals between dry-docking, much remains to be done, and further progress depends upon close collaboration between the chemical industry and marine engineers.

The corrosion of structural steel work is an ever-present problem and engineers are paying increasing attention to designing structures so that protective coatings can be more easily applied and maintained. In cases where the conditions are very severe, the use of corrosion-resistant alloy steels or non-ferrous metals may sometimes be necessary and justified, but in many cases it can be shown to be economical to coat the steelwork with metallic zinc or aluminium before the appropriate primers and finishing paints are used. It is to be hoped that the steel industry will, before long, install equipment at the mills to coat suitable rolled sections with such protective metallic coatings.

In the paint industry, as in industry at large, standardisation of equipment and, where possible, of product, greatly assists the rationalisation and flow of production. A simple but typical example of this is the use of paint tins of standardised volume to eliminate unnecessary weighing and packing operations. When lead was an almost invariable constituent of paint, weight may have had significance, but covering power is more likely to be linked with volume.

Standardisation.—The chemical industry has been particularly active in pressing, through the B.S.I., for a greater measure of standardisation in the field of overall dimensions, such as those for pipes, flanges, and valves. It is also concerned to secure better standardisation of material specifications based on physical as well as chemical properties. In the long term, it cannot be in the national interest to have a multiplicity of similar specifications linked with particular end uses, when suitable materials could be selected from a general range giving a gradation of properties; for example, it appears unnecessary and wasteful to users and producers alike to have three specifications for mild steel boiler plate for marine, locomotive, and land use, respectively.

Conclusion

The role of chemistry is no less vital in modern civilisation than that of engineering. It is concerned with all the great physical problems which mankind has to face, such as the provision of heat and energy, the production of food and clothing, the attainment of health and hygiene, with an increased span of useful life. Thus, the fears of Malthus with regard to food supply have not materialised, due largely to the industrial fixation of atmospheric nitrogen, and the aid which agriculture now has from the ever-widening range of fertilisers, selective weed killers and pest control chemicals. The industrial revolution was based on coal, and has been extended by petroleum and the products resulting from its chemical treatment. For the future, and in face of the increasing difficulties of coal getting and the eventual limitation of oil supplies, it is indeed fortunate that physics and chemistry are opening up new vistas with atomic energy. The pace of chemical discovery continues to accelerate with a corresponding challenge to ensure that the potential benefits of this advance become available to all. These possibilities appear boundless, if mankind by proper philosophy and action will allow their free and effective development.

Oil and Engineering

By A. C. HARTLEY, F.C.G.I., B.Sc., M.I.C.E., M.I.Mech.E., F.Inst.P.*

OIL has played such an essential part in the development of all the engineering discoveries described in this section of the Centenary Number that it is difficult to realise that the first number of THE ENGINEER was published four years before the discovery in the United States of the world's first natural oil well! The early numbers of THE ENGINEER could therefore only have dealt with oil by describing the work of Dr. James Young, a Glasgow chemist, who, in 1847, refined oil for lighting and lubrication and made an improved material for candles from oil seepages in the Derbyshire coal measures. That was the beginning of the oil industry as we know it to-day, but the seepages were too small for the establishment of a permanent industry and Dr. Young, believing that oil could be produced by distilling coals and shales, studied the artificial production of oil and took out patents in 1850 in which he described processes of distillation and refining by chemical treatments, many of which are in use to-day.

Engineers collaborated with him and enabled him to establish a plant at Bathgate, near Edinburgh, to produce oil from a rich Cannell coal. The supplies soon ran out owing to the keen demand for his products at home and on the Continent and even in the United States of America. Further engineering developments, however, enabled him by 1858 to make similar products economically from oil shale, a raw material which, although cheap and abundant, gave only a fraction of the yield obtained from Cannell coal. Yet again, engineering improvements in the plant used led to rapid developments and there were no less than 120 shale works in operation by 1865. Then, however, oil products from the United States—where there had been even more rapid development following the discovery in 1859 of the first natural oil well by Col. Drake—began to compete in the European market, being much easier to produce and refine than oil from shale, and the consequent rapid fall in prices led to the abandonment of many of the shale works. Some, however, fortunately survived by applying the closest attention to the development of their processes and using to the full advances in engineering to improve their retorting and refining plant. The old horizontal iron retorts were replaced eventually by batteries of vertical steel refractory lined retorts burning the fixed carbon in the spent shale as fuel and capable of handling 1000 tons of shale a day.

Civil, electrical and mechanical engineering have all contributed to the full in the development of economical methods of mining, handling, crushing and retorting the shale and in discovering, producing and transporting natural crude oil and in refining and marketing the products, thus paying back the debt they owe to the oil industry for providing the fuel and lubricants that have made their own engineering developments possible. The steady and continuing development of the oil shale industry, in spite of all its difficulties, has been of great importance in providing experience for British engineers which has enabled them to play a very large part in the rapid development of the natural oil industry in many parts of the world following Col. Drake's discovery well.

Within ten years of Col. Drake's discovery, crude oil was being produced in Rumania, Russia, Italy and Canada and by 1900 in Poland, Japan, Germany, India, the Dutch East Indies and Peru. Discoveries in Mexico, the Argentine, Trinidad and Persia had followed by 1911. Engineers and engineering plant and services of all kinds have been used by the industry frequently in previously uninhabited places in this world-wide search for oil. Throughout its whole history, the oil industry has been among the foremost in encouraging the development of promising new engineering discoveries by placing early orders for their use and helping them through their teething troubles and by meeting in so many cases their need for improved fuel, lubricants or other oil products which have, in their turn, led to yet further developments.

After oil has been discovered, its production, transportation and refining involve the establishment of large communities requiring all the public services and amenities and all the industrial facilities of a large provincial town in this country, and in many cases additional special services, such as air conditioning to temper the severe climatic conditions abroad.

The extent and scope of the oil industry at the present time will be dealt with later in this article, but before first describing briefly some of the developments in the various branches of the industry, it is interesting to note that although natural oil was discovered less than a century ago, the annual production in 1900 was 20,000,000 tons; this annual rate has been doubled each decade and is now more than 700 million tons. The story of oil is therefore one of great achievement and some of the contributions made by engineers in the various branches of the industry will now be briefly described.

Oil Exploration

The origin of oil has been the subject of acute controversy for a very long time, and even to-day agreement does not go much beyond the general acceptance of the view that the original source was organic in nature and that it consists of the bodies of marine organisms and possibly of some plant life formed at the bottom of seas, lagoons, &c., and preserved by the steady deposition of fine grain sealing formations such as mud, clay, lime, &c. There is still much conjecture as to the chemical processes by which they have been changed into oil and gas, whether this has been by heat and pressure or by the effect of hundreds of millions of years irrespective of heat and pressure, or possibly even by biological processes. The fact remains, however, that unlike coal, which is solid and remains where it is formed, oil is liquid and may migrate considerable distances laterally and vertically, and only

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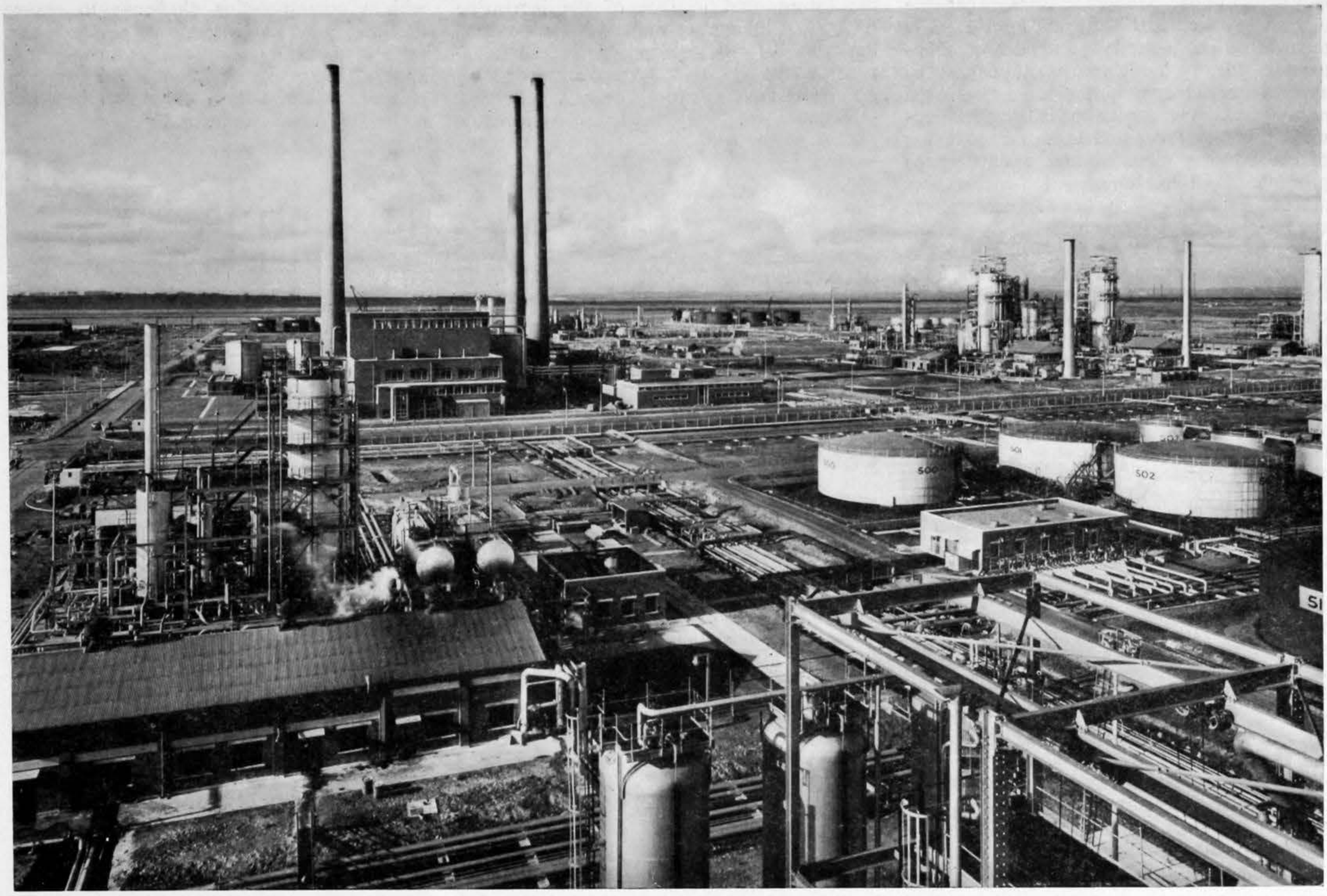


Fig. 1—A section of the British Petroleum Company's Kent oil refinery with (left to right, background) power station, vacuum distillation units and distillation unit with propane de-asphalting storage in right foreground

provides a prospective oilfield if it is trapped in reservoir rock or sand sealed in by impermeable cap rock.

The civil engineer has always played his part in oil exploration by surveying, map making, road building and providing means of access and subsistence to enable geological surveys to be made. These have been greatly helped in recent years by air reconnaissance, air photography and photo-geological interpretation preceding the detailed ground geological survey. During recent years, also, engineers in many other branches of engineering have contributed to the improved methods now used for supplementing the efforts of the geologist and making more certain the location of the prospective oilfield. They have assisted geophysicists in the development and use of gravimetric, magnetic, electrical and seismic methods of survey. The gravimetric method depends upon highly sensitive instruments such as pendulums, gravimeters, or torsion balances to measure the slight variations in the gravitational forces of the earth. These forces are affected by the distribution of rocks of different density, heavier or lighter areas in depth. The presence and magnitude of slight variations of the force of gravity can by mathematical analysis afford evidence by which the presence of concealed structures may be indicated or mapped with great accuracy. The magnetic method measures the earth's magnetic field to find local variations which may be related to the distribution of rocks of different magnetic attractions. These variations may indicate structures. Probably the most important of these new methods is the seismic method, which consists of creating an artificial earthquake by firing explosives and then observing the rates and times of travel of the waves so created through the formation rocks. Two forms of this survey have been developed, the reflection method and the refraction method. In the reflection method, a shot of only a few pounds of high explosive is placed in a bore-hole 10ft to 50ft below the surface and fired electrically. The seismic waves so created are reflected for some physical reason from certain rock surfaces at depth and the returning pulses are recorded in geophones suitably aligned nearby on the surface and electrically recorded centrally in a truck. Each geophone records the total travel time of the particular wave entering it and provides the operator with data to plot the underground contours and what it is hoped may prove to be cap rock. The refraction method takes advantage of the fact that different formations transmit seismic waves at different speeds. Shots of from 1 to 3 tons are exploded and the vibrations radiate out and down in all directions, some being reflected from the high-velocity formations, while those which strike those formations at a critical angle are refracted along it and travel at a higher velocity in it until they emerge again and make their way up to the surface, where they will be recorded on suitably located geophones. The large explosive charge used enables the geophones to be located at from 5 to 15 miles away from the shot point to ensure that the refracted high-velocity waves get so sufficiently far ahead of the reflected waves as to be easily identifiable.

The instruments used in geophysical surveys are being continuously improved and means have recently been developed for transporting and handling them in difficult marsh and sea areas in which oil is now being sought. Diving bells and floating platforms with spud legs are being used to provide steady support for gravimeters ; and magnetometers are actually being flown on surveys by radar-controlled aircraft, thus enabling vast areas of sea or land to be covered by a preliminary survey. The use of one or more of these geophysical methods often establishes the existence of favourable underground conditions, but cannot indicate whether oil has ever been trapped in the structure and, if so, whether it remains there now. The only method of proving an oilfield is by drilling wells, but further developments in geophysics are assisting in the location of test wells so that fewer dry holes are now being drilled.

Oil Well Drilling

The only equipment available to Col. Drake when he drilled his first well in Pennsylvania in 1859 was that normally used for drilling water wells and it is fortunate that he had only to reach a depth of 69ft. It says much for the pioneers who produced the early drilling rigs, largely from rough hewn timber, that there were traces of many of their ingenious devices in the design of drilling rigs for the next 60 years or more ! Drilling during that period was by the cable tool method, in which a heavy steel bit of the chisel type was suspended in the earlier days by manilla rope and later by steel wire cable, motion being imparted to it by a crank and beam which utilised the stretch and spring of the rope or cable to produce an impact on the formation somewhat like the cracking of a whip. The chippings were baled out after 5ft or 6ft had been pulverised and a good day's progress was usually of the order of 15ft to 25ft if the going was

good. Mechanical engineering developments just before the turn of the century led to the adoption of the rotary, or mud flush, system of drilling and faster progress began to be made. This system, as its name implies, depends upon the more orthodox method of rotating a bit of special design which cuts the formation with a combination of a cutting and paring action imparted by cutter wheels revolving in the bit head. The bit is connected to screwed drill pipe rotated at surface by a special rotary table, a continuous flow of mud being pumped down the drill pipe and up the annular space, cooling and lubricating the bit and bringing the cuttings to the surface. The mud is loaded with barytes and other materials to specific gravities of 1·25 or more in order to counterbalance the pressure of the oil in the formation and to prevent the oil gushing to the surface when the well is drilled in. A special hydraulic packing gear has been devised to enable drilling to be carried out under pressure and it is used in the case of very deep wells where the weight of mud alone would not counterbalance the oil pressure. It has been necessary to develop throughout the years improved drilling techniques to enable ever deeper wells to be drilled and deeper oilfields to be discovered. At these depths, higher pressures are encountered and reservoirs having rock pressures of more than 6000 lb per square inch can now be explored without difficulty. The very special problem of drilling 3 miles or more below the surface calls for a highly specialised design of casing, drill pipe, rotary tables and particularly of lifting gear, which is the key to the operation. The necessity for very rapid hoisting speeds, so that the drill pipe can be drawn from the hole for changing bits and lowered again with the minimum loss of time, has produced a special design of hoisting gear which has no equal in any other branch of mechanical engineering. The handling of high pressures both in mud, oil and gas calls for very special designs in valves and surface fittings, as well as in oil well casing.

The requirements of the oil industry have led to the development of special types of steel in order to produce the toughness and high tensile qualities required at these great depths, where dimensions permit of only the minimum factors of safety. Steam was used extensively in the early days of drilling to drive the drawworks, rotary table and mud pumps and is still the most satisfactory power because of its flexibility. It cannot, however, be used economically in all oilfields, for water is often extremely scarce or unsuitable for boilers. In such conditions, the internal combustion engine and electric motor drives have been increasingly used. The necessary flexibility to enable steady pulls to be maintained by the draw-works on the drill pipe and steady pressure on the mud, &c., has been obtained by fitting hydraulic couplings. Drilling by electric motors has usually been adopted where a large number of wells have had to be drilled in a fairly restricted area and where it has been possible to obtain sufficient electric power. The depth of the early wells was rarely more than 3000ft, but wells are now regularly drilled to 17,000ft and in some cases even to 20,000ft.

The industry has used each advance in the design of new tools for " fishing " in case of " twists off " of drill pipe, of new methods of coring and of testing wells. Production in tight formations has been increased by shooting and by acid treatments. More recently, methods of electrical logging have been used to survey wells before the casing is lowered and have provided valuable geological information and have in many cases done away with the need to core and have greatly speeded up operations. There is still great scope for engineers to develop improved methods of drilling, such, for instance, as by using the mud flush to drive the rotary bit by means of a turbine at the bottom of the hole, thus avoiding having to use the rotary table to rotate the drill pipe.

Oil Production

In the early low-pressure oilfields relatively small quantities of gas came out of solution when the oil was reduced to atmospheric pressure, and this gas separation could be allowed to take place in tanks working at atmospheric pressures with very little effect on the quality of the crude. In the deeper oilfields now being tapped the pressure of the crude oil in the reservoir may exceed 5000 lb per square inch and flowing pressures at the top of the well may be more than 3000 lb per square inch. Natural petroleum gas in proportions varying from 2000 : 1 by volume to 4000 : 1 by volume is dissolved in the oil. If these high pressures were released in a single stage, large quantities of light oil fractions of great value as a constituent of petrol would be carried away with the gas. The flow of oil is therefore directed after a preliminary separation of the leanest gas at the well head to a series of heavy steel separators, each being at a lower pressure than the one before and ranging from about 1500 lb per square inch to 15 lb per square inch. The gas is taken off at each stage and the crude oil is then delivered to flow tanks, from which it is pumped down pipelines to the refinery or to the crude oil loading terminal. The gas is used as far as possible in the oilfields and in the pumping stations and refineries and is processed for production of special products. There is great scope for engineers in improving the plant, compressors, pumps, instrumentation and automatic controls for dealing with the increasing pressures and higher rates of production now being met.

Oil Transportation

Oilfields are usually found a considerable distance from the refinery or crude oil loading terminal site, which must necessarily be alongside deep water to enable products and crude oil to be loaded into ocean-going tankers for delivery to the world's markets. Oil was for many years transported from the wells in oak barrels, but proposals were made as early as 1861 for a wooden pipeline, 4in diameter and 6 miles long. The first successful line was made of cast iron pipe, 2in in diameter with screwed joints. It, too, was 6 miles long and had steam-driven pumps which delivered about 70,000 gallons of oil a day. Further lines were built during the next year or two, and by 1878 a 6in line, 125 miles long, had been built across the Alleghany Mountains. By 1910 about 20,000 miles of line were in operation and this was increased to 70,000 by 1920 and to 112,000 by 1930. The use of cast iron pipe was replaced by lap-welded steel pipe and later by seamless steel pipe. Diameters had been increased to 16in by 1939 and screwed joints had been replaced by welded joints, first with swelled ends and inner rings and later by plain butt joints.

Problems of expansion and contraction had quickly asserted themselves in the earliest days and lines buried in the ditch during the hot summer weather suffered from pulled-out joints in the next cold weather. Similarly, lines laid in shallow ditches in cold weather expanded and threw themselves out of the ditch in the next hot weather. These difficulties were overcome by crowding an excess of pipe into the ditch with sufficient cover to hold the pipe in position, but serious corrosion problems were the next difficulty. An extra thickness of steel was first used as a corrosion allowance, but this only postponed the trouble. Methods of pickling, priming, wrapping and enamelling the pipe were then developed to provide protection against corrosion and means have been devised for testing the soundness of this protection.

The alternative method of laying and supporting lines above ground has been successfully used in Iran, where there is no atmospheric corrosion. There was first a tendency for lengths of some miles of pipe to move in one direction under the influence of the daily expansion and contraction due to the variation of 100 deg. Fah. in day and night temperature, but this was overcome by making a sharp bend in the pipe of a few degrees alternately in each direction every 70 yards or so, thus zigzagging the pipe across country.

During the 1939–45 war a 24in pipeline, 1352 miles long with twenty-six pumping stations, was built in America to carry Texas crude oil to the industrial areas of New York and Philadelphia, and this was followed by another pipeline, 20in in diameter and 1475 miles long, for conveying finished products. These lines worked at 700 lb per square inch pressure and were made necessary by the severe losses being inflicted on tankers carrying oil along the Atlantic seaboard, but apart from these losses, they proved so much more efficient in the use of steel, power and men than tankers that they quickly led to proposals for more large-diameter lines. Every inch in diameter of line gives an appreciable reduction in capital and operating costs, but brings new problems to the mechanical engineer to solve. Seamless pipe cannot be made at present in diameters larger than 26in and there is great difficulty in maintaining reasonably uniform wall thicknesses. Pipe of uniform wall thickness has been made for many years by rolling single steel plates in the form of a circle and then fusion welding the longitudinal seam. The pipe is then subjected to a hydraulic pressure sufficient to stress the steel beyond its yield point and expand the pipe into a die. The pipe is thus made truly circular and straight and the yield point of the steel is raised.

The oil industry, and particularly that part of it laying gas lines, has been quick to take advantage of the higher permissible working pressures of this type of pipe by reducing the wall thickness and making great savings in steel. This fusion weld process involves the use of very heavy plant, which limits the diameter of the pipe produced to about 26in and engineers have made a valuable contribution to the oil industry by adapting the submerged arc welding process for the reliable production of welded and expanded pipe of up to 36in in diameter. This increase in diameter has enabled great savings to be made in the capital and operating costs of pipelines and has led to the construction of the 30in diameter Trans-Arabian pipeline, 1000 miles in length, from the Persian Gulf to the Mediterranean, the 30in/32in Iraq Petroleum Company's line from Kirkuk to Banias, also on the Mediterranean, and many large-diameter lines in North and South America, and in Canada, notably the Trans-Mountain pipeline, more than 700 miles long, from the Alberta oilfields to Vancouver.

The oil industry has encouraged the development of specialised earth-moving, ditching and back-filling machines for preparing the right-of-way and the trenches, and side boom tractors and cleaning and priming and wrapping machines for handling and

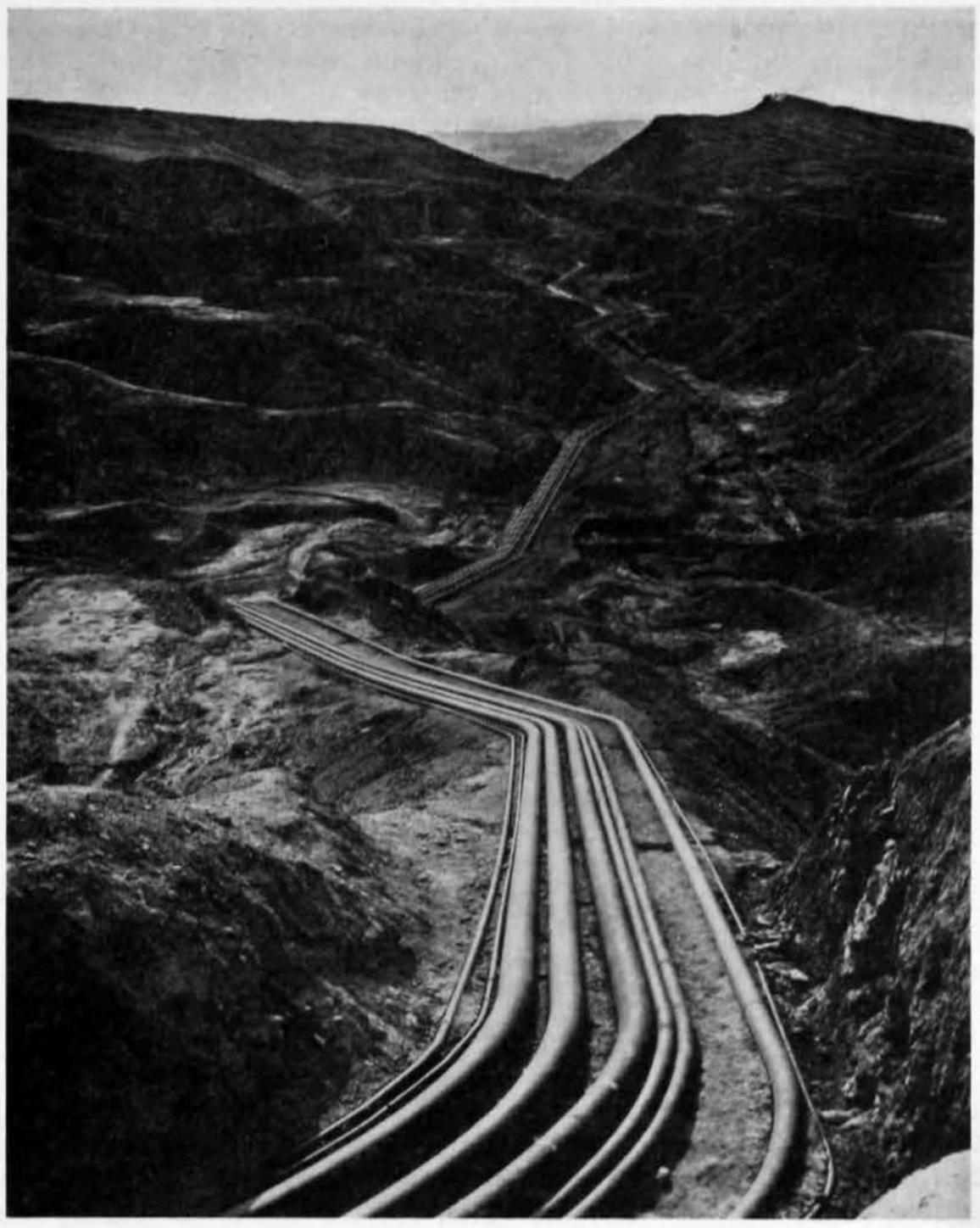
protecting the pipe against corrosion. Civil and mechanical engineers have made great contributions to these developments and more recently electrical engineers have contributed to the development of cathodic protection, which is now almost always applied to pipelines to deal with the inevitable faults or damage to coatings called " holidays." In this method, current is drained from the pipelines either by coupling them to magnesium anodes or, when an electric supply is available, by using transformers and rectifiers and ground beds. Experience has shown that when correctly applied, complete protection can be given to pipelines even when considerable damage has been suffered by the coating, but in these cases it is at the expense of greatly increased consumption of anode or current.

Reciprocating pumps of the duplex and triplex double-acting ram type were almost universally used for oil pipelines operating at pressures of 600 800 lb per square inch in the earlier days and were driven either by steam, compression ignition engines or electric motors according to circumstances. In 1916, multi-stage centrifugal pumps driven by steam turbines were installed in the Persian pipelines and proved to be very flexible and capable of running very long periods without shut-down. In the case of desert lines, where water was not available, centrifugal pumps have been driven by compression-ignition engines through speed-up gears, and heat exchangers have been installed to enable the circulating water of the engines to be cooled by the oil which is being pumped. In the early centrifugal pump installations, each pump operated in parallel, developing the full line pressure, but more recently pumps have been arranged in series so that the full throughput passes through each pump in turn and each adds its proportion to the full pressure. More efficient, flexible and simpler installations have thus been achieved.

The pipelines deliver oil to storage tanks in the refinery or the crude oil terminal tank farms, where all-welded steel tanks are now the common practice. They are usually of 10,000 to 16,000 tons capacity, but some of more than 30,000 tons capacity are being built. They are usually surrounded by bunds capable of containing the oil should the tank be damaged. Fixed roofs are used for heavy, non-volatile oils, but steel roofs floating on the oil are now used for crude oil and for light oils in order to reduce loss by evaporation and to reduce fire risk. Great care is now taken to earth all parts of the tanks and protect them against lightning. Cathodic protection is frequently applied to prevent corrosion of the tank bottoms and tanks are carefully insulated from the pipelines to prevent increased corrosion if they should become anodic to the pipeline system. The pipelines so far referred to have been for handling crude oil and pipelines for supplying finished refinery products to the marketing depots will now be described.

Pipelines for Refinery Products

Pipelines for refinery products have been developed chiefly in the United States where refined products are handled in larger quantities than elsewhere and there are now 25,000 miles of product lines in operation. At first, a different line was used for each product, but during recent years it has become almost universal practice to pump aviation and motor gasolene, kerosene, gas oil and light heating oil, through a single line and, in some cases, butane and propane and heavy fuel oil have also gone through one line. Plugs of water or mechanical separators were at first put between the different products, but experience has shown that provided the velocity of the oil in the pipe is kept well into the turbulent region, and if the sequence of products is carefully chosen, the amount of co-mingling is tolerable and products can be kept to specification when delivered to the depots. Inhibitors, either water or more recently oil soluble, are introduced into the line at the first pumping station and their amount is regulated to prevent corrosion inside the line. It has been found that the friction factor of the line can be kept low by



Oil pipelines in Iran

these means. Facilities are always provided for running scrapers through the line.

Products pipelines have been installed of diameters from 6in to 20in or more and they are operated at pressures of up to 1000 lb or 1200 lb per square inch, chiefly by centrifugal pumps. These are almost always designed for series pumping in each station and the lines are operated throughout from the initial station through the boosting stations as a closed or tight system, without the product going in and out of tanks. Reliable displacement meters have now been produced commercially and are used wherever oil is put into or taken out of the system. Provision is made for the regular checking and calibrating of the meters under the working conditions of temperature and pressure and the passage of the interface between any two products can be accurately forecast to enable the operators to carry out the necessary switching operation at intermediate take-off points and at the terminal into the appropriate tanks.

Standby pumping capacity is installed at the initial station, but frequently not at the intermediate boosting stations, because in series pumping the spare at the initial station can raise the pressure to some extent and help the booster. Electric motor drives are generally preferred where an electricity supply is available, but compression-ignition engines are frequently used with speed-up gears of ratios of up to 10 : 1. Centrifugal pump speeds of 3500 r.p.m. are generally used, but in some cases pumps with speeds as high as 5000 r.p.m. taking 2500 h.p. have been installed. There has recently been a tendency towards unattended pumping stations, both electric and engine driven, and the sequence of starting and shutting down operations is automatically timed and controlled and is set in motion and monitored by means of telephones and teleprinters hundreds of miles away. During operation, these stations automatically report to the central control room readings of suction and delivery oil pressures, speeds, temperatures, &c., at pre-arranged intervals.

Products pipelines are almost always buried in order to avoid undue variations of temperature and therefore of expansion and contraction of the oil which makes accurate forecasting of the position of the interface more difficult. Where sufficient movement of oil products in one direction is required, bulk pipeline transport has proved to be more economical than rail or road transport, even in average terrain and much more so in difficult or mountainous country, and many lines are at present under construction or in the design stage. One interesting case is the 10in Trans-Iranian products pipeline to be built to take Abadan products to Teheran with a first stage capacity of 1,000,000 tons a year and a second stage with extra pumping stations of 2,000,000 tons a year. This line will be more than 600 miles long and will cross difficult mountain ranges at 6200ft elevation, through which at present there are only difficult roads and a single track railway, whose capacities are urgently needed for general traffic. Branch lines will later be added.

During the war, military rather than economic considerations were all-important and even where the quantities of products required to be moved in one direction were relatively small, pipelines of small diameter were laid to avoid the use of packages or bulk road or rail transport and to ensure regular supplies. Indeed, difficulties in ensuring regular supplies by tins, barrels or jerricans, with losses of more than 50 per cent in extreme cases, led to the laying of pipelines to follow as closely as possible the advance of the armies in North Africa and elsewhere in 1941. These were " victaulic " jointed steel lines of 4in, 6in, 8in, and 10in diameter laid on the ground or buried lines with other types of joints. Petrol or diesel engine-driven pumps were installed to boost the oil every 10 or 20 miles or so. The success of these pipelines and the increasing fuel demands of the modern mechanised army led to the requirements stated by Lord Louis

Mountbatten in April, 1942, and referred to the Rt. Hon. Geoffrey Lloyd, Minister of Petroleum, for a cross-Channel petrol pipeline to supply the Allied armies when the re-invasion of the Continent took place. This involved the laying of two types of 3in pipe which would have been completely uneconomic in peacetime, but which eventually supplied 172 million gallons of motor spirit across the Channel with the loss of only 1·1 per cent.

"Operation 'Pluto'" (Pipe Line Under The Ocean) has been fully described in THE ENGINEER (1945) and it will suffice here to say that one type of pipe was of more or less standard submarine telephone cable construction with a lead pipe of 3in internal diameter, wrapped with layers of paper and cotton tape followed by four overlapping layers of steel tape to enable working pressures of 1500 lb per square inch to be used. Then followed layers of jute and of steel armouring wires and of more jute. The steel tapes were wound in right-hand lays and the steel armouring wires in left-hand lays to balance the cable and keep it from moving when pressure was applied. Four merchant ships, two of 10,000 tons, able to handle 100 miles of cable in one length, were fitted with cable storage tanks and cable-laying machinery for laying the main lengths and, six Thames barges were equipped for laying the shore ends. Mechanical joints were designed for coupling the main lengths and shore ends at sea. Cable pipes were laid successfully by ordinary cable laying methods at speeds up to 6 knots and eleven pipes were in operation from Dungeness to Boulogne until well after VE-day.

The other type of pipe was 3in diameter steel tube of 0·22in thickness. Standard 40ft lengths were flash welded together into 4000ft lengths at specially installed plant at Tilbury and stored in racks between the plant and the dockside. These lengths were then welded into one continuous length and neatly wound by holding them back with a 3-ton pull on to a floating drum or Conum, which was rotated to pull the pipe round its 40ft diameter while floating in the water. Six Conums were built and could carry 90 miles of 3in pipe on their 60ft wide drum. They were then towed across the Channel by powerful Ocean Rescue type tugs, while the steel pipe peeled off and sank to the bottom. Difficulties were at first experienced in pulling the steel pipe ashore, but these were avoided by using lengths of flexible cable coupled to the steel pipe for the shore ends. Six of these lines were laid and their time in service exceeded that estimated, having regard to their vulnerability to erosion.

Well-camouflaged compression-ignition-driven reciprocating and electrically-driven pumping stations were installed at Sandown and Shanklin in the Isle of Wight to pump across to Cherbourg, and at Dungeness to pump across to Boulogne. The pipelines were all run in parallel and the pressure was varied from 900 lb per square inch to 1500 lb per square inch, to deliver the quantity of motor spirit ordered each day from headquarters in Brussels. The total available daily capacity was approximately 1,500,000 gallons. These lines had no commercial value after the war and were pulled up to salvage the lead and steel.

It will be seen that there has been great progress in the transportation of oil during the past century and it is certainly true that there are still great opportunities for engineers to develop and improve plant and techniques and so enable the rapidly increasing quantities of oil required to be transported.

Oil Refining

Refining is a combination of physical and chemical operations designed to convert crude oil into a series of fractions or cuts and to treat these raw products chemically to remove any undesirable impurities, such as sulphur compounds and unsaturated hydrocarbons. In the early days separation was achieved by distillation in simple batch stills, which produced a few impure fractions, such as petrol, paraffin and fuel oil. A simple treatment was used to improve the colour and odour and the products were marketed. Demands for better products in ever-increasing quantities led to the development of continuous shell still distillation units and later to pipe stills with fractionating columns. These methods produced straight-run motor spirit up to the limit of that naturally available in the crude. In the 1920s, demands arose for a much improved motor spirit and processes of thermal conversion or cracking were developed. In recent years, further processes called thermal reforming, catalytic cracking, polymerisation, alkylation and isomerisation have been developed. These processes enable the proportions and qualities of the various fractions to be adjusted to market requirements. Vast plants requiring power stations, water pumping plants and services, on the scale of a large provincial town, are required. There is no space here to deal further with this branch of the industry, but some of the products will be referred to later.

Oil Loading

Reference will now be made to loading of oil at the seaboard to sea-going tankers. Until the outbreak of the war, tankers were rarely more than 16,000 tons capacity and required a depth of about 32ft at low water. Since the war the size of tankers has been increased to 32,000 tons or more. They require a minimum depth at low water of 40ft. Where this depth could be obtained in a river close to a suitable site for a loading terminal, light jetties were generally used to carry the oil loading pipes and more substantial dolphins were constructed against which the tankers could be berthed. In the early development of new fields, where river loading facilities were not available, sea loading lines were pulled from the shore, in some cases to a distance of 2 miles or 3 miles, to supply tankers moored at buoys, where the depth of water was sufficient. These loading lines were, until fairly recently, 10in or 12in in diameter but greater experience in laying sea lines has made it possible to use diameters of 20in or 24in with greatly increased throughput.

When an oilfield has been established and greatly increased throughput has to be dealt with, the very great capital cost of constructing a deep-sea jetty becomes justified by the savings that can be made by a quicker turn round of the large modern tankers and the reduction in days lost due to bad weather. In the case of the Kuwait Oil Company, a jetty was built 4200ft out to sea, with accommodation for six tankers and two cargo vessels. This has recently been adapted to take eight tankers and more sea loading lines have been pulled. The jetty has been fitted with gravity type fenders in groups of three, consisting of steel cylinders, 21ft long and 6ft in diameter, filled with concrete and weighing 43 tons. The cylinders were slung by links in such a way that the impact of a tanker when berthing or riding in a choppy sea was absorbed by pushing them back and upwards against the force of gravity. They have been very successful in enabling operations to be continued without damage to tankers or jetty during bad weather. Tanker loading rates of 3000 tons an hour and more are now common practice.

Oil Distribution

The crude oil and products shipped from overseas oilfields and refineries in ocean-going tankers are discharged at ports or special oil terminals where jetties having an adequate depth at low water can be installed, and the oil is pumped out of the tanker by its own pumps to tanks as near the jetty as possible. Thereafter, oil is distributed by pipeline, road or rail tank cars, or by small tankers or barges for coastwise and inland traffic. There is no space in this article to describe the distribution of products to the smaller depots and eventually to the service pump or to the containers.

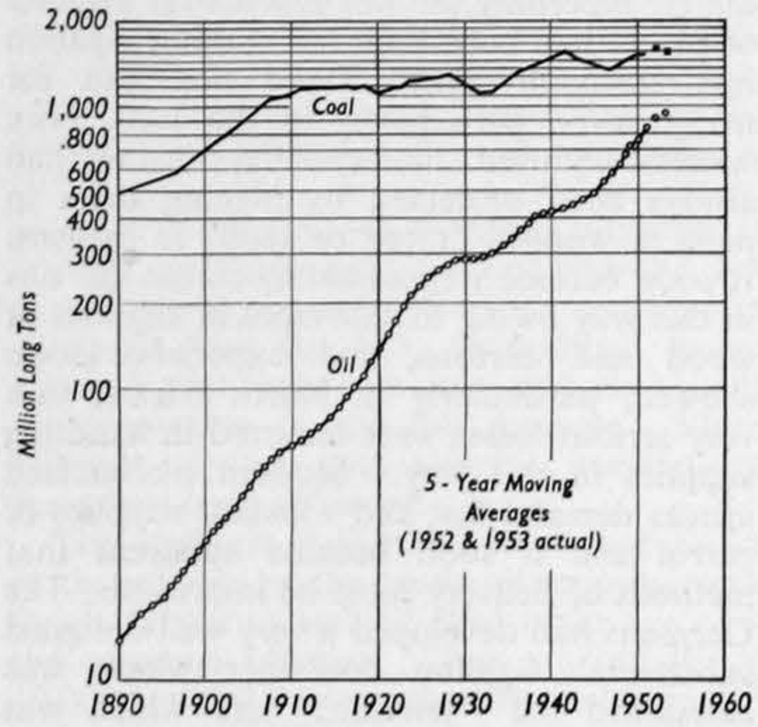
Oil in War

Reference has been made under "Pipelines for Refinery Products" to "Operation 'Pluto'" as a special wartime activity of the oil industry, which was sufficiently developed by 1939 to play a very full part in the war. Perhaps the greatest achievement of the industry was the production of aviation petrol of the quality and in the quantity required to meet the ever-growing demand of the Allied Air Forces. Plans for the distribution of motor spirit and aviation spirit to the Forces had been made in the years immediately preceding the war and a large number of plants had been built for making 4-gallon non-returnable tins. These tins had for many years, particularly in the East, been successfully used commercially, but they had always been protected by placing them in pairs in wooden crates, or singly in cartons. It soon became impossible to clothe the tins in this way owing to shortages in supplies of wood and cartons, and experience soon showed, particularly in North Africa, that very serious losses were incurred in handling supplies in this way. Modern mechanised armies demand fast and constant supplies of petrol and it soon became apparent that methods of delivery must be improved. The Germans had developed a very well-designed substantial 4-gallon container which was christened the "jerrican" and which was used as a returnable container. It had a particularly good filler and pouring cap and was quickly reproduced by the Allies after the first samples had been captured. These replaced the non-returnable tins, which had been christened "flimsies," and reduced losses.

Apart from the normal contribution of the oil industry to the war effort, which enabled official reports after the war to record that "the planning and execution of no single Allied operation was prevented or even delayed by lack of petrol, oil and lubricants where and when wanted," the industry made great contributions in special ways. It was largely responsible for the development of flame weapons, the most effective of which were the "Wasp," made by equipping Bren gun carriers, and the heavier "Crocodile," comprising a Churchill tank towing, by means of a most ingenious mechanical joint, a 6-ton, two-wheel trailer, carrying the special flame thrower fuel. The mechanical joint, in addition to providing for universal freedom of movement, had to transmit the controls and the fuel under high pressure. Two troops of "Crocodiles" landed in Normandy on D-day and they took part in practically every succeeding action, having by the end of August firmly established themselves as battle winners.

On September 26, 1942, the Prime Minister, knowing the heavy losses incurred by the very large number of aircraft

engaged in night bombing operations when attempting to land at home airfields under mist or fog conditions, addressed a personal Minute to the Rt. Hon. Geoffrey Lloyd, the Minister of Petroleum, phrased as follows :— " It is of great importance to find means to dissipate fog at aerodromes so that aircraft can land safely. Let full experiments to this end be put in hand by the Petroleum Warfare Department with all expedition. They should be given every support." A team, largely drawn from the oil industry, studied reports of all previous attempts to clear fog and decided that the best approach to the problem was to develop means for generating heat along each side of the runway, sufficient to raise the temperature of foggy air by 7 deg. Fah., when experiments had shown that crystal clear visibility would result. Eventually, burners were designed which, when placed in two parallel continuous lines, 50 yards on each side of the normal 50-yard runway, would burn 20 gallons of petrol each yard each hour when supplied by converted N.F.S. fire pumps at 100 lb per square inch. It was soon proved that these would clear the densest fog, whether stagnant or drifting, This operation became known as " Operation ' Fido ' " and was fully described in THE ENGINEER (1945). Seventeen airfields were equipped in England and France



World coal and crude oil production in tons of hard coal equivalent. (1 ton oil assumed equal to 1·5 tons coal)

and assisted the landing of 2500 bombers under misty or complete fog conditions. " Fido's " greatest achievement was to enable Bomber Command to keep up its attack at the time of the Ardennes offensive in December, 1944, when almost the whole of its airfields were covered with fog for several days.

GROWTH OF THE INDUSTRY DURING THE PAST SIXTY YEARS

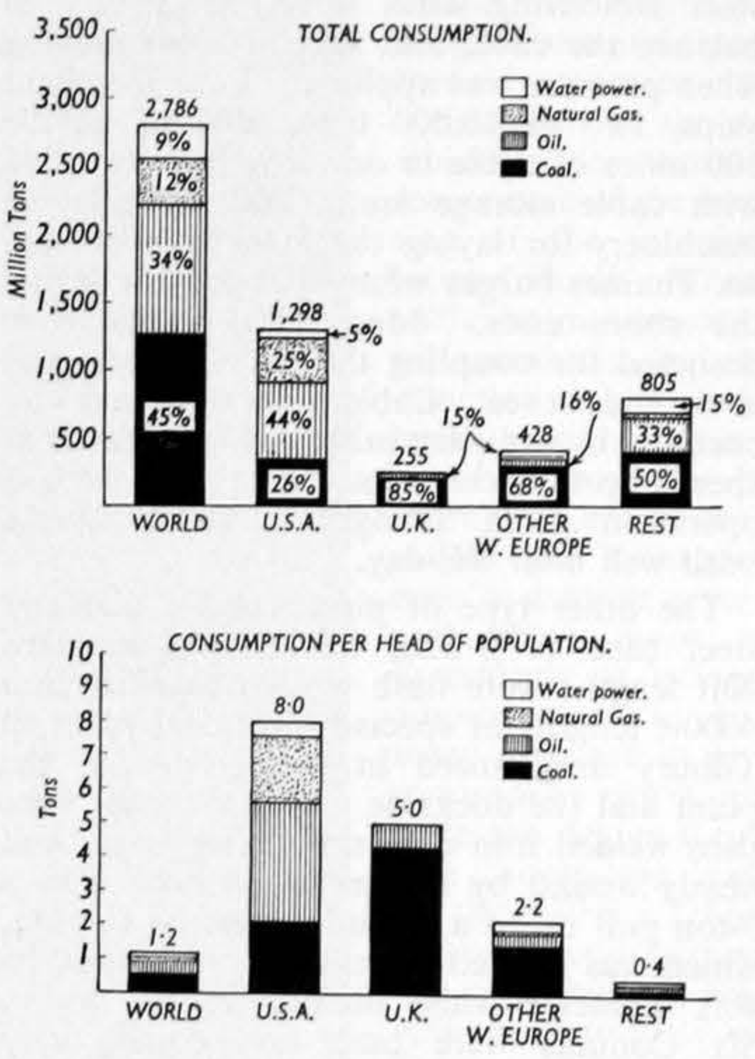
As has already been stated, the main market in the earliest days of the oil industry was for lighting oil or kerosene and though the widest possible fraction of crude was used, the refiner was often obliged to burn off surplus light spirit for which he could find no outlet. This was the position until about sixty years ago, when the internal combustion engine was first used to any considerable extent and so created a market for the surplus light spirit. During this period (see the diagram above) oil consumption has grown from 8,000,000 tons a year to 650 million tons a year, that is more than eighty times, fairly reflecting how the availability of liquid fuels stimulated engineers to make advances in the design of oil and petrol engines. During the same period, coal consumption has increased from 500 million tons a year to 1700 million tons a year, an increase of a little more than three times. Put in another way, the average growth in the use of oil has been $6\frac{3}{4}$ per cent per annum and of coal only 2 per cent per annum.

PRESENT POSITION OF THE OIL INDUSTRY

The early history and some of the developments during the past century have now been described, and it is interesting to consider the present position of the industry and see what contribution it is making, although not yet 100 years old, to the world energy supply, remembering that the material welfare of the world is a direct function of the use of non-animal energy. Another diagram on this page shows the world energy consumption, excluding U.S.S.R. and associates, in 1954, expressed as long tons of hard coal equivalent in the form of total consumption and consumption per head of the population. When considering these figures, it should be remembered that 1 ton of oil is equivalent in heat value to roughly $1\frac{1}{2}$ tons of coal, and in terms of heat value of coal, the total world energy consumption was more than 3000 million tons. Of these, coal represented 50 per cent and petroleum in the form of oil 32 per cent and in the form of natural gas, 10 per cent, making 42 per cent altogether, and leaving water power providing 8 per cent. It will also be seen that energy consumption *per capita* (coal equivalent) was 8 tons in the U.S.A., 5 tons in the U.K., and 0·8 ton for all other parts of the world taken together. This remarkable growth of the use of oil has hardly ever been due to its price because on a British Thermal Unit basis, it is almost always more costly than coal. The growth in the use of oil is due to the fact that the industry has always been prepared to spend large sums of money in research and development into new processes in order to provide products best suited for each individual use. This is in direct contrast to the policy of the coal industry, which with very rare exceptions, has continued to sell what is essentially a raw material. The diagram overleaf, " Main Products of Petroleum and Their Uses," shows approximately to scale the main products now obtained from crude oil and the order in which they are produced from the crude. Starting with the lightest products at the top, it also differentiates between products used for transport and those used for other purposes. It is interesting to see that contrary to popular belief, only a little more than half the total—even including ships' bunkers—is used for transport. It can well be appreciated from this diagram how much the advancement of engineering during the last fifty years has been influenced and, indeed, directed by the availability of oil.

Modern methods have enabled the kerosene, previously used almost entirely for lighting, now to contribute largely to the production of aviation turbine fuel, vaporising oil for agricultural tractors and, to some extent, to the special boiling point spirit, such as white spirit, used in the paint industry for solvents and dry cleaning, and more recently for feed stock for petroleum chemicals. The light spirits previously burnt produce the motor spirit used in all petrol engines. The gas produced from straight distillation of the crude is now synthesised and blended with cracked spirit produced by residue cracking processes to provide the aviation spirit required for civil and military piston-engined aircraft. A large market has more recently been developed for using propane and butane as bottled gas for use in caravans, boats, and elsewhere, when a piped gas supply is not available. It is also used for the cutting of steel.

The next heavier fraction to kerosene is gas oil, and this produces fuel for the diesel engines used on rail and road, and for marine and stationary purposes. Very recently it has been used by the coal-gas industry for the enrichment and augmentation of gas produced from coal. The straight run residue remaining from the distillation of gas oil, kerosene and light spirit from the crude has long been used as fuel for ships, both naval and mercantile, and is finding an increasing use in stationary power plants, steel furnaces, industrial heating plants and other such uses. The residue oil has also been processed for producing lubricating oil and, in recent years, gas oil, paraffin wax, lubricating oils and bitumen have all been produced from the fuel oil by vacuum distillation processes. The gas oil so produced augments supplies of straight run gas oil and the paraffin wax has long been used for candles and more recently for waxed papers for electrical insulation and many other uses. Bitumen (asphalt) has long been



World energy consumption excluding U.S.S.R. and associates, 1954, expressed as long tons of hard coal equivalent

used for road-making and repairing and for water-proofing. Very much work has been done in producing grades of bitumen best suited for the climatic conditions under which they are to be used and they have played a vital part in the development of highway systems.

It was stated at the beginning of this article that oil has played an essential part in the development of all the engineering discoveries described in this section of the Centenary Number and sufficient has probably now been written about the development of the oil industry and its present position to make this statement readily believed. Without the oil industry it would have been impossible to develop the internal combustion engines now so widely used, and road transport and aviation as we know it to-day would have been impossible. Internal combustion engines have made possible the development of civil engineering contractors' plant such as bulldozers, graders, &c., and these have now made it possible to construct main highways straight across country and enable road systems which had previously been built around hills and valleys to be straightened so as to cater for the ever growing demands of road transport.

It has been seen that oil is a very large

scale industry, embracing a great range of activities : the finding, production and transportation of the crude oil, refining it and manufacturing a wide and ever growing range of finished products, transporting these by land and sea and delivering them to the consumer or retailer everywhere. In carrying out these activities, it also has to carry out road making, housing and ancillary services ; to provide health and medical services, to encourage education and to co-operate with local governments.

Its research programme is helping in the development of the petroleum chemical industry, which produces solvents, detergents, plastics and synthetic fibres, synthetic rubber, agricultural chemicals, glycerine and many other products, for example, disinfectants, anti-freeze compounds and a whole range of pharmaceutical products.

A word or two on the world oil reserves behind this great and expanding industry may be of interest. The proven oil reserves of the world were estimated to be about 21,500 million tons at the beginning of 1955, an increase of 3200 million tons over that at the beginning of 1954 in spite of a production of 700 million tons during that year. The Middle East is credited with more than 60 per cent of these reserves. Calculations of proven reserves are based on available technical data and refer only to oil that can be economically obtained from wells by existing production methods. There are in addition possible reserves based upon reasonable conjecture and which may be produced by deeper drilling (the deepest producing well in 1953 was 17,892ft). These might amount to 40,000 million tons. The world's oil reserves are still large, but like all mineral products are wasting assets. The oil industry is paying much attention to developing the further reserves of natural gas, oil shales, tar sand and oil from coal by hydrogenation or the Fischer-Tropsch (synthesis) process.

Oil and Other Industries

Oil is very closely linked with many other industries, notably with steel. The almost uninterrupted increase in the output of Britain's steel industry ever since the war has been in no small measure due to the greater use of oil fuel. The oil industry, being one of the largest users of steel for its tankers, pipelines and oil equipment of all kinds, has been one of the chief beneficiaries of the larger supplies that have become available and has used them to increase its output of oil. The steel industry is becoming an increasing user of oil for oil fuel in smelting, metal melting, welding and bending and forging of steel bars because of the close control that can be obtained by automatic means on temperature, the freedom from ash and the greater output of better quality work which results. The steel industry also uses petroleum for cutting and quenching purposes.

Oil has played a great part in the development of agriculture by making mechanisation possible. Before the 1914-18 war, very few tractors were available, but by the early 1920s, their number had increased rapidly, particularly in the U.S.A. where there were half a million by 1925. At the outbreak of the second world war, there were 2,500,000 tractors in use throughout the world and by 1952 about 7,000,000. Oil alone has made possible the light general purpose tractor which has done so much to speed up production and eliminate much of the toil previously associated with agricultural practice. In addition to drawing an untiring plough capable of working round the clock if necessary, it will load manure, distribute fertilisers, pull trailers and harrows and use some sixty interchangeable implements for planting, mowing, sowing, post-hole drilling, &c. With a power take-off, it is transformed from a mobile to a stationary power unit.

Petroleum also assists agriculture by providing improved insecticides and pesticides by providing kerosene and other light oils as carriers instead of water for toxic substances and so making possible a much greater spread and ensuring an even quantity being distributed more effectively over a wider area. Petroleum is also used for weed killers, soil conditioners and for veterinary uses, where it has contributed largely to animal health. It is estimated that about 8 per cent of this country's consumption of oil products, is used for agricultural purposes.

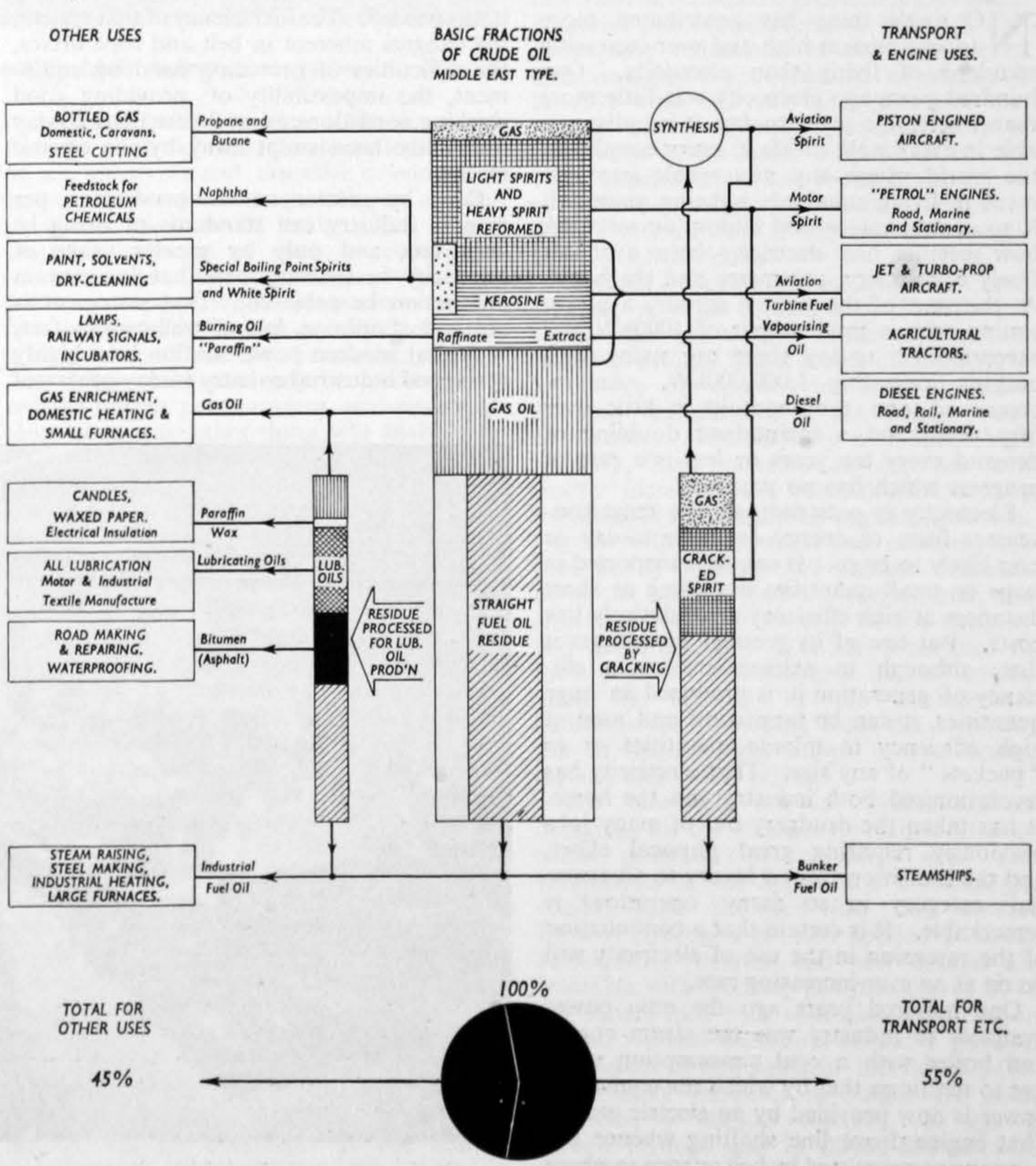
Lubrication

But petroleum's most important contribution to industry is the provision of probably 90 per cent of the whole of the lubricants, without which not only all the motor-cars, aeroplanes, ships and tractors driven by oil fuel, but also all the steam engines, electric trains and coal-fired vessels, would stop. Without oil to lubricate its machines hardly a single industry, however small, could survive and the industrial world would cease to exist.

A hundred years ago the only lubricants available were of animal or vegetable origin and were called fixed or fatty oils because they could not be distilled. These oils were excellent lubricants when used by the methods then adopted of pouring on the bearings in what was called the " all loss " manner—that is, once only through the bearings. Owing to their tendency to combine with oxygen and to undergo internal changes at higher temperatures, they could not be used under present-day conditions, which demand efficiency and economy. They have, however, the great advantage of adhering to metals and forming durable adsorbed layers. Vegetable oils have a drying tendency, which, particularly in the case of linseed oil, makes it valuable for making paints, but bad for lubrication, and the animal oils become rancid, objectionable to handle and active on certain of the metals in general engineering use. Castor oil, rape oil and many other vegetable oils were available. Lard, whale sperm and neat's-foot oil were typical of the oils of animal origin which had proved valuable as lubricants.

The petroleum industry provides a source of mineral oils having very good lubricating properties and the advantage over the fixed oils of being stable and resisting oxidisation both at normal and elevated temperatures. They are also chemically inert to all the metals used in engineering construction and can experience many cycles of heating and cooling without change of essential lubricating properties. They have the great advantage of being able to be blended and their characteristics adjusted in the manufacturing processes to provide oil suitable for lubricating the finest instruments or the heaviest engineering plant. The availability of improved lubricants has made it possible to design engine gears and many forms of machinery with heavier bearing loads, thus enabling space and weight to be saved and so gaining great advantages in road, rail, marine and aircraft propelling machinery.

It was early discovered that 5 or 10 per



The main products from petroleum and their uses

cent of the fixed vegetable oils could be blended with mineral oils so as to increase their adsorption. Probably the best early example was the combining of rape oil with mineral oil for the lubrication of main line steam locomotives. This has led to the development of a whole series of additives to mineral oils in order to provide the most suitable oil for any particular purpose. Additives have been used to develop oils with " extreme pressure characteristics," which are called E.P. oils. These oils have enabled gears to work satisfactorily with greatly increased pressures between the teeth.

In conclusion, the essential part that the oil industry has come to play during the past century in the life of an industrial nation such as Britain may be summarised as follows :—

It provides petrol and diesel oil for more than 4,500,000 cars, vans and other vehicles for carriage of passengers and goods.

It provides fuel for every aeroplane, naval vessel and the vast majority of the merchant fleet.

It provides fuel for the increased food production achieved in recent years.

It provides oil fuel for the steel, pottery, glass and ceramic industries and improves the quality and output of their products.

It helps the gas and electricity industries to increase their outputs.

It provides lubricating oil for 90 per cent of the world's requirements.

Oil is now helping industrial life by producing literally hundreds of petroleum derivatives used in processing and manufacturing products as diverse as insecticides, synthetic detergents and also fibres, plastics, rubber, paint and artificial silks.

The oil industry has spent, since 1947, about £200,000,000 in new equipment in Britain at refineries like Fawley, Grangemouth, Isle of Grain, Llandarcy, Shellhaven, Stanlow, &c., and has increased the refining capacity from 2,500,000 tons a year to some 28,000,000 tons a year, and has thus made Britain the most important refining centre in Western Europe.

During the first quarter of this year British engineering firms received orders for oil equipment and materials valued at £32,773,500, an increase of 40 per cent on the comparable orders for the previous quarter.

British chemical firms also benefited from oil company orders to a total of £8,704,900.

The oil industry has reached its centenary well prepared while meeting all the normally increasing demands for its products, to take over some of the burden of the coal and gas industries until nuclear power brings relief.

The author wishes to acknowledge the help he has received from his former colleagues and to thank them for their assistance in preparing this article.

Electricity

By SIR CLAUDE GIBB, C.B.E., D.Sc., F.R.S.*

NO single thing has contributed more to our present high and ever-increasing standard of living than electricity. One hundred years ago electricity was little more than a scientific toy ; to-day, it is indispensable in every walk of life in every country of the world where any measurable improvement in living standards is being made. It is so commonplace that seldom do we think how recently has electricity been available freely to industry, commerce and the home. At the start of the present century a power station with a total output of 1000kW was exceptional ; to-day there are many with outputs exceeding 1,000,000kW. An increase of one thousandfold in little over fifty years and a maintained doubling of demand every ten years or less is a rate of progress which has no parallel !

Electricity is outstandingly the most convenient form of energy available to-day or ever likely to be so. It can be transported in large or small quantities over long or short distances at high efficiency and relatively low costs. But one of its greatest advantages is that, although to achieve maximum efficiency of generation it is produced in huge quantities, it can be tapped off and used at high efficiency in minute quantities or in " packets " of any size. Thus electricity has revolutionised both industry and the home. It has taken the drudgery out of many jobs previously requiring great physical effort, and the transition from a luxury to an essential category in so many operations is remarkable. It is certain that a continuation of the extension in the use of electricity will go on at an ever-increasing rate.

One hundred years ago the only power available to industry was the steam engine and boiler with a coal consumption some five to ten times that by which the equivalent power is now provided by an electric motor. That engine drove line shafting whence the power was transmitted by belt or rope to where it was needed. The inefficiency of that system, the dangers inherent in belt and rope drives, the difficulties of providing handling equipment, the impossibility of providing good working conditions as we know them to-day —all have been swept away by the electric motor.

Only by greater annual production per man in industry can standards of living be improved, and only by greater usage of electricity in industry can that increase in production be achieved. That statement is not one of opinion, but of well-proven fact. A typical modern power station in a highly developed industrial country to-day generates power equivalent to half a million kilowatts or more and utilises the coal, which often is of poor quality, with an efficiency of 30 per cent or better. It is not often realised that present-day power station boilers can be and are designed to burn coal of such high ash content that otherwise it is almost unsaleable. The extending use of electricity underground in coal mines for coal cutting and conveying has resulted in a greater proportion of small coal of high ash content, and reduced the amount of good-quality coal available for home and factory and in turn led to a marked increase in the electricity demand.

Electricity in Home and Factory

An improvement in human living standards is effected in several ways. The elimination or reduction of drudgery in the factory and home is one way, but an improvement in comfort standard in the home is always of great importance. This latter invariably means a general raising of background temperature in cold weather in temperate climates, and a reduction of temperature and humidity in the tropics. In the tropical home it is only with the advent of electricity that air conditioning has become readily possible. Living and sleeping rooms may be kept comfortably below the normal outside temperature by cooling the incoming air with refrigerating plant, which at the same time reduces humidity. The household food and drink may also be kept at a low enough temperature to keep it safe for consumption. Many millions of refrigerators have been installed in all parts of the world for this essential service. (Even in Greenland food has to be kept warm enough by refrigeration !) All this equipment has played no small part in Colonial and Empire development. It required electricity where none existed and with the coming of power stations industrial development became possible.

Electricity has made possible the more extended use of electricity. Without the extensive use of electricity in the factory mass production and therefore low-cost production would not have been possible. Without it vacuum cleaners, washing machines and the scores of other adjuncts to a high standard of living could not be produced at prices which the average man could afford. Mass production reduces costs not

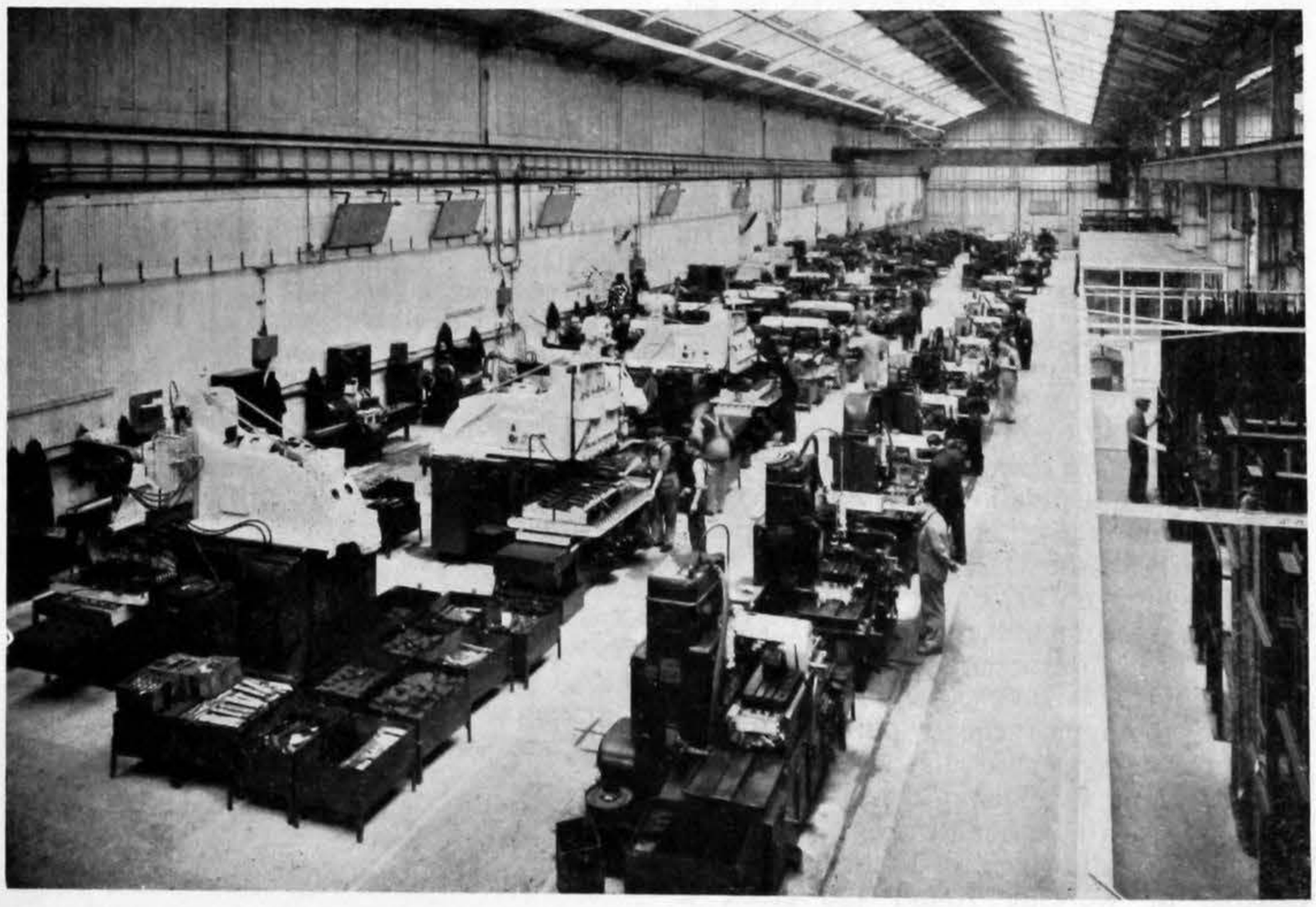


Fig. 1—Modern machine shop with individual motor drives to the machine tools

* Chairman and Managing Director, C. A. Parsons and Co., Ltd.

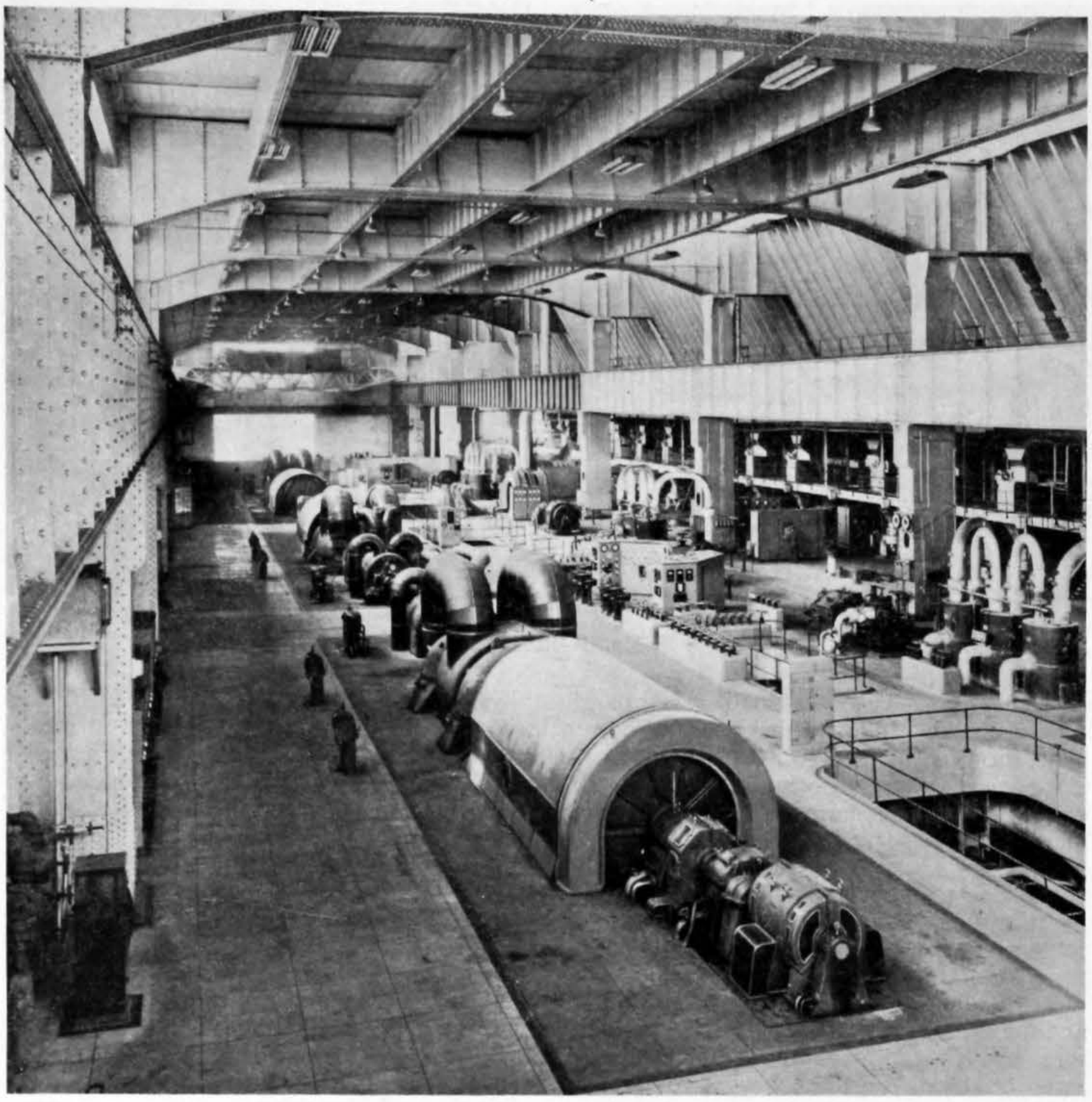


Fig. 2—The turbine hall of a typical Central Electricity Authority power station

so much because of materials saving, but by drastic reduction of labour costs. Handling charges add nothing to the value of a product, but may add considerably to its cost ; hence automatic movement between operations and during assembly can be important in eliminating or reducing an item of cost which is of no value to the product. Individual electric motor drives to presses, machine tools (Fig. 1), winding machines and other tools which replace hand work have speeded up production by building more power into each operation, whether for material removal as in machining, for multiple instead of individual stamping and, in textile and papermaking, for higher speeds. But primarily the change from belt to motor drive, 'with its faster production' demanded and enabled conveyor movement of raw materials, component parts, swarf, and finally the finished and tested product. These first reductions in manufacturing costs stimulated sales, increased demand and enabled further economies to be made by the bigger output justifying more extensive tooling of plant, the introduction of automatic or special-purpose machines leading eventually to " automation."

Automation

Very large numbers of a particular component or product are required before the high capital cost of a special installation can be justified, and the design of the product must have been fully developed and stabilised. But when those conditions hold, it is possible so to design and plan the production of a complicated component or even complete article that practically no human hands touch the product other than to feed from raw material stores to the beginning of the production flow line and from the end of it to the despatch vehicles. " Programmed factory control," or " automation " will be an inevitable and essential development in many industries consequent upon an ever increasing standard of living. This is not the place to begin an essay on elementary economics, yet there are so many who even yet do not accept the simple yet inescapable fact that the only way for everybody to have a bigger slice of cake is to have a larger cake. That larger cake can only be made by increased output per man-year, and electricity more than any other thing will make that increased output possible.

To prepare for automation and the increased standard of living we all desire so ardently to see and have, there must be a drastic change in our approach to education. Automation means more scientists, more engineers, more skilled tool and machine designers and makers and less unskilled labour ; these all add up to a higher standard of general and technical education. The openings in industry for technically trained men are several times the available supply today and unless the supply can be increased rapidly that position will worsen, and improvements in living standards be delayed.

Electricity and the Standard of Living

When will Governments and people generally realise that the niceties of life—in other words an improved standard of living—can only be paid for out of production and still more production ? Increased output per man-year is the basis of any reduction in working hours with more money to spend on greater leisure time. And it is through electricity that the maximum increase in output will be obtained. If the annual consumption of electricity, per head of population in a dozen countries is tabulated and compared with the standard of living in those countries, it will be found to agree except in a few cases where a particular country has some especial advantage in natural resources. Electricity consumption per head of population is a measure of living standards not only between countries but between individual families in any country. These facts are so plain to anyone who has made a study of them, that they find it difficult to understand those who are not wholeheartedly in favour of extending the use of electricity in the factory, in the home and in every walk of life. Governments, executives, managers, workmen, housewives —all must realise the vital part which electricity will and must play in our life.

Turbo-Generators

The growth in the use of electricity has brought many problems to the designers of electricity generating plant and that wide field of associated equipment concerned with its control, transmission and utilisation. The steam raising equipment in modern thermal power stations with pressures exceeding 1000 lb per square inch and temperatures of 1000 deg. Fah. or more have demanded of metallurgists and forgemasters larger and thicker walled steam drums produced under carefully controlled conditions with rigid inspection at every stage. Superheater tubes and steam piping in alloy steels, turbine casings of double walls and considerable complexity have all called for the utmost ingenuity of engineers in design, manufacture and operation. Larger and larger turbo-generators (Fig. 2) have been required and this trend has enabled higher and higher steam pressures and temperatures to be used, with consequent reductions in the amount of coal consumed to produce a unit of electricity. In 1884 when the first turbo-generator was built a unit of electricity required 22 lb of coal burnt in the boiler to produce it. By 1900, improvements had reduced that figure to 3 lb, but today, appreciably less than 1 lb of inferior coal is required to produce one unit of electricity.

Turbines of an output of 200,000kW and utilising a steam pressure of 2350 lb per square inch are already under construction in Great Britain, whilst a unit of 275,000kW at 5000 lb per square inch steam pressure is being manufactured in the United States of America. The majority of modern high pressure, high temperature turbines still further increase their thermal efficiency by reheating of the steam after partial expansion. Further improvements in fuel economy are possible by making still further demands upon the metallurgist, the forgemaster, the steel founder, and the skill of the designer and manufacturer. Yet the economics of these possible improvements depend largely upon the amount of the considerable additional cost resulting from the extensive use of special steel alloys in the boiler, turbine and steam piping.

The increased size of prime movers demands, for the efficient generation of electricity, generators of equivalent size. Developments in the application of hydrogen cooling have provided just this answer. Initially hydrogen gas was applied at about atmospheric pressure and now designs are available with working gas pressure of 30 lb per square inch with appreciable increase in output without exceeding tolerable physical dimensions and weights of individual parts. Still further increases in output are made possible by designs whereby the gas is passed through and in direct contact with the rotor and stator conductors—designs which are designated " inner cooled." These

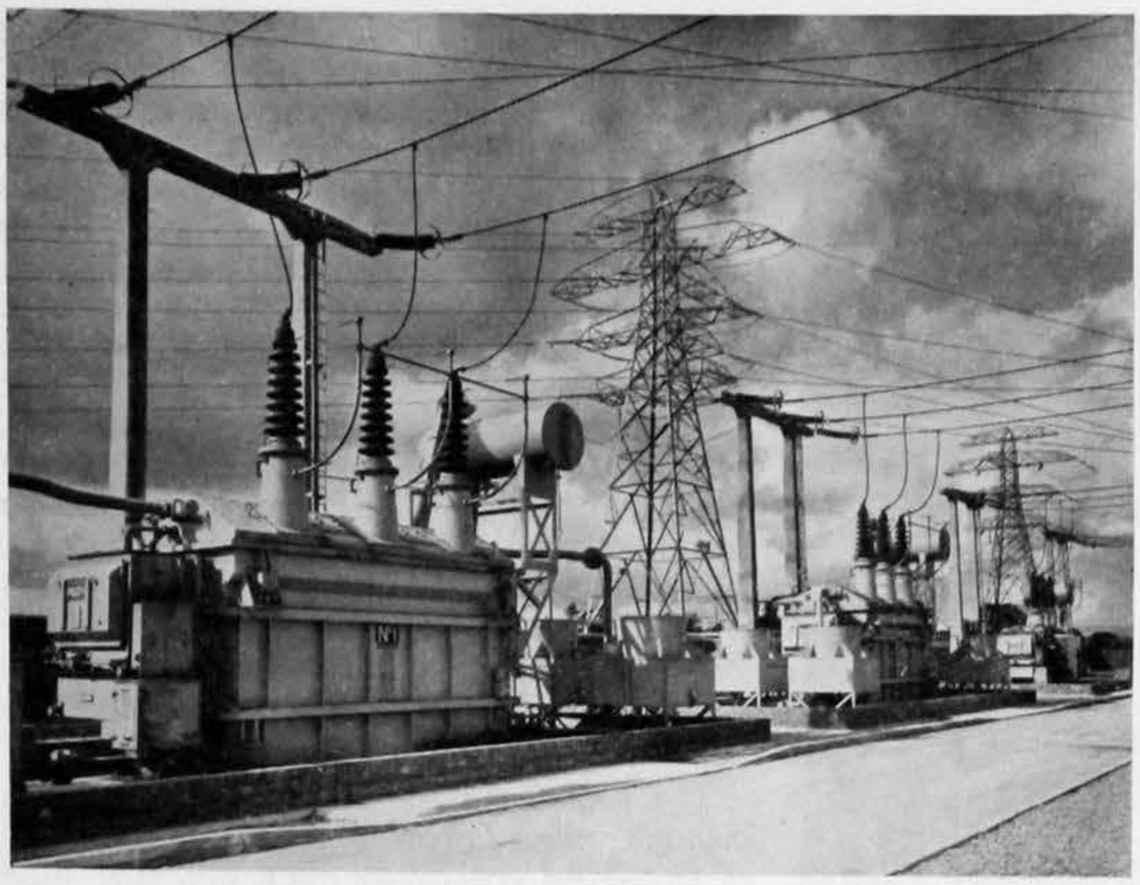


Fig. 3—Generator transformers at a Central Electricity Authority power station

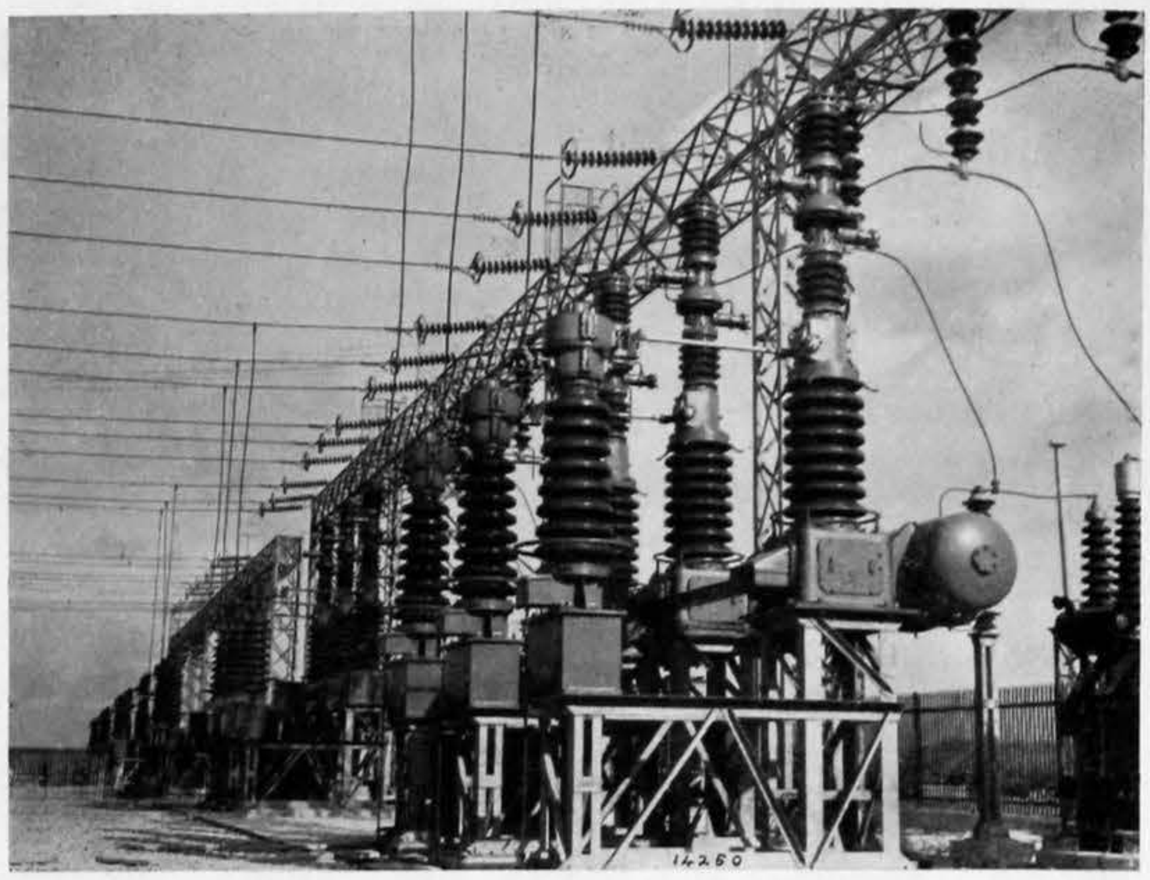


Fig. 4—132kV, 2500MVA air-blast switchgear

latest developments in generator construction have raised the output of single machines to well over 200,000kW.

Power Transmission

In parallel with advances in power plant there has been considerable and no less spectacular progress in the field of power transmission. Electricity in an alternating current form can be conveniently transformed and transmitted at voltages suited to the amount of power involved. The well-known " grid scheme " is an example of this facility, and when launched in 1927 its primary objective was to interconnect at 132,000V major power stations to ensure security of supply with a minimum of spare generating plant. The war years showed clearly the benefit of this scheme of interconnection when the continuity of electricity supply was outstanding. The spare generating capacity was of the order of 70 per cent of an installed capacity at the inception of the grid ; this figure was reduced to less than 25 per cent after a few years' complete operation.

The rapid expansion of the electricity supply industry after the war with its high maximum demand and much larger capacity power stations made further extensions in the existing 132,000V grid both difficult and costly. At this stage a decision to build a Supergrid was taken and to-day the countryside is linked by main trunk overhead lines capable of transmitting blocks of power of the order of 500,000kW at 275,000V. The commissioning of the Supergrid will take several years to complete, and when this is achieved the supply industry in this country will have the largest interconnected system in the world to supply the needs of industry, commerce and the home. The benefits which accrue from a large national project such as the Supergrid are many and widespread. Primarily the additional interconnected trunk lines will give a greater margin of security and will substantially reduce the spare capacity of capital plant. It will also enable the supply authority to use the most efficient power stations to supply the electricity demand.

The cost of coal at a power station varies widely with its location, and the low costs of bulk transmission of power at 275,000V will lead to a reduction in the amount of coal moved by rail, since it can be shown that it is more economical to transmit electricity if the rail haulage distance exceeds about 50 miles. It would be expected that as a general policy more and more very large power stations will be built near coalfields, their output being transmitted to the load areas through the Supergrid. In fact, this pattern of power generation, if pursued, will eventually make it an economical proposition to construct even higher-voltage lines—380,000V has been mentioned—to serve as the main trunk transmission for large blocks of power from the coalfields to the load centres. British manufacturers have expanded their factories to supply the necessary equipment—overhead lines, switchgear and transformers—to meet the demand for 275,000V transmission, and the experience gained in design, manufacture and operation is proving a valuable asset in undertaking similar work for export.

Transformers

The growth of electricity supply has naturally brought a demand for larger three-phase transformers at extra-high voltages (Fig. 3). Apart from the insulation techniques which have been developed to keep pace with increasing voltages, the major problem in obtaining high outputs is the physical size and weight of a three-phase transformer, which is probably the largest indivisable load met in electrical engineering. The improvement in the magnetic performance in electrical sheet steels has enabled the design engineer to work at higher flux densities with consequent reduction in the core weight and physical size for a given transformer. Reduction in overall weight by advances in mechanical design of clamping structures and tank fabrications have also contributed. The limitation in the weight which can be handled by railways and roads is now reached, but fortunately this will not prove a deterrent to the larger sizes of power station plant, since it is possible, at increased cost, to divide the transformers into separate single-phase units. The present pattern of worldwide developments in bulk transmission of power at extra-high voltages shows clearly that in this field no retarding influence may be expected in the natural progress and exploitation of electricity.

Transport

It is paradoxical, in such an industrial-minded country as Britain, that electricity makes such a minor contribution to transportation. It is, of course, true that the movement of suburban traffic in highly populated areas would be impossible without electrification but it is only in these areas that electricity is playing any appreciable part. Main line electrification is long overdue and recent forward plans for major reconstruction of the British Railway system, including main line electric traction, are very welcome. Out-dated steam locomotives

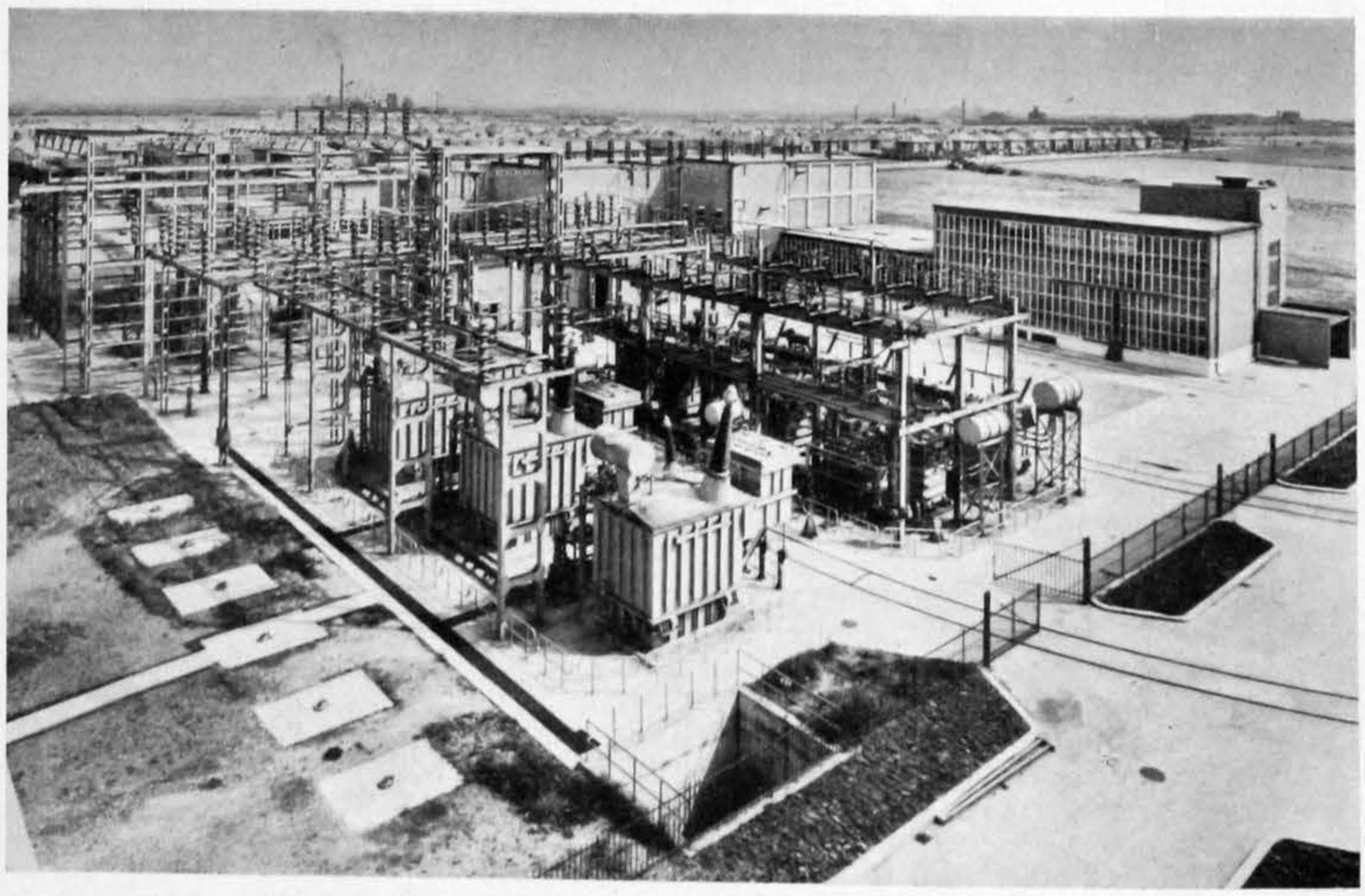


Fig. 5—Short-circuit testing station for proof testing switchgear

consume about 10,000,000 to 14,000,000 tons of coal each year with a fraction of the efficiency of a modern power station. The application of electricity to the railways will release annually a considerable bulk of good quality coal. Apart from the obvious benefits which will accrue from the reduction in smoke and grime at present an inherent by-product of the railways, electrification will provide an improved service of fast, comfortable trains with operating crew quarters more in line with the best modern factory conditions. Enormous capital expenditure is involved in main line electrification which cannot be obtained from the revenue from the present system. Nevertheless, in other countries railway electrification has been a financial success and there appears little doubt that a comprehensive scheme could be developed into a sound investment.

The technical problems involved in the application of electricity to railway electrification are highly controversial subjects. Whether electrification should go ahead with 1500V or 3000V d.c. overhead systems with the rectifier substations located at intervals along the rails, or whether high-voltage, single-phase a.c. systems should be used whereby the rectifier equipment is transferred to each locomotive and the whole supply to the railway is given at power frequency from orthodox a.c. substations, are some of the technical aspects which must have consideration. Whatever form of supply is adopted electricity will provide the main motive power, probably supplemented by gas turbine driven locomotives for special duties.

Heating

Where an industrial process requires a form of heat which can be quickly applied and precisely controlled, electricity is the answer. The use of electricity for industrial heating is now becoming widespread. In non-ferrous and the steel industries more and more use is being made of this form of heat. Arc furnaces for melting steel scrap with an electrical input of 15,000kVA to 20,000kVA are now commonplace, and special steels for the tool-making industry are invariably produced in high-frequency induction furnaces. The advantages of electricity in such industrial applications are broadly twofold. It enables processes to be monitored under controlled conditions and invariably shows in the finished product an overall saving in fuel cost. Electricity is now being employed for heating non-metallic materials by dielectric loss generated within the material by the application of a suitable high-frequency voltage. This process is finding many applications in the plywood and veneer industries.

For domestic purposes electricity forms a safe and convenient way of supplying heat at the time required. In this field, however, the growth of electricity is not as spectacular and there is still controversy on the most efficient method of providing heat for domestic purposes. If the problem of atmospheric pollution is to be solved within a measurable time there is little doubt that solid fuel appliances in the home must disappear. With more abundant electricity available this tendency might well become a national policy whereby solid fuel is consumed under controlled conditions in large power stations and the domestic heating load is taken over largely by the application of electricity.

One form of heating which is making progress is the use of electricity for space heating in commercial buildings. The obvious advantage of thermal storage methods if an attractive night tariff is available will lead to considerable expansion in this field. The capital expenditure involved in the application of thermal storage heating to domestic properties is a deterrent which is being reduced by underfloor or embedded heating cables and is growing in favour rapidly for new buildings.

Lighting

Electricity reigns supreme in the field of lighting whether it be in the home or in industry or on the highways. People are becoming more and more light-conscious, demanding at work and during their leisure hours the bright cheerful conditions made possible by electricity. Industry now appreciates the advantages to be gained in applying modern tubular fluorescent lamps. The capital outlay on fluorescent lighting schemes is usually greater than other sources, such as tungsten, but the increased life of the fluorescent lamps and their appreciably greater light output makes their application an overall economic proposition. Cold-cathode fluorescent lamps have even better characteristics than the more orthodox hot-cathode type, but the former may, on account of the high discharge voltage used, initially cost more to install. In road and street lighting, applications of high-pressure mercury and yellow sodium discharge lamps still remain the major sources of illumination on main thoroughfares. Much research work has been done to establish the relative merits of these two forms of lighting.

Agriculture

One outstanding contribution made possible by the integrated British supply industry under nationalisation is the ever expanding supplies of electricity now available to agriculture. Electricity is doing much to arrest the drift of population from rural to urban areas by providing in the countryside amenities enjoyed by the town dweller. Again electricity is, in its various applications to farm work, assisting food production to reach the desired level of productivity. Annually, the expansion of the electricity industry is permitting the connection of about 10,000 farms to public supplies in addition to a much greater number of rural houses. Under these conditions, farmers are enabled to take advantage of many labour-saving devices which allow them to direct their labour force to more essential tasks in the farm or the fields. It has been estimated that the present number of farms supplied by electricity from power systems is just less than half the total in Britain, so that future expansion in the use of electricity in this field is ensured for some years. It should be remembered, however, that as more and more supplies are made available, the remainder are becoming more difficult and more costly to connect, and it is here that much research and ingenuity is being applied to reduce the capital cost of such remote connections.

Control Equipment

Control equipment for the great blocks of electricity now in common use must be capable of interrupting supply in six hundredths of a second if safety of generating plant is to be assured, Figs. 4 and 5. The development of circuit breakers capable of doing this is a story in itself. To improve the capabilities of circuit breakers under system fault conditions, huge testing stations have had to be designed and built. The electricity industry has been outstanding in all industries in the application of science in fundamental research and in the incorporation of research results into current designs and manufacturing techniques. Advanced nations have installed research and development tools, in some instances costing over £1,000,000, to further the extension of electricity in the service of man. These tools, and the equipment they evolve, call for more and more scientists, engineers and craftsmen of greater skill. They call for a change in the emphasis of education, for a change in our whole approach to living. Without the skill of the engineer, the greater use of electricity with its consequent improvement in living standards must be delayed.

Electricity as the servant and helpmate of man has contributed more to human comforts than any other factor during the century through which THE ENGINEER has been published. In the next century its contribution will be even greater, whether it be generated by water power, coal or oil or, as is most likely, by the heat produced by nuclear fission. THE ENGINEER will report faithfully its progress and in so doing report the progress of the human race.

Nuclear Power

By SIR CHRISTOPHER HINTON, F.R.S., M.A., M.I.C.E., M.I.Mech.E., M.I.Chem.E.*

DEVELOPMENTS in nuclear physics reached a climax early in 1939 with the discovery of nuclear fission, and in so doing threw out a challenge to the engineer, the extent of which even now, sixteen years later, it is difficult to gauge. During the early years of the century there had been a steady accumulation of knowledge about the atom, about radioactivity and the relationship between mass and energy. There had been speculation as to whether a method could be found of releasing the large amounts of energy locked up in the atomic nucleus ; but, despite success in bringing about nuclear reactions by the bombardment of nuclei with accelerated charged particles, the chances of causing such reactions were so slight that more energy was used up accelerating the particles than was obtained from any reactions thus produced.

Then came the discovery that a thermal neutron could induce fission of the uranium atom with the release of approximately 10^{10} times as much energy as that possessed by the incident neutron, and also, of great importance, the reaction was accompanied by the ejection of further neutrons. This at once offered the possibility of producing a self-sustained chain reaction in which the neutrons ejected from one fission process might be induced to cause further fissions and so on, all this accompanied by the release of tremendous amounts of energy in the form of heat. It was evident that if, from each fission of a nucleus, on average more than one of the neutrons ejected could be made to cause further fissions the rate of the reaction would increase rapidly, whereas if for every fission event one only of the ejected neutrons was made to cause further fissions a steady state reaction could be maintained. The first of these possibilities offered the chance of developing the atomic bomb ; the second, the controlled reaction with the hope

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that practical methods could be found for harnessing the energy produced. Since the afternoon in December, 1942, when the first experimental atomic pile began to operate at the University of Chicago, it has been amply demonstrated that both the rapidly multiplying reaction and the controlled reaction are feasible, and we in this country are now on the very threshold of producing useful electrical power from a nuclear reactor.

Developments in the last decade have been so rapid, with many of them shrouded in secrecy, that engineers trained in the more traditional disciplines of engineering have had little opportunity of recognising the scope of engineering in this field, and nuclear engineering has come to be regarded by many as a highly specialised type of engineering closely linked to nuclear physics. This is far from true, and in order to exploit the opportunities revealed by the physicist, all branches of engineering and science must play their part. Indeed, the true nuclear engineer, far from being a specialist, must be prepared to work over a very wide field.

In order to comprehend the effect these discoveries in nuclear physics have had on engineering practice, and what they might have in the future, it must be realised that the

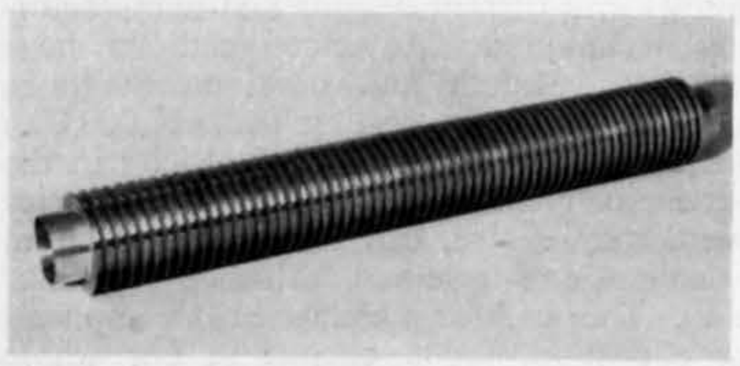


Fig. 1—Fuel element can

engineer is faced with two categories of problem which are very closely interwoven and cannot be entirely separated. In the one category we have a series of ever-expanding technological developments which, although necessary to exploit the discoveries of the nuclear physicist, can be understood by the engineer without reference to nuclear physics. These developments touch and overlap the developments in other forward moving spheres of engineering, such as the gas turbine and aircraft industries. Examples of such developments are the use of liquid metals on a large scale as heat transfer media and the many technical problems that have had to be solved to build gaseous diffusion plants for the separation of uranium-235 from uranium-238, plants which need to be completely vacuum tight and which demand the application on a plant scale of techniques that until a few years ago would have only been found in the laboratory. The second category of problems is entirely new and to understand these we must return to the source of nuclear energy, i.e. nuclear fission. As stated earlier, an important feature of the fission of a uranium nucleus is that during the fission process further neutrons are ejected. In this process 83 per cent of the energy released is in the form of kinetic energy, carried by the fission fragments, which almost immediately appears as heat ; 3 per cent is carried by the neutrons that are released : 3 per cent emerges as instantaneous electromagnetic (or gamma) radiation and the remaining 11 per cent appears as radiation energy during the radioactive decay of the fission products. Now, although on average 2·56 neutrons are produced when a uranium-235 nucleus is split and only one of these is required to maintain the reaction, it is by no means easy to make sure of this, for neutrons can be lost to the reaction by absorption in the reactor core and by escape from the reactor surface. For example, in a natural uranium reactor where graphite is used as a moderator to slow the neutrons down to thermal energies a typical balance sheet is made up as follows :—

TABLE I

Neutrons produced in fission of uranium-235 and in fast fission		2·56
Neutrons carrying on the chain reactions	1·0	
Neutrons absorbed in uranium-238 to produce plutonium	0·9	
Neutrons absorbed in uranium-235 to produce uranium-236	0·2	
Neutrons absorbed in the moderator	0·3	
Neutrons absorbed in structural materials	0·05	
Neutrons escaping from the core	0·09	
Excess neutrons	0·02	
		2·56

It will be noted that, excluding the neutrons carrying on the reaction and those absorbed by the fuel and the moderator, the excess neutrons available for control are only 12½ per cent of the remainder. It is obviously vital that materials are not used which would mop up this small percentage, and for other types of reactors it can also be shown that for economic use of the fissile material neutron economy is a vital feature of design.

Thus, in harnessing the fission process the engineer finds himself faced with several entirely new factors, quite apart from those due to the magnitude of the energy release, which affect far more than the design of the reactor itself, and which become dominating factors in his design considerations.

They are :

(1) The problem of neutron economy in reactors.

(2) The fact that a reactor is a vigorous generator of fast neutrons and high-intensity gamma radiation.

(3) The fact that the products of the fission process are intensely radioactive and any subsequent processing or disposal has to take this into account.

A fourth factor arises when processing or handling high concentrations of fissile material :

(4) Inadvertent critical assemblies must be prevented.

Thus, besides giving a tremendous impetus to scientific and engineering developments in many fields because of the discovery of a new source of energy, the developments in nuclear physics have presented the engineer with several new considerations which must be fed into certain of his design optimisations if he is to make a reactor work or to make its associated plants safe to operate.

Neutron Economy

Reference again to Table I, which shows what happens to the neutrons that are ejected by the fission process in a natural uranium, graphite-moderated reactor, reveals clearly that neutrons can be absorbed or lost in many ways before they have a chance to initiate a fission event themselves. It therefore becomes apparent that in selecting materials of construction for the reactor core, the coolant, the moderator, &c., and in specifying the maximum impurity content that can be tolerated in these and in the uranium itself, an over-riding factor, and an entirely new one for the engineer, that has to be considered, is the extent to which the elements concerned are neutron absorbers. The significance of this can best be understood by reference to the problem of canning solid uranium fuel elements.

In the fission of the uranium nucleus by a slow neutron the fission fragments lie generally in the mass number range 95 to 139, and some of them are associated with high levels of radioactivity. Because of this it is usually undesirable to allow them to pass into the coolant stream and, therefore, the uranium bars are sealed into cans (Fig. 1). In order to make use of the heat that is produced by the fission process it is obviously desirable to run the reactor core at as high a temperature as possible. The can therefore needs to be of a material that will withstand a high temperature and, as the heat is generated within the uranium itself, a high temperature gradient across the wall. In a similar problem of heat transfer through a tube wall to a coolant in more orthodox fields, the engineer would make his choice after considering the compatibility of the tube material with the fluids it was in contact with, the temperatures and stresses it would be subject to, the ease of manufacture, &c., and ultimately his choice would to a large extent be an economic one. In a reactor the additional factor of neutron economy is paramount and to meet this requirement the engineer is forced to use materials that are poor absorbers of neutrons. In the

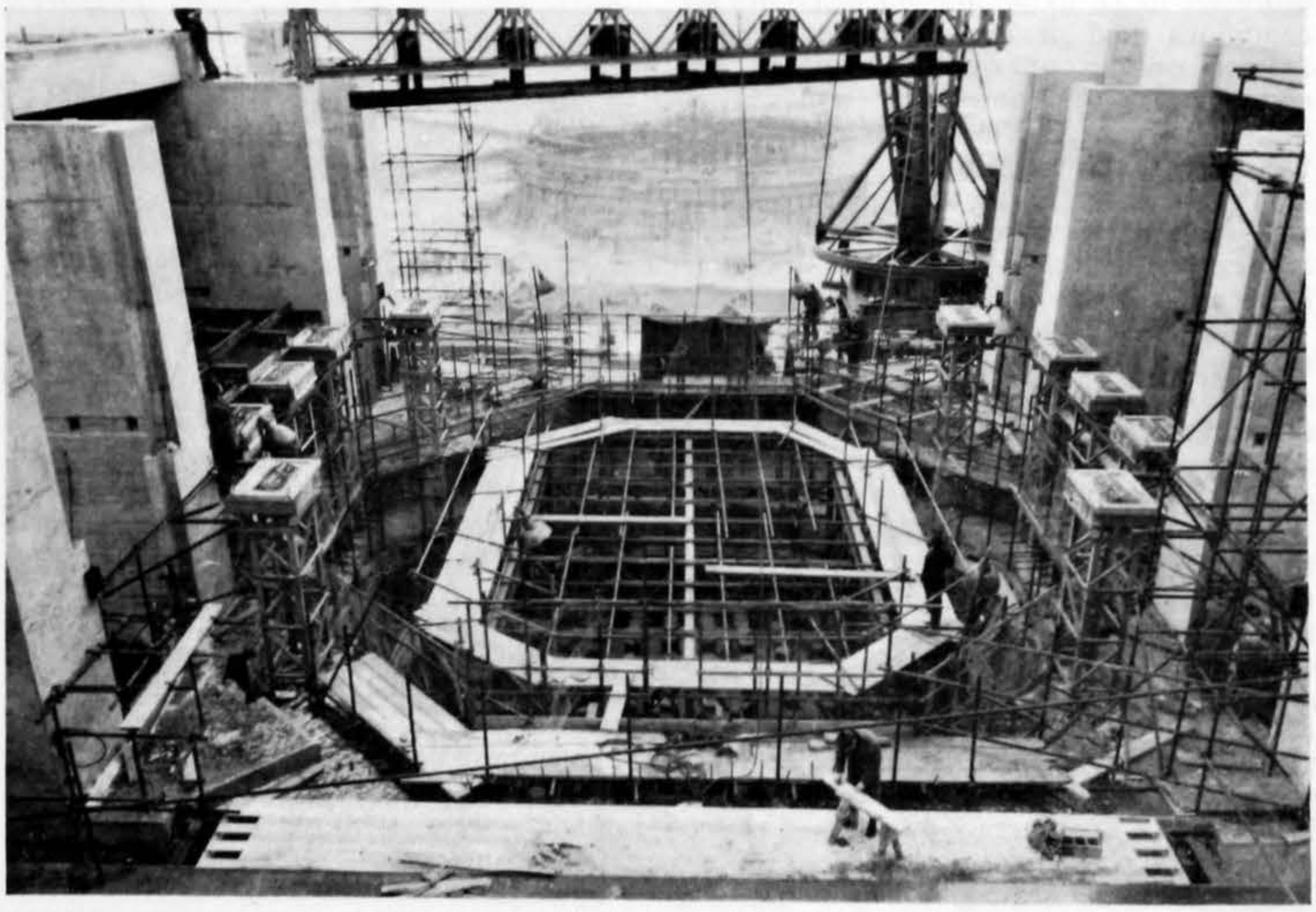


Fig. 2—No. 1 reactor, Calder Hall, showing pile vault and shielding

thermal reactor this means that he must at present use either aluminium or magnesium, and the maximum temperature at which the reactor can be operated is limited by this choice. Even having done this his problems of canning are not over, for, though aluminium is a poor absorber of neutrons compared with, say, stainless steel, it does absorb some neutrons and the amount used must therefore be kept to a minimum. The endeavour then is to make the lightest possible can that will give good heat transfer and will be completely gas-tight when sealed and remain so, in the reactor, during a period of operation which may be as long as five years. Even the method of manufacture of the can must be examined from the viewpoint of neutron economy. For example, lithium halides frequently form part of the flux mixture for brazing aluminium, but as lithium 6, which is present in natural lithium to the extent of about 7·5 per cent, is a very high neutron absorber, any such process may well have to be ruled out of the method of can manufacture. Again, if a can is drawn as a tube, then the lubricants used in the drawing operation need to be scrutinised.

In setting specifications for the impurity levels in materials to be used in nuclear reactors the absorption cross section, or ability of these impurities to capture neutrons must be taken into account, and frequently these values fix the permissible level of these impurities. This represents a new departure in extraction metallurgy since the normal levels of impurities in metals are usually determined by the economics of extraction or the use to which the metals are to be put in normal practice. The whole process of uranium extraction and purification is influenced by this faet, and a basic difference between the Springfields Works where uranium is processed and any other chemical plant where there are certain toxic risks is that in the former metal is being produced on a large scale to a specification in which impurities are set at parts per million.

Irradiation in Nuclear Reactors

The second of the entirely new factors associated with the nuclear fission process which has been mentioned is that account must be taken of the fact that the nuclear reactor core is a source of high-speed neutrons and it is permeated with high intensity gamma radiation. This means that materials in the reactor core and surrounding it are subjected to intense neutron bombardment. The isotopes of some elements exposed to this treatment may suffer nuclear changes with consequent transmutation, becoming radioactive in the process. This fact is made use of in the production of radioisotopes in the Harwell piles, suitable elements being exposed for controlled periods to the high neutron flux in the reactor core. Other materials may, because of this bombardment of their nuclear structure, change their physical properties completely. In this field a tremendous and laborious amount of work has yet to be done in order to find out what happens to the materials that might eventually be used in nuclear reactors, and this work should have a marked influence on the subsequent use of materials for power producing reactors.

It is this feature of high neutron flux and high intensity gamma radiation that makes it impossible for a man to enter a reactor while it is in operation even if operated at a very low temperature, and why he has to be shielded from it when outside. Even if the uranium is discharged from the reactor sufficient residual radioactivity remains, due to some of the structural materials having become radioactive by the neutron bombardment, to prevent proper access. The effect this has on engineering design cannot be too strongly emphasised, as inspection of the interior of the core becomes wellnigh impossible and it therefore places considerable emphasis on the reliability of construction materials and fabrication techniques.

The problem of placing biological shielding around a nuclear reactor to reduce the neutron and gamma radiation to a tolerable level is an important one and in a large reactor can involve major civil engineering work, Fig. 2. As a rough rule each foot of concrete reduces the radiation level by a factor of ten. The shield for Harwell's B.E.P.O., for example, contains 6·5ft of heavy barytes concrete, and 6in of steel and this reduces the radiation level by a factor of 10^9. It must, however, be borne in mind that the purpose of shielding is to protect persons working at or near the reactor not to shield the reactor itself, and therefore it is not always necessary to shield completely areas where a man does not need to work and which he can be prevented from approaching. For example, suppose we intend to cool a thermal reactor with carbon dioxide, as is being done in the power reactors being built at Calder Hall. The coolant must pass through the reactor core and it is, therefore, subjected to neutron bombardment as it does so. The effect of this is that some neutrons take the places of protons in the oxygen-16 nucleus, forming nitrogen-16, which is unstable, and the coolant becomes gamma active. Now the coolant must pass from the core to the heat exchanger and back via a gas main, and as it is radioactive it might be thought that the best place for such a main would be within the reactor shield. On the other hand if valves are required on the main they need to be accessible for maintenance and, as access to the main shield would be difficult, it is desirable to keep such fittings outside. Suppose that a straight length of main 50ft long outside the main shield is contemplated. When the reactor is in operation, after a short period of time corresponding to several half lives of the coolant activity, as many active nuclei will be produced in each second as decay and the activity in the system will be stable. If the circulation time for the coolant outside the reactor core is short compared with the half life of N_{16} (7·5 seconds) the activity will be substantially constant, if it is long then it will vary round the circuit. For this example we will assume it is short. Then from a knowledge of the total volume of the coolant, the volume of coolant in the reactor core, the mean activity flux in the core and the macroscopic activity cross section of the coolant it is possible to calculate the mean activity of the coolant. A realistic example gives about 140 disintegrations/cm³/sec. In about 70 per cent of the disintegrations a gamma photon is given off and the energy of these photons is about 6·5 MeV.

The effect of this is as shown in Fig. 3. At the gas main surface the level of radiation is 7½ times the maximum permissible level (M.P.L.), i.e. a man who remained there throughout the working day would receive a radiation dose 7½ times the maximum normally allowed, whereas 12ft away it is equal to the M.P.L. In order to reduce the level of activity to 1 M.P.L. at the pipe it would have to be encased in 10in of concrete. This small example is typical of many shielding problems. Obviously a number of courses are open to the engineer. If the main runs horizontally, say 20ft or more above the ground, then, subject always to control on painters and other maintenance workers, no shielding is necessary, Fig. 4. If the main is at ground level either the main can be cased or an area 12ft either side of it can be fenced off. Even if staff have to carry out occasional operations closer to the main than 12ft when the plant is running, the fence would still be adequate if a limit was placed on the time a man spent in the fenced area.



Fig. 4—Shielded radioactive liquid mains—chemical separation plant, Windscale

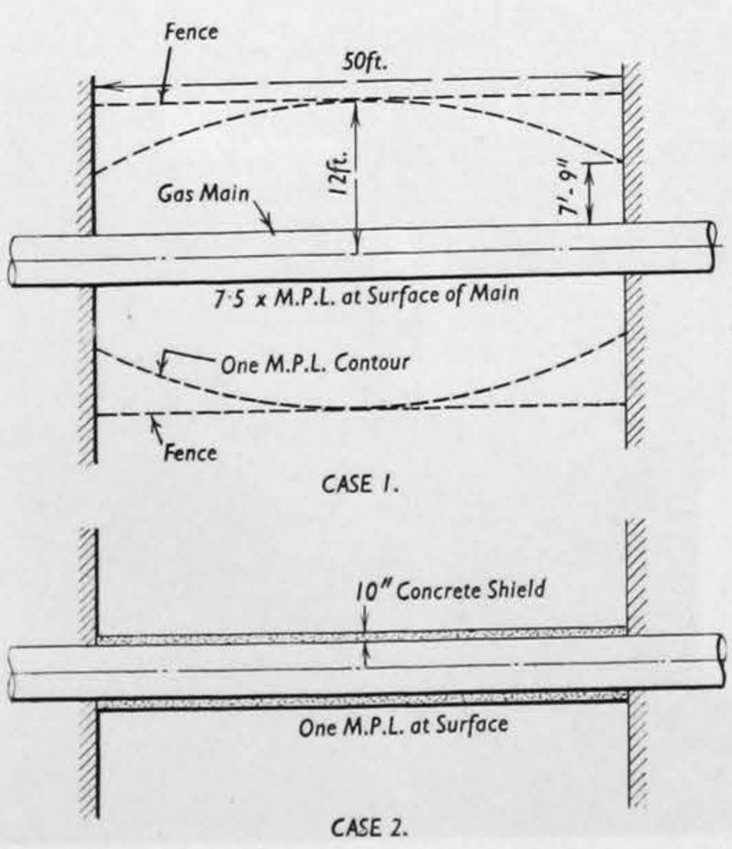


Fig. 3—Case 1—Unshielded main, danger region fenced off. Case 2—Shielded main, no fencing required

Radioactivity of Fission Products

As already pointed out, a significant proportion of the energy released by the fission of a uranium-235 nucleus is made up of the radioactive decay energy of the fission products, some of which go through several stages of decay with the emission of beta and gamma radiation. Although some of these fission products have very short half lives, varying between a few seconds and a

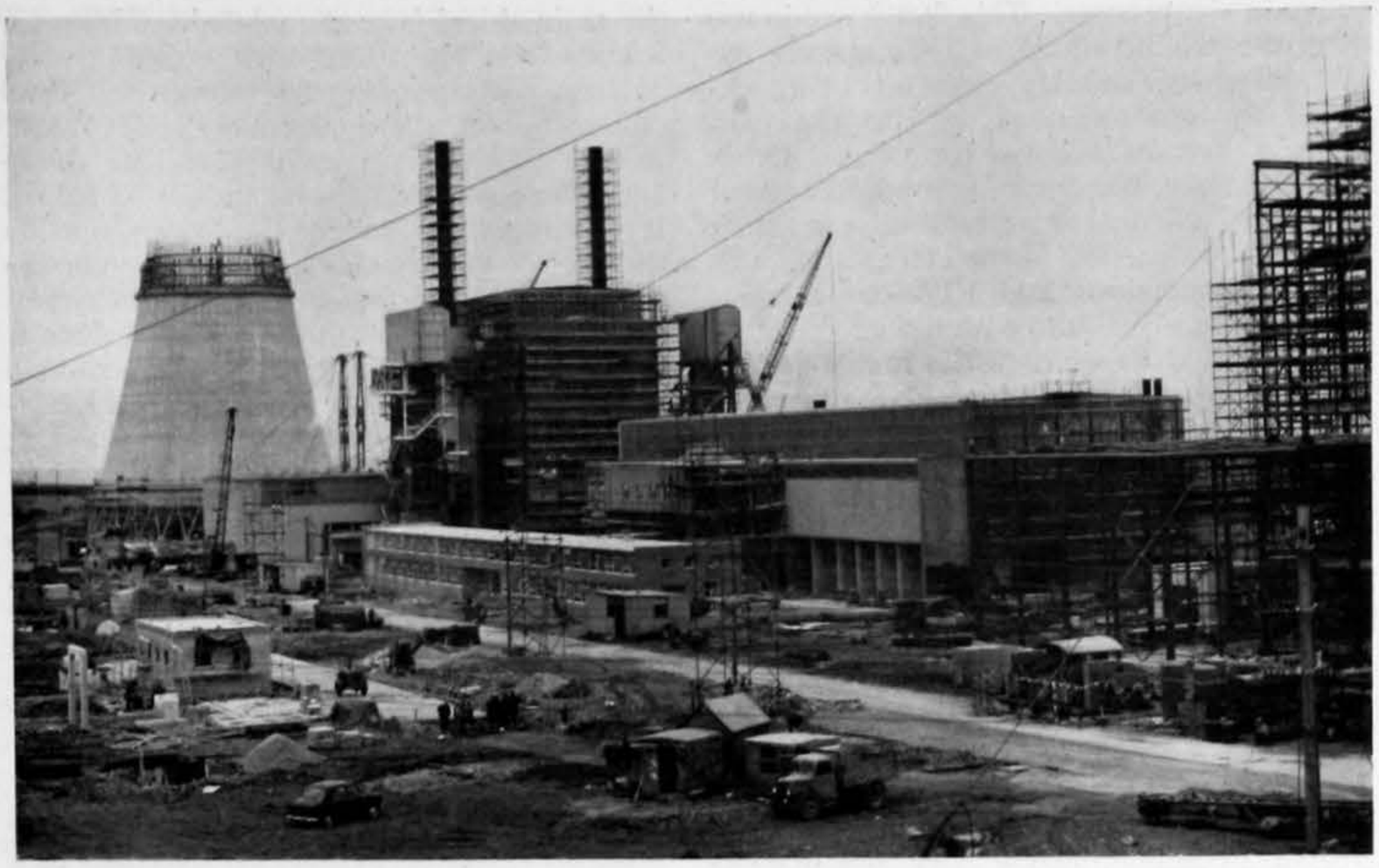


Fig. 5—Construction of Calder Hall cooling tower, No. 1 reactor, turbine hall, office block and No. 2 reactor, looking from left to right

few days, a representative sample of fission products after several months' " cooling " is still sufficiently radioactive to make it necessary to protect anyone approaching it, by a biological shield of concrete or lead. Thus chemical processing of the reactor fuel after it has been used in a reactor cannot be carried out by straightforward methods in an unshielded chemical plant.

It may be wondered why anyone should want to process used fuel and why it is not just treated as waste. The answer is that, even though the fissile content of natural uranium (i.e. uranium-235) amounts to only 0·7 per cent of the total, the remainder being almost entirely uranium-238, it is only possible in any one operating cycle to burn up a small part of the uranium-235. For example, some of the fission products formed are themselves neutron absorbers and so they gradually tend to poison the pile and upset the delicate neutron balance by mopping up the excess neutrons that on initial charging were available for control. In addition, plutonium is made in the reactor by the capture of neutrons by uranium-238, the process being :

$$^{238}U + n \longrightarrow {}^{239}U \longrightarrow {}^{239}Np + \beta \downarrow {}^{239}Pu + \beta$$

Hence periodic removal of the fuel from the reactor permits the isolation of pure plutonium, which in itself is an extremely valuable fissile material, and the removal of the fission products. Before the reactor fuel can, however, be returned to the reactor, uranium-235 must be added, as some of the uranium-235 has been destroyed during the fission process. This is done by the addition of uranium of high uranium-235 content prepared in the gaseous diffusion plants.

Thus in order to reprocess the reactor fuel the engineer has (*a*) to provide means of removing the fuel elements from the reactor while they are still highly radioactive, (*b*) to build industrial scale chemical plants (Fig. 6) that will permit chemical processing to be carried out without hazard to the operating staff or to menace in any way the environment in which the plant is situated, despite the fact that in the early stages of processing the materials may be very radioactive.

Because many of the fission products have short half lives it is possible to ease the processing problem slightly by allowing a decay period of several months to elapse between removal of the fuel and the time it enters the chemical plants. But this is of little help when it comes to withdrawing the fuel from the reactor, as it will be readily appreciated that whether a reactor is built for power or plutonium production, or both, it is obviously economically desirable to keep the shut-down periods to as short a time as possible. If a reactor could be shut down instantaneously then the power level would drop to about 5 per cent of its operating level, this being the energy release due to the beta and gamma activities of the fission products. Immediately the chain reaction ceases, however, this fission product activity level will begin to fall away exponentially, but even so its value within a reasonable time in some reactors may be quite high. The problem is obviously accentuated in high-powered reactors using highly enriched fuel (i.e. fuel with a high concentration of fissile material), for then the operating power rating of each fuel element becomes high, and obviously its residual fission product radioactivity level will rise in proportion. It is thus quite possible to have to consider the extraction from a reactor of comparatively small fuel elements radiating several kilowatts of energy largely in the form of heat. This becomes a major problem for remote handling, as not only is heavy shielding required but also it may be necessary to cool the fuel elements with some secondary circuit to prevent them melting their containers during their removal. In fact, the need for safety and reliability in this operation will have an important bearing on the whole layout and design of the nuclear reactor. Particularly is this so when considering small high-powered units.

In the chemical plants the choice of process is again to a large extent controlled by the same factor that controlled the processing of the fuel before it entered the reactor, viz. the need to ensure a remarkably high standard of purity in the final products that will eventually be used again in the fission process. A second factor is that a process that gives an early removal of the most active fission products may help materially to relieve the shielding and handling problems in the later stages of processing.

Three types of radiation have to be considered in the plant design :—

Alpha particles, which are positively charged particles identical with the helium nucleus.

Beta particles, which are negatively charged particles identical with the electron.

Gamma rays, which are electromagnetic waves similar to X-rays.

Both alpha and beta particles are quite easily stopped, a few sheets of paper being sufficient to stop the latter and the equivalent of several millimetres of aluminium the former. Being charged particles, however, they can do damage to body tissue by ionisation, and it is therefore important to ensure that alpha or beta active isotopes, particularly those with long half lives, are not ingested and allowed to deposit in the body where they would be able to damage surrounding tissue. This leads to very stringent conditions being set on the amount of contamination that can be tolerated in the air. It also means that very high standards of surface cleanliness in working areas are required as the undetected deposition and accumulation of radioactive particles on some inaccessible surface might, if they became dislodged, render the whole area for a period unfit to work in.

Gamma rays, however, are extremely

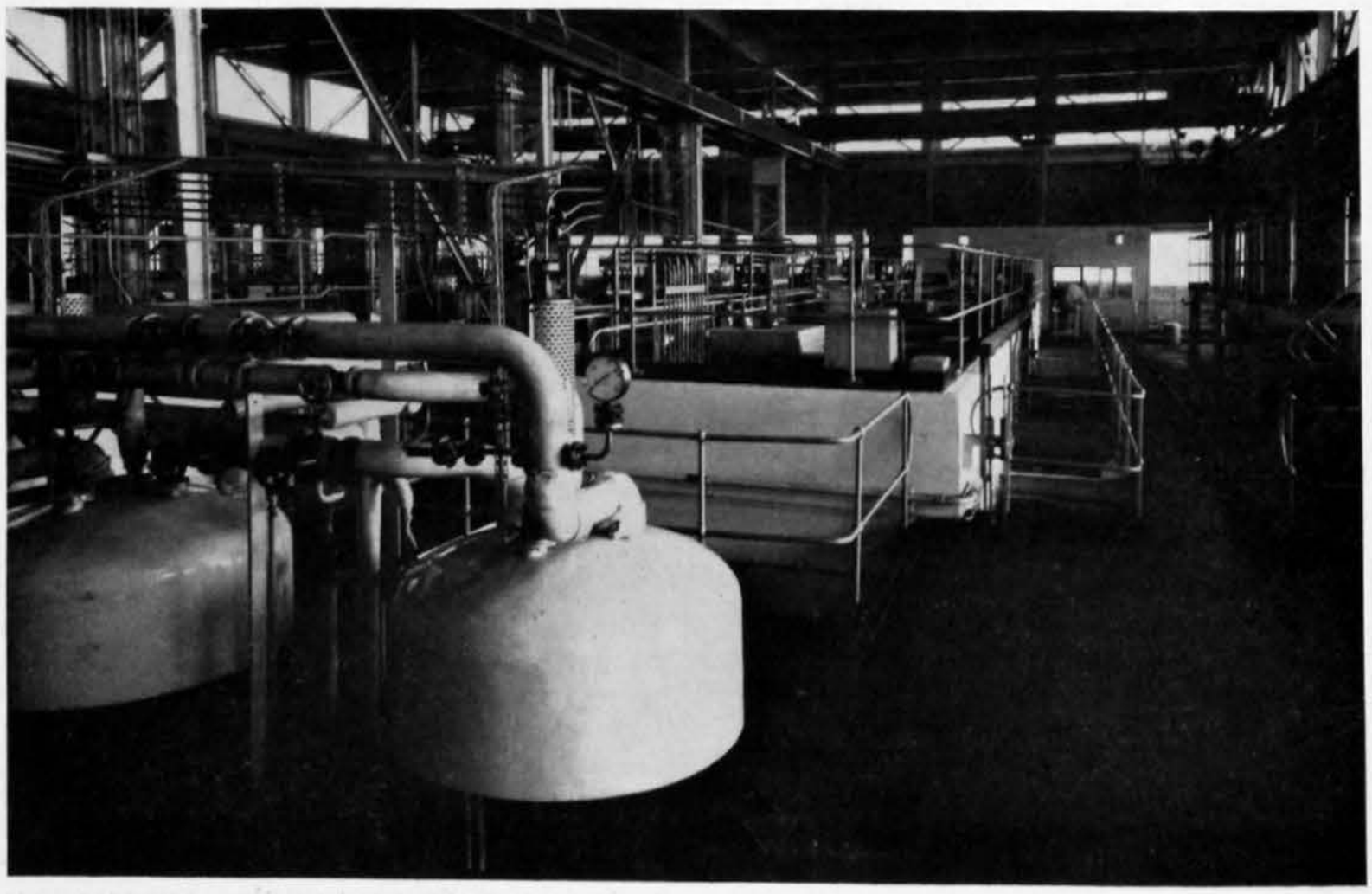


Fig. 6—Uranium purification plant, Windscale

penetrating and can only be stopped by the use of heavy shields. These may be a few inches of lead where only a thin shield is all that can be accommodated, e.g. round an instrument, or several feet of concrete where a whole plant needs to be surrounded by shielding.

The total amount of radiation a man is allowed to receive during a given period has been set at a figure low enough to ensure that he will suffer no cumulative ill-effects. The engineer, therefore, has to design a plant to operate to a given flowsheet, with its associated effluent treatment and disposal plants and control laboratories, which may be operated and maintained without exposing anyone, either inside or outside the factory, to hazardous doses of radioactivity.

At first sight, this might appear to be a problem that is best resolved by the design of all sorts of remote handling equipment and other special pieces of plant. These, however, are only the means to overcome particular difficulties, and though essential for dealing with certain specified duties, such as sample taking, the principal objective

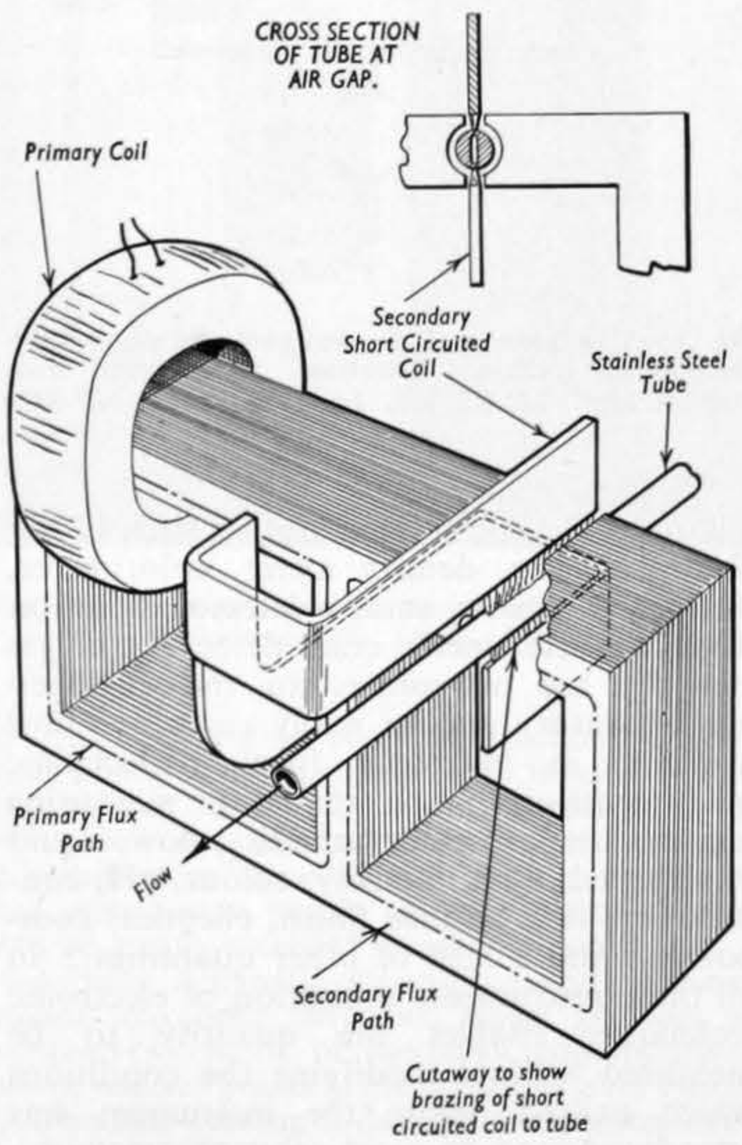


Fig. 7—Typical single-phase electromagnetic pump

in this kind of chemical plant design is containment of the activity. Wherever possible, in order to eliminate dust hazards, wet chemical processes are used. Even so, a leak of a few cubic centimetres of active solution, not large enough to give rise to a radiation hazard, may, if it dries out, give rise to a serious dust hazard. Therefore, whatever the process, a leak-tight plant becomes desirable and hence, as in reactor engineering, reliability and quality of construction become a major feature. At the Windscale works of the Atomic Energy Authority many of the chemical processes are carried out using nitric acid solutions, and the material of construction is largely stainless steel. Probably the biggest single factor in plant design that enabled these plants to be operated satisfactorily was the perfection of stainless steel welding techniques and inspection methods. In developing the latter nuclear physics played a part, for much of the welding was radiographed and gamma-active sources obtained from the Harwell piles were used for this purpose.

It is interesting to examine the possible lines of approach when designing such a plant. For example, in order to obtain a flow between two points in the plant, either one can attempt to use dynamic plant specially developed for remote operation and maintenance, e.g. a centrifugal pump with the impeller sealed off in the plant and driven through a magnetic coupling, or use some more fundamental method of getting a head on pipes, such as vacuum lifting to a head tank and flowing down by gravity. The choice is by no means a simple one, for always in the design of active plant the engineer has to consider not only the operational problems, but also the reliability of the plant and what it involves to carry out any maintenance. If the engineer in this example considers that for the duty it has to perform he cannot rely on the pump impeller assembly being entirely trustworthy for a reasonable portion of the plant life, then he must consider whether it is feasible to make provision for draining it of all active liquor, washing it through to decontaminate it, and providing means of getting at it through the biological shielding and cutting it out of the plant pipework. He will then have to set these possible complications in his plant, and the expense involved in carrying out maintenance, against the advantages to be gained from the use of a pump. It must be realised that the aim is to make the running of the plant sufficiently straightforward to permit the use of process labour, and simplicity and reliability become keynotes in its engineering.

Heat Removal from Reactors

Although the problem of heat removal from a source of energy is not a new one to the engineer, there are certain novel features that are encountered in nuclear reactors. As pointed out earlier, the choice of coolant is influenced by considerations of neutron economy, as is the choice of material for containing it. The degree to which the coolant becomes radioactive due to neutron bombardment as it passes through the core will influence the design of the cooling circuit and heat exchanger system. In power-producing reactors using enriched fuel it would be quite possible to generate more than 100MW of heat in a core no bigger than a 2ft right cylinder, and the problems involved in the transfer of heat from the fuel to the coolant and the heat transport from the core are, in such circumstances, formidable indeed.

The search for suitable reactor coolants had led to considerable work being done on liquid metals and in particular sodium or sodium-potassium alloys are likely to be of use. They are, however, chemically reactive to a high degree and the presence of sodium oxide can cause greatly accelerated rates of corrosion. As the sudden loss of coolant from a reactor might cause a very violent temperature rise in the core leading to extensive damage, again reliability in the choice of materials for the coolant circuit and in the methods of its construction and fabrication become all-important. Naturally, an all-welded circuit is to be preferred and this fact has given an impetus to the development of electromagnetic pumps, Figs. 7 and 8. They are not in themselves, however, a direct result of the discoveries in nuclear physics—they were studied as far back as 1907—but their development has been accelerated because they offer a means of pumping a liquid metal without glands or moving parts in the system. It is, though, not unlikely that for some purposes a suitable mechanical pump could also be developed and in future years, if liquid metal-cooled reactors became common, the ultimate choice of pumps for certain duties might well be decided on pump efficiencies.

The Present and the Future

What, then, are the real and lasting effects that developments in nuclear physics are making on the advancement of engineering, and what repercussions will follow in other fields of engineering endeavour? Undoubtedly the dominating result in the world to-day is that in a civilisation that depends on an ever-increasing use of energy to maintain and increase its standard of living another source of energy has been tapped. So far it is only possible to consider using this energy in the form of heat, and for general power production it is most likely that the reactor will take the place of the furnace in electrical generating stations. In the Government's White Paper published in February, 1955, plans were announced for the construction of twelve nuclear reactors to be built during the next ten years to supplement the output of more conventional coal-fired stations. Since then, and in addition, it has been decided to double the size of Calder Hall and build a replica of it near Annan. Thus, it is probable that within a few years' time the gas-cooled thermal reactor, similar to that being built at Calder Hall, will be looked upon as a conventional piece of engineering plant.

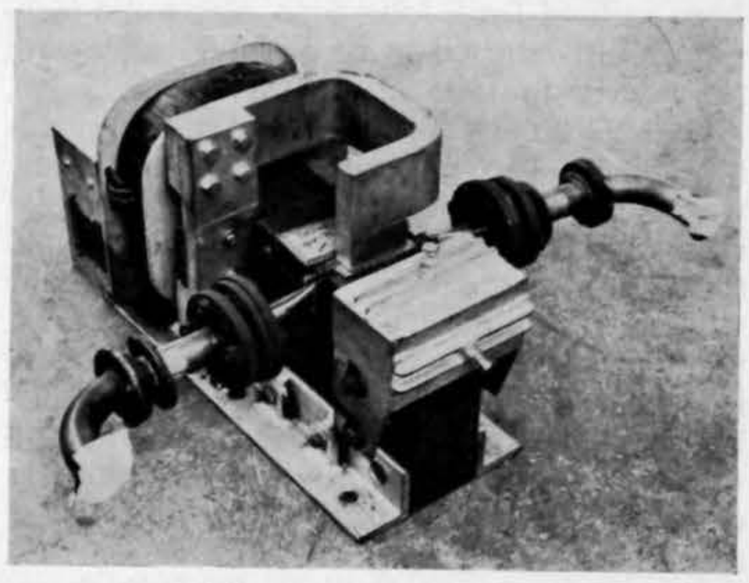


Fig. 8—Electromagnetic pump

In arriving at this position in such a remarkably short time the demands of the nuclear engineer have already made their mark on the engineering industries of this country. The need for complete reliability in the construction of the active chemical plants has inevitably given a stimulus to the development of improved welding techniques for stainless steel. The construction of the gaseous diffusion plant has led to the application of high-vacuum techniques to large-scale plant, and laboratory standards of vacuum tightness are now accepted on such a plant as being normal practice.

Future developments in reactor engineering will be towards smaller and more efficient reactors. The fast breeder reactor offers the possibility of a reaction that will produce more fissile material than is burnt, so making full use of all available uranium and not just the 0·7 per cent fissile content as mentioned previously. But all these developments, including special reactors for propulsion, more efficient thermal reactors, &c., depend for their fulfilment on the right materials of construction being available. Thus, nuclear engineering is placing tremendous demands on the metallurgist, not only to find out what happens to known materials when exposed to irradiation and how they behave under arduous high-temperature conditions, but also to find ways and means of producing many of

the less common metals, which might have promising properties, in very pure states. The techniques of forming these materials and the methods of welding and fabrication must also be established.

In trying to assess the contribution nuclear engineering may make to other fields of engineering it must always be remembered that it is essentially a sphere of engineering in which, as pointed out in this article, certain requirements arising from the fission process must be met. It would be wrong to imagine that new techniques developed in this field and the design methods that have been adopted, necessarily offer great advantages in other fields where these stringent requirements are not needed. The real contribution being made to engineering in general is that nuclear engineering is creating a most pressing demand for new materials, a better knowledge of the behaviour of existing materials under a variety of conditions, more reliable methods of fabrication, and more rigorous inspection techniques. Thus, nuclear engineering, in exploiting the discoveries of the physicist, is providing the motive force for an extensive research and development programme in those fields from which all branches of engineering may draw knowledge and feed their own advances.

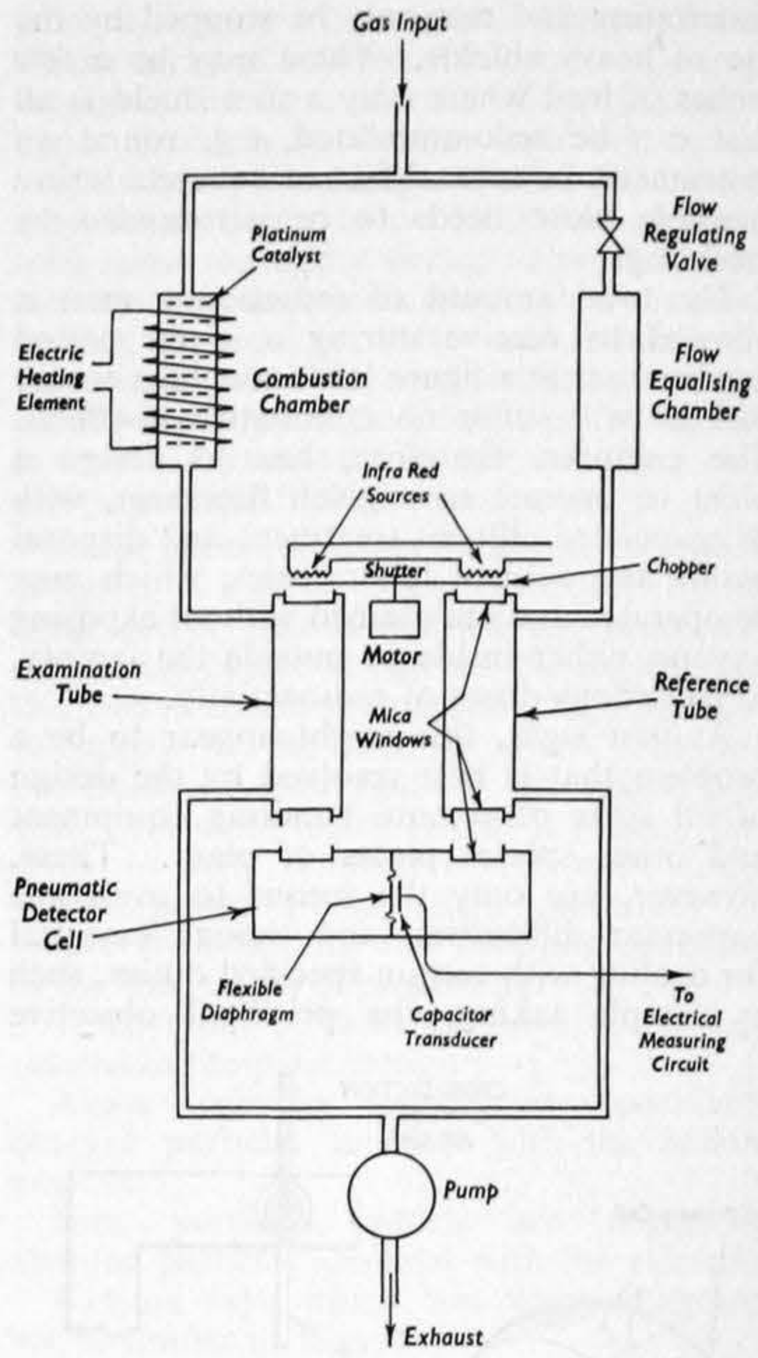


Fig. 1—Arrangement of gas analyser and combustion chamber for methanol detection. (Reproduced from Journal Brit. I.R.E., Vol. 14, 1954, pages 527-543)

Electronics

By H. A. THOMAS, D.Sc., M.I.E.E., S.M.I.R.E., M.Brit.I.R.E.*

THE term "electronics" covers a very wide scientific field, difficult to define precisely in few words, essentially involving all phenomena relating to the motion of free electrons, such as in thermionic valves, photo-electric tubes, gas rectifiers, cathode- and X-ray tubes, but also embracing devices such as photo-voltaic cells, magnetostriction and piezo-electric transducers, transistors, &c., in which the motion of free electrons is not the essential feature.

Although certain electronic devices have been utilised for a long time, electronic techniques only started to be of significance with the advent in 1905 of the thermionic valve. Applied initially for detecting radio signals and later for generating electromagnetic waves, the "valve" became the essential component in radio communication. Around this electronic device there grew up the whole technique of telecommunication, which has now become an important industry in itself. In the early 'thirties radar, television, and various radio aids to navigation were developed. During the last war enormous growth took place in these latter techniques, resulting in the stimulation of a vast variety of technologies, all of which are now being applied to many problems not associated in any way with the original ones which initiated their development.

"Electronics" has, therefore, during the past twenty-five years been responsible for creating several entirely new engineering industries of high importance in themselves. It is not the intention of this article, however, to review the growth of these specific industries but rather to indicate the manner in which the growth of applied electronics has influenced general engineering and how this young technology is likely to affect future engineering trends.

"Electronics" is now well established as a production aid in three engineering fields—electric motor speed control, radio-frequency heating, and electric welding. In many industrial applications of electric motors machinery has to be driven at constant speed independent of supply and load variations; speed can now be maintained constant to 0·1 per cent by very simple electronic controllers. In machine tool operation it is often necessary to change speed at a certain point in the process either after a certain fixed time or more usually at a particular stage in production; in the former case a "timer" and in the latter an "electronic observer" can be combined with a speed controller to give the required performance. In other applications, notably in the winding of thread, wire, paper, cloth, &c., on drums or reels, maintenance of constant tension is essential; in such cases the motor speed can be reduced as each layer is wound by a controlling device sensitive to tension.

There are two kinds of radio-frequency heating, "eddy current" or "induction" heating, and "dielectric" heating. In induction heating circulating currents magnetically induced in a metal produce heat which by suitable choice of frequency can be localised to a given depth below the outer surface—this is of great value in case hardening; by suitably proportioning the "work coil" it is possible to localise the heat to one or more portions of a metal member, this being of importance in annealing, soldering, and brazing. In "dielectric" heating the material is subjected to an alternating electric field and the power absorbed raises the temperature. The outstanding feature is that heat can be generated uniformly throughout a substance and is not conducted inwards from the surface. By utilising microwave techniques and plastic glues localisation of heat has been achieved; considerable application of such techniques is now being found in the mass production of wooden furniture.

In "resistance" welding, which involves the pressing together of two pieces of metal and the passage of a definite current through the joint for a definite time period, timing of the current impulse to an accuracy of a hundredth of a second is necessary if uniformity of product is to be obtained; with electronic controllers it is now possible to ensure such uniformity and, in consequence, to make types of weld not possible by other methods. In "arc" welding, maintenance of constant current between a metal electrode and the workpiece is required; this can be ensured by an electronic controller which observes the voltage across the arc and drives the metal electrode forward so that constant arc length is always maintained.

Measurement

Electronic developments in this field have been so startling during the past three decades that not only have improved methods been developed in practically every sphere of measurement, but entirely new techniques have been evolved for measuring physical parameters which previously could not be measured at all or at best only by slow and laborious methods. Instruments such as the absorptiometer, density meter, colorimeter, titration indicator, smoke detector, aeration meter, moisture meter, crack detector, and gas analyser, are newcomers to the engineering laboratory and in many cases are now available in industrial form. Electronic instruments are now available for measuring temperature, pressure, humidity, flow, liquid level, speed, light intensity, colour, pH, conductivity, size, surface finish, chemical composition and a host of other quantities; in all these instruments utilisation of electronic techniques enables the quantity to be measured without modifying the conditions which existed before the instrument was introduced, and in most cases the measurement is instantaneous and a permanent record is provided.

Certain special instruments are now available which provide quite new tools for the research worker; for example, the electron microscope has improved upon the magnifying power of the best optical instrument by a hundredfold, the mass spectrometer now

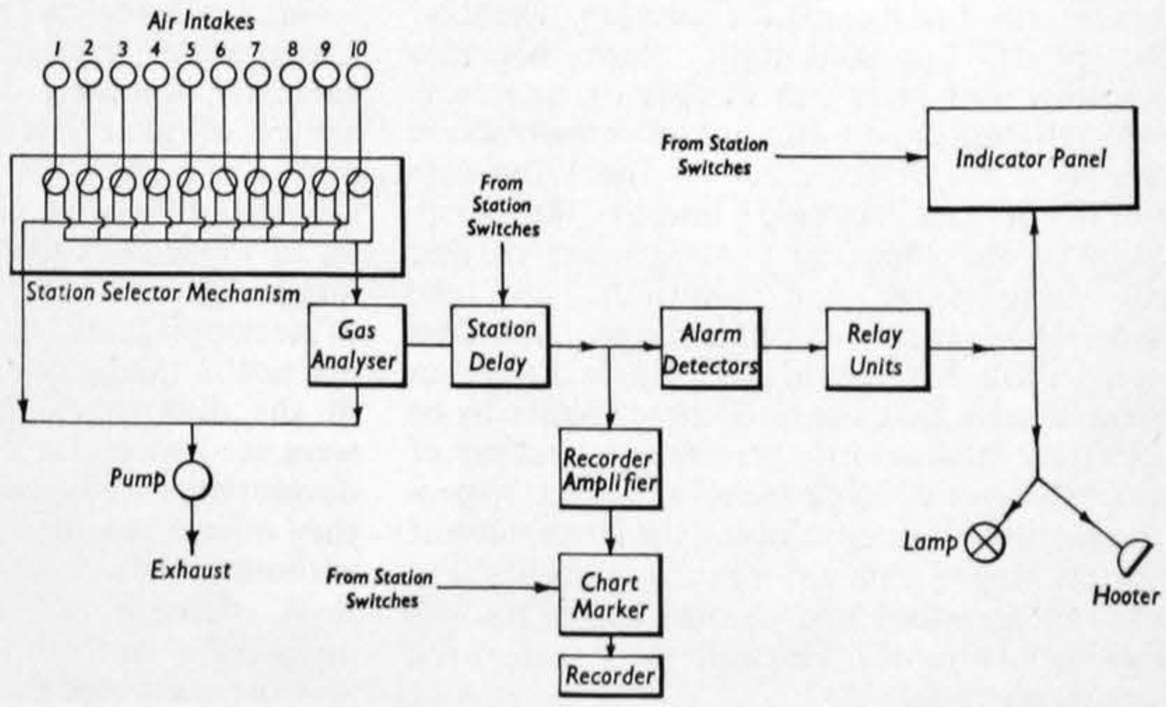


Fig. 2—Basic components of system for methanol detection. (Reproduced from Journal Brit. I.R.E., Vol. 14, 1954, pages 527-543)

*Head of Instrument and Control Section, Engineering Dept., Unilever Ltd.

enables rapid analyses to be made of metals, the cathode-ray spectrograph provides an instantaneous indication of the light spectrum absorbed or emitted by a substance and can be utilised to control a process involving change of chemical composition.

Examples of such electronic measuring instruments, both for laboratory and industrial use, are increasing so rapidly that the mere cataloguing is a formidable task. In choosing a particular example to illustrate the application of electronics to measurement, a brief description will be given of a new and rather special piece of equipment[1] designed to solve a difficult industrial problem relating to plant for fractioning fatty acid mixtures in which methanol is used as the partitioning agent. Diffusion of methanol in air constitutes an industrial hazard because concentrations exceeding 200 parts in a million are injurious to health and this concentration can be greatly exceeded if leakages occur.

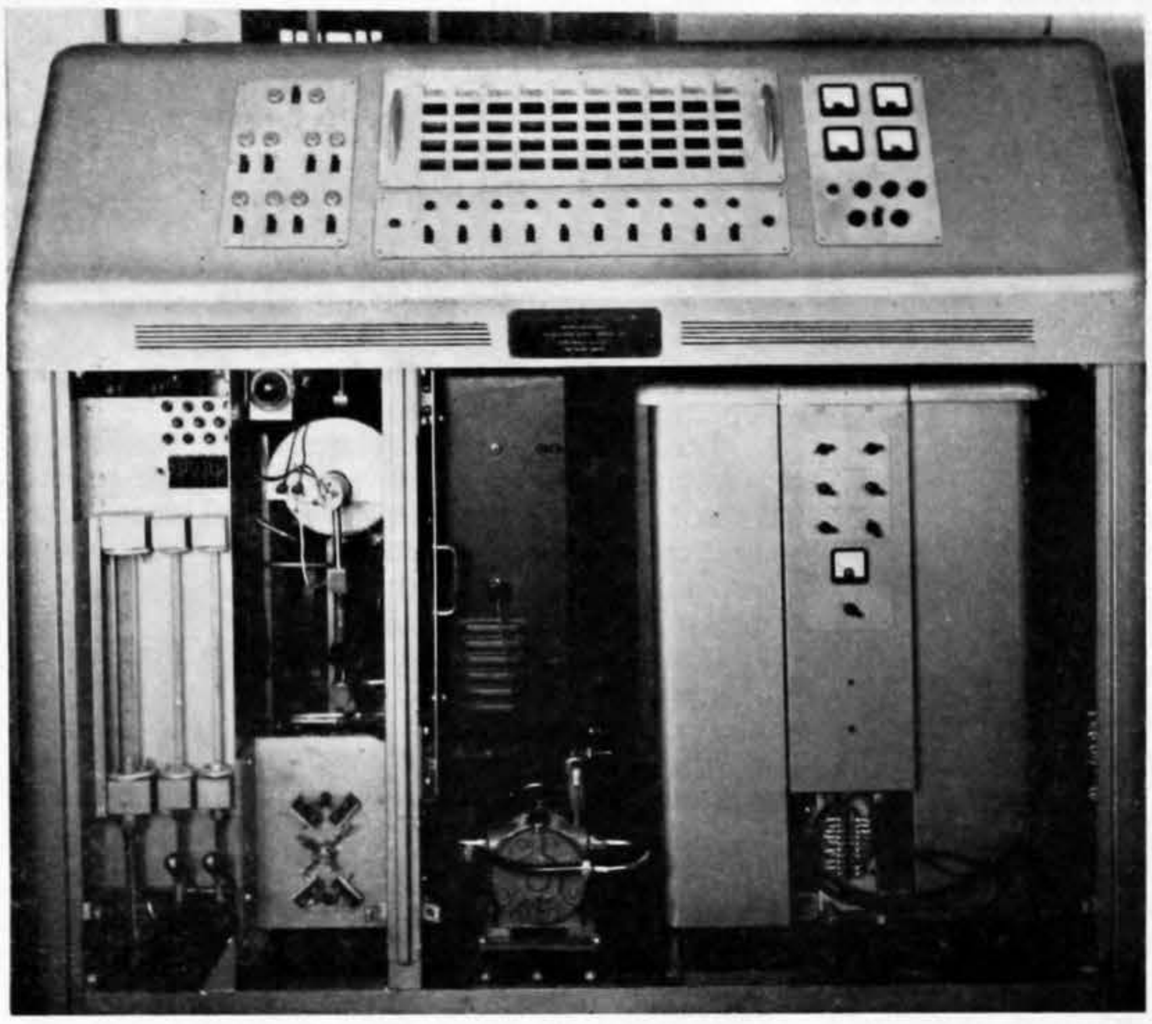


Fig. 3—Methanol detection equipment with covers removed. (Reproduced from Journal Brit. I.R.E., Vol. 14, 1954, pages 527-543)

A fully automatic monitoring and warning system has been developed which provides a continuous record of methanol concentration at ten selected points in the plant and gives visual and audible warning of dangerous concentrations in excess of 1000 parts in a million. Experiments showed that conventional methods of gas detection were not sufficiently sensitive or selective, but that by combustion of methanol to CO_2 and its subsequent detection by an infra-red technique it was possible to obtain adequate sensitivity. Referring to Fig. 1, the gas stream, pumped slowly from each inspecting point, is divided equally ; one portion flows through a specially designed combustion chamber, heated electrically to 680 deg. Cent. and fitted with a platinum catalyst, and then through one tube of a standard infra-red gas analyser ;[2] the other portion flows through a dummy chamber, having the same pneumatic resistance and capacity, and then through the other tube of the analyser. The presence of methanol thus produces a greater concentration of CO_2 in the examination tube than in the reference tube, irrespective of the ambient atmospheric concentration.

This differential CO_2 concentration can be detected by successive examination of the absorption to infra-red radiation in both tubes ; with two sources, a shutter and a differential pneumatic detector cell filled with a mixture of carbon dioxide and nitrogen, equality of absorption (i.e. no methanol) gives similar temperature rises in each compartment of the detector cell during each short pulse of radiation and, in consequence, no differential pressure and no deflection of the inter-compartment membrane. If the absorptions are dissimilar, however, a temperature and pressure pulse occurs which vibrates the diaphragm. This vibration is detectable by a capacitor transducer which, with appropriate electronic amplifiers, can be made to operate suitable recording equipment.

The basic components of the system are shown in Fig. 2 ; the air/methanol mixture is drawn continuously by a pump from all ten selected inspection points in the plant ; sequential inspection is provided by temporarily diverting the gas from any one station through the analysis system instead of exhausting it to atmosphere. The sequential selection is provided by the station-selector mechanism which comprises ten two-way valves operated in turn by a motor-driven cam.

The electrical output from the gas analyser is interrupted by a "station delay" circuit actuated by switches mounted on each of the two-way valves ; this circuit interrupts the signal from the analyser for about half-a-minute at the beginning of each examination period whilst the gas from the previous station is being expelled.

The signal from the station-delay circuit is applied to the "recorder-amplifier" and also to the "alarm detectors." The recorder amplifier raises the power level of the signal sufficiently to operate the recorder to which it is connected through the "chart marker" circuit ; this circuit introduces discontinuities in the record to facilitate identification of each station and of each complete cycle in the sequential inspection.

The alarm detectors operate relays (which, in turn, raise the appropriate alarms) when the input signal reaches a level of 200 and 1000 p.p.m. methanol. Both detectors comprise an "integrator" and a "trigger" unit. The integrator of the 200 p.p.m. alarm summates the periods of concentration in excess of this value and is interposed between the relays in its trigger unit and those which operate the "indicator panel" and alarms ; warning of this concentration is given only if it has existed for thirty seconds during any one examination period. The integrator of the 1000 p.p.m. alarm triggers its alarm when this concentration has existed for five seconds.

The indicator panel co-ordinates the alarm signals with the station switches ; it shows at a glance which station is being examined, whether a concentration of 200 or 1000 p.p.m. exists, and what concentration existed at the other nine stations during their previous examination.

The general arrangement of the equipment is shown in Fig. 3. Two independent analysis systems are incorporated so that failure of one does not interrupt the monitoring service. The station-selector mechanism with all its pipework is at the extreme left ; the two combustion chambers are shown to the right ; then the two gas analysers and pumps below ; and on the extreme right the several electronic units. The main indicator panel is at the top.

This equipment has been in continuous operation (twenty-four hours a day) for four years and has required very little maintenance. Not only has it provided a fully automatic monitoring service, but has been the means of locating leaks in the plant, so enabling savings to be effected which already have exceeded the initial capital cost of the equipment.

Automatic Control

The automatic control of a process or machine involves the introduction of means for detecting changes in one or more of the process variables from a preselected value and means for utilising this information to make appropriate changes in other process factors so as to re-establish the normal operational value. The earliest steam engine governor was an automatic speed control device utilising a mechanical linkage between the rotating member and the steam valve.

Innumerable mechanical devices have been developed to control the operation of machines or to stabilise some parameter of a process ; such devices are limited in application, however, and particularly in sensitivity by the fact that the power provided by the device sensing the deviations is usually insufficient to actuate directly the device which produces the required correction. Progress in automatic control techniques has thus involved the development of suitable power amplifiers, and hydraulic, pneumatic, and electric systems have all been utilised for this purpose.

Possibly the most concerted development in automatic process control has been inspired by the necessity in the continuous chemical process field for maintaining steady states of internal balance. In fact, the continuous chemical process is so dependent on the instruments that control it, that it would be necessary, if these instruments were not available, to confine the operations of chemical manufacturing to simple batch processes hardly capable of producing the cheap chemical goods available to-day !

The science of automatic control is comparatively new in its more complex forms. Simple controls have been available for nearly as long as the primary instruments upon which they depend for their operation, but the more complex controllers have been in use for only a comparatively few years and have followed the requirements of the modern continuous process.

The study of automatic control is essentially a complex subject and the exact rational solution of many control problems requires knowledge of process characteristics usually not available when the equipment is being designed ; in fact, many control problems are so complex that a rational mathematical solution is never possible. This complexity has hitherto fostered the practical approach, but with increasing applications and greater experience the science is now becoming more exact.

In view of the importance of automatic control to the chemical industry, manufacturers of industrial control equipment have tended to concentrate on satisfying the specific requirements of this industry, the most important of which are the stabilisation of temperature, pressure, flow, liquid level, and to a lesser degree humidity, viscosity, specific gravity, pH, and gas content. Furthermore, development of suitable controllers has been conditioned largely by the requirement that the equipment should not introduce a fire or explosion hazard. This latter requirement has encouraged development of pneumatically-operated controllers, resulting in the present considerable industry in this field. In most chemical control problems the actuator is a valve, and control of valves pneumatically is so reliable that additional encouragement has been given to development of the pneumatic controller.

Pneumatic controllers, however, require that the sensing device shall provide mechanical motion of a delicate member—the "flapper"—and there are many process parameters which cannot readily be arranged to provide such motion. In these cases electronic techniques are becoming of increasing

[1] "The Automatic Indication and Recording of Minute Concentrations of Organic Gases in Air," H. A. Thomas, *Journal Brit. I.R.E.*, 1954, Vol. 14, pages 527–543.

[2] Manufactured by The Infra-Red Development Company, Ltd.

value ; in some cases the initial electrical signal after amplification is converted into mechanical motion by a suitable electro-mechanical transducer and a pneumatic controller is utilised, but in others the controller itself is all-electronic. By comparing the electrical input with a preset electrical standard and utilising the error signal so produced to actuate the controlling mechanism reliable control can be obtained.

There is a tendency towards the all-electronic controller even in those cases where hitherto the pneumatic type has been predominant. For example, in a recently constructed American refinery,[3] control is entirely electronic and it is claimed that substitution of electric cabling for air lines has eliminated the disadvantages of such lines particularly at low temperatures ; that electric cabling is cheaper ; that operating experience has shown that electronic control instruments have a smaller dead band ; and that elimination of moving mechanical parts has increased reliability and sensitivity.

Whatever may be the ultimate optimum system in cases where either pneumatic or electronic control is permissible, there is a very large field in which electronic controllers only are possible—in all those cases, in fact, where the sensing device is purely electronic. Two examples of such automatic controllers will now be given, one in which a mechanical dimension is required to be controlled, and the other in which optical alignment is necessary.

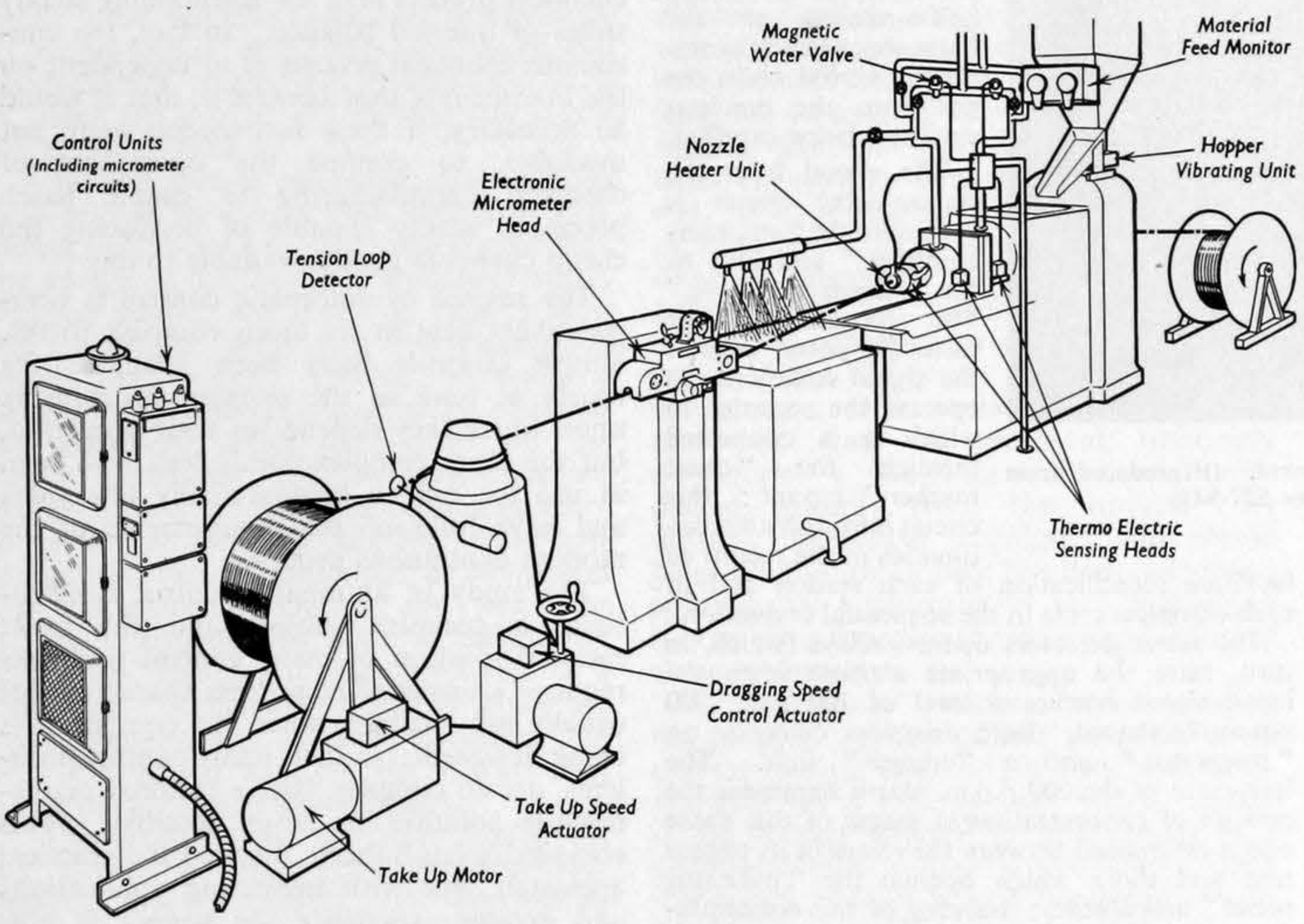


Fig. 4—General scheme for controlling wire diameter. (Reproduced from Electronic Engineering, Vol. 24, 1952, pages 193-195)

Examples of Automatic Control

The first example relates to the control of overall diameter in the manufacture of p.v.c.-sheathed copper wire. The established production method involves drawing the wire rapidly through a die and extruding the hot plastic material around it. The extrusion machine itself consists of a feed hopper which introduces chips of raw material to a screw conveyor closely fitting in a cylindrical barrel ; this screw has a central hole right along its entire length to allow the wire to pass through it from a spool at the rear and to emerge sheathed in plastic material at the nozzle ; the barrel is heated and the material subjected to considerable pressure as it is forced by the screw towards the nozzle. After the soft tube of sheathing has emerged from the nozzle it is cooled by being drawn through water until it is hard enough to be handled without deformation, the towing of the wire being effected by a variable-speed geared capstan.

Due to the nature of the plastic material, the extruded hot soft sheathing expands immediately on emerging from the die and, since the final diameter must be held to close limits, it was found with manual control of the several process parameters that considerable scrap was produced. Examination of the problem by the National Physical Laboratory suggested a means of controlling the diameter, and equipment has been developed which finally was constructed commercially[4] and installed at W. T. Henley's Telegraph Works Company, Ltd.[5]

Analysis of the problem showed that the diameter was a function of:—

(1) The head of material in the intake hopper.
(2) The speed of the feed screw.
(3) The temperature of the compression chamber.
(4) The temperature of the die.
(5) The velocity of the towing capstan, and
(6) The speed of the take-up spool.

Reference to Fig. 4 shows the general scheme which has been introduced for controlling diameter.

First, variations in head of raw material in the hopper were eliminated by introducing a vibratory conveyor fed from a larger hopper ; a "photo-electric material-feed monitor," consisting of an optical system which looks into the mouth of the extruder, controls the conveyor so that the feed screw is always just covered. Secondly, the speed stability of the feed screw was improved by fitting a more powerful motor. Thirdly, the temperatures of the compression chamber and die were stabilised by introduction of sensing elements and controlled water and steam valves, resulting in temperature stabilisation to 0·1 deg. Cent.

The diameter of the wire is monitored to an accuracy of 0·0001in by a specially designed electronic micrometer capable of withstanding shock and of absorbing a large overload ; it is also immune from changes of temperature and mains fluctuations. This micrometer head, which is totally enclosed and capable of operation with wire travelling up to 2000ft per minute, will operate continuously under the difficult conditions of dirt, dust, and water which exist. The signals from this micrometer head, which can be preset to any required dimension, actuate a speed controller associated with the towing capstan.

Lastly, the speed of the take-up spool is varied in accordance with the amount of wire on it by incorporating a tension-sensing device. As more cable is wound on the drum the rotational speed is reduced so as always to maintain constant tension in the wire from the towing capstan.

A number of these equipments have been made and the original one has been in satisfactory operation for several years.

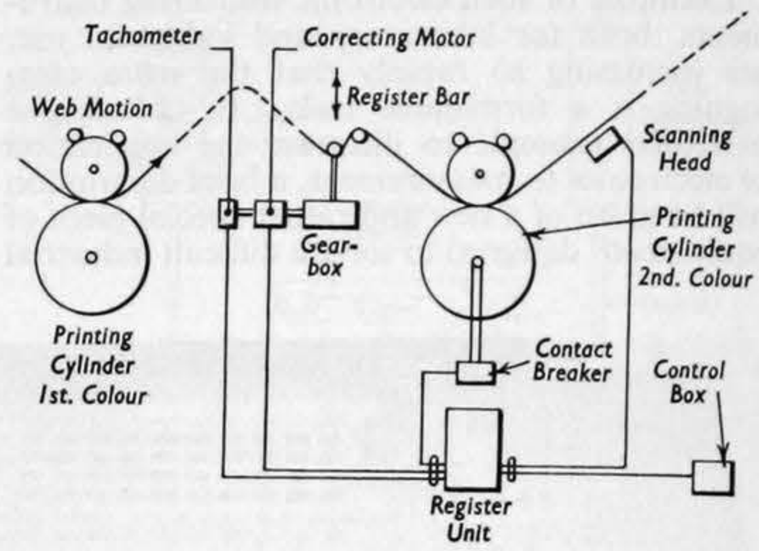


Fig. 5—Diagrammatic arrangement of register controller—Elliott Brothers

The second example relates to the continuous and automatic maintenance of colour register in rotary multi-colour printing machines. Bad register spoilage is often caused by variations in reel tension, joints in the paper, and changes in press speed. It can be eliminated by continuously checking colour register as the impression leaves the printing cylinder by detecting any tendency to shift and immediately applying correction.

One system[6] of control is shown diagrammatically in Fig. 5. This system utilises register marks engraved on each printing cylinder ; these marks are printed on a margin or gutter between successive impressions which subsequently is trimmed or arranged in a fold where the marks are not seen ; the appearance of these marks is shown in Fig. 6.

The equipment comprises a scanning head and register unit for each colour cylinder ; the scanning head has a pair of photo-tubes which "look" at the appropriate printed register mark on the web and produce corresponding electrical impulses, one pulse relating to the first colour and the other to the colour just printed ; the two pulses are transmitted to the register unit, where they are amplified and their timing compared. If register is correct the register marks will be in alignment and there will be no time difference between the pulses and, therefore, no need for correction ; if misalignment exists, however, of the order of 0·001in, the time difference is detected and a signal passed to the correcting motor to move the control in the appropriate direction. The signal strength is proportional to the time difference between the pulses, and thus the greater the register error the faster is the correction applied ; as the error is reduced the motor slows down and finally stops when correct register occurs. The detection system operates from the leading edges of the register marks, the thickness of which does not affect the accuracy of control.

A tachometer generator is incorporated to provide a feed-back signal opposing the operating signal and thus to ensure dead-beat action. To prevent spurious operation from the main printed matter on the web, a contact breaker driven by the printing cylinder is introduced which switches on the comparison circuit only while the clear gutter is being examined.

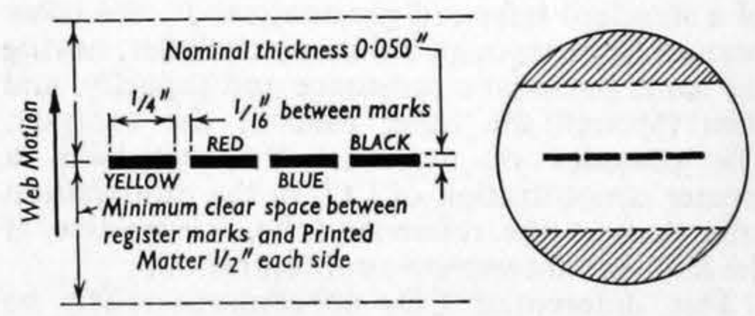


Fig. 6—Appearance of register marks, register controller—Elliott Brothers

This type of controller may be fitted to prac-

[3] The Rock Island Refining Corporation, Indianapolis.

[4] Sargrove Electronics, Ltd., Hounslow, Middlesex.
[5] "Automatic Product Handling and Qualitative Control," J. A. Sargrove, *Electronic Eng.*, 1952, Vol. 24, pages 193–195.

[6] Elliott Brothers (London), Ltd.

tically any type of rotary printing machine and has application also to the cut-off control on bag-making machines, control of the position of the fold on printing press folders, guillotines, and so on.

Electronic Computers

In no electronic field during the past decade has progress been more rapid than in the development, design and construction of electronic computers. Charles Babbage, between 1812 and 1871, attempted almost single handed to construct a mechanical calculating machine capable of performing a large number of mathematical operations sequentially, but the technical competence of his era was inadequate to permit completion of a satisfactory model. Later in the century William Thompson—later Lord Kelvin—proposed solving mathematical problems by machines and described how integration and differentiation could be accomplished mechanically, but again tools of the required precision were unavailable, and so a machine was never built. In 1930 Vannevar Bush constructed a machine for solving differential equations using mechanism and electric motors.

The electronic developments of the 1940s made possible what could not previously be accomplished by mechanical means. By introducing such techniques the limitations of mechanical devices were at once eliminated and the speed was increased to fantastic limits. The enormous speed of these machines (in millionths of a second), their ability to follow extensive lines of logical reasoning, and their ability to choose between built-in alternatives make them ideally suited to the handling not only of complex and lengthy mathematical computation, but also of large quantities of data. By performing a long series of elementary mathematical steps in rapid sequence a computer can solve highly intricate problems in very little time. Since mathematical numbers are merely symbols, and since the symbols we use in ordinary communication, namely words, can be changed to correspond with the symbols which the computer can understand, it is possible for computers to handle information other than mathematical. They can compare, collate and make logical choices between alternatives ; it is basically no more difficult for computer circuits to handle logical problems represented by word symbols than to handle mathematical problems.

All computers involve :—

(1) An input device to insert data into the machine (punched cards, punched tape, magnetised tape or wire, film, &c.)

(2) A memory unit to store information (magnetic drum or tape, cathode-ray tubes, &c.).

(3) A controller to schedule the sequence of operations.

(4) An arithmetic unit to do the calculations.

(5) An output device to get the information out of the machine in a form which can be understood by a human being (printers, punch performers, film, &c.).

In programming such a computer, i.e. in setting up operating instructions which the machine can follow, each problem must be reduced to a series of elementary steps. At each stage in the calculation the machine must figuratively ask a question which can be answered by "yes" or "no." Once properly programmed such a computer can automatically process a great variety of information and can take all necessary action in connection with its analysis.

Electronic computers were initially constructed, first in America and later here,[7] for solving complex mathematical problems impossible of solution by normal means, and the enormous effort put into their design has already been justified. In scientific problems connected with aerodynamics, nuclear physics, ionospheric research, hydrodynamics, meteorology, and statistics they have enabled solutions to be obtained which without them could never have been attained.

Utilisation of such computers is not, however, confined to solving scientific problems. A far wider field lies in their application to business organisation and industrial engineering. Just as the machine has relieved man of tedious manual labour, so can equipment of this kind relieve man of tedious mental labour. A revolution in business methods is imminent if only business executives can appreciate the vast potentialities ; all clerical routines can be made cheaper and faster, necessitating considerable changes in organisation and methods. This revolution has already commenced ; in America there are over a hundred organisations working on various aspects of the design and manufacture of electronic computers and some commercial models are now available — over 2000 machines are in use preparing payrolls, tax statements, cost controls, accounts, cash and time records, inventories, etc. "Memory" drums are being used by the Pennsylvania Railroad and by American Air Lines for bookings, reservations, and the printing of reservation coupons ; telephone bills are being prepared automatically in Philadelphia by an "automatic-message-accounting centre" which notes who talked to whom for how long, prepares the bill, and automatically addresses the envelope.

In this country, manufacturers[8] are studying the needs and possibilities and offering equipment which, with further development, will become cheaper ; with one notable exception—LEO, or the Lyons Electronic Office,[9] developed from the Cambridge EDSAC—business executives have not yet appreciated the economies and improvements in accounting techniques which can be effected by these machines. It is significant that several of the manufacturers of such equipment are setting-up computing centres which provide a service to industry, and that the D.S.I.R. is giving a much-needed lead in this direction by setting-up a new Division at the N.P.L. to study such business applications.

The main requirement is undoubtedly that the business world shall specify its real requirements for a general-purpose electronic computer so that a range of machines may be manufactured at an economic price.

Automation

The pursuit of manufacturing efficiency has shown considerable contrast as between different industries, although the basic pattern is essentially the same in all. Originally the craftsman made his product by his own hand and skill ; advent of the machine enabled the output of similar products to be increased with less-skilled labour and also in most cases resulted in an improved, or at least more consistent, product.

At first the machine did not provide much more than a very useful tool which the craftsman could apply enjoyably and profitably ; with improved mechanisation, however—the introduction of power-driven machine tools, drills, saws, conveyors, hoists, trolleys, &c.—manual effort was reduced and output increased, and by introducing jigs and fixtures for the work and for the supply of components the consistency of the finished product was improved.

The technique of modern mass production necessarily implies that the human being is an essential part of the fabricating process ; study of the most efficient use of human beings is, therefore, an essential aspect of production study. Elimination of unnecessary effort—time and motion study—consideration of physiological factors, and indeed the whole planning of the factory lay-out for easy work flow is now of immense importance.

The most difficult problem in the efficient use of human beings is, however, the provision of adequate interest ; man is not efficiently productive unless interested in the work,[10] and the requirement that work should be interesting may conflict with plans based solely on the unqualified application of physiological and mechanical principles. It has been shown by careful studies of work on a mass-production assembly line that financial inducement of the order of 50 per cent increase in income will bring labour into an uninteresting job but will not eliminate the worker's dissatisfaction ; in routine clerical work it has been found that over-specialisation can lower productivity through boredom by as much as 40 per cent. The function of applied psychology is to secure a sense of participation by the worker in the productive enterprise and to provide a degree of variety at least to the extent of allowing the operator to control his own working pace at any instant while maintaining a fair average output for the team.

Production study can be pursued to the point where more is known about operational detail than can usefully be dealt with by equally-detailed human control ; human intervention and movement can degenerate into a series of retarding interludes between smart and precise machine-driven periods. In fact, the operation of some semi-automatic machines is so complex that more than average skill or intelligence is required from the operator. One attempt to minimise this effect expands, instead of confines, human interest in more of the jobs which have to be done ; another pursues the use of machines towards the limit and aims ultimately at eliminating human intervention altogether. This latter is what is generally known as "automation."

The term "automation" is often applied to any technique adopted to raise output, i.e. to devices which use human labour more efficiently, such as precision machinery, cyclic automatics, information-processing equipment, and error-actuated automatic process-control systems. If one accepts this broad definition, then the Ford or Austin car assembly plants may be regarded as examples of automation, for their chief function is to ensure that the human operator who connects together the various components shall always receive the appropriate items at the correct time and place. Operation of the system is maintained at a central point, simple mechanisms at the various assembly points sending information of the form "There is, or is not, one component A ready for delivery to the assembly line" ; there is no processing of data but merely responses such as "Hold back, or deliver, another component A from the conveyor."

The cyclic automatic machine tool has been elaborated in the form of the "transfer machine" now used in large car factories for machining engine castings ; each of the conventional machining operations of facing, drilling, boring, &c., is carried out consecu-

[7] By Manchester and Cambridge Universities and the N.P.L.

[8] Ferranti Ltd.; Elliott Brothers (London), Ltd.; English Electric Company Ltd.; British Tabulating Machine Company Ltd.

[9] "Operating and Engineering Experience Gained with L.E.O.," J. M. M. Pinkerton, Automatic Digital Computation, N.P.L. Symposium, 1953, H.M.S.O.

[10] This does not in general apply to those workers who are happiest when they can do a completely routine job which is automatically controlled by their subconscious minds.

tively, the work being transferred automatically from one work station to the next and in some cases automatically inspected between stations. Such automatic single-purpose machine tools are suited, however, only to special cases—extremely long runs on a non-varying product. Present machines contain the elements of the future automatic factory, namely, the automatic and flexible materials-handling and machine-loading devices. Only when the automatic production of medium and short runs of product is possible will automatic control mechanisms be used to the fullest advantage.

The profile-following miller, the contour-following lathe, and the photo-electrically guided cutter, which cuts steel plate to a contour drawn on paper, are all automatic machines but are essentially copying devices in which a pattern is provided in a material more easily worked than the product. The limitation of such machines is that the labour required to prepare the pattern is usually only justified for reasonably large runs of product. A much more promising method of automatically controlling a machine tool, which has the great merit of versatility, is to programme the tool motions electronically. A particular example will illustrate the technique which can be applied to any machine tool.

In Fig. 7 is shown an electronically-controlled milling machine[11] capable of cutting almost any three-divisional shape to an accuracy of 0·0002in from instructions prepared as perforations on a strip of paper tape. The whole system comprises :—

(1) A "tape perforator," which perforates paper tape in accordance with coded instructions regarding dimensions and machining procedure provided by the planning engineer.

(2) A "tape recorder," which transfers these instructions to a computer.

(3) A "computer," which calculates from these instructions the movements which must be made by the table of the machine tool.

(4) A "magnetic tape recorder," which memorises the required movements.

(5) Tape-controlled servo-mechanisms and measuring devices, which move under the control of the tape-playback unit.

The method adopted to obtain the high degree of accuracy attained is shown in Fig. 8. A suitable length of optical grating with 5000 lines per inch[12] is attached to one section of the machine slide, and a short length of similar grating to the other section, so that one grating traverses the other with the two surfaces almost in contact. If a beam of parallel light is projected through the pair of gratings, the fringe pattern will modulate the light when there is relative movement ; one complete cycle of intensity variation will occur for a movement equal to the pitch of the grating, and two discrete electrical pulses per grating line can readily be obtained by the double photo-tube arrangement shown ; the phase of the light variation is different in each tube and so a two-phase electrical system can be formed, the deviation of phase rotation of which reveals the direction of movement of the slide.

The servo mechanism controlling the table movement is arranged so that on receipt of a command pulse the table is moved in the correct direction until a pulse from the grating cancels the command pulse. Thus, if a train of pulses is received, the slide is moved at a rate such that a similar train, lagging by an amount not exceeding one pulse, is produced. This means that the error can never exceed one-ten-thousandth of an inch unless the servo-mechanism is over-loaded.

Other methods of controlling machine tools utilise magnetic recording of the actual motion of the tool when operated by a skilled machinist ; on playback, all movements are repeated, faithfully reproducing the skill of the original craftsman and the peculiarities of the particular machine.

[11] Ferranti, Ltd.
[12] Developed by the National Physical Laboratory.

Techniques such as these are likely to become of increasing importance, particularly for short runs ; the versatility of such systems will appeal especially to small-scale precision manufacture, a feature being the



Fig. 7—Electronically controlled milling machine —Ferranti

ease with which a library of taped instructions can be built up.

The construction of radio and electronic apparatus by printed-circuit techniques has been hailed as automation, but the essential fact here is the modification of the construction of the product to permit manufacture by a cyclic automatic machine ; by using "printed-circuit" resistors, capacitors and connecting leads consisting of carbon or silver deposits on a ceramic base, assembly by automatic machinery is possible.[13]

Although these previous examples contain varying degrees of automation, none of them are cases of true automation, which in the fullest sense should be applied only to equipment which is self-correcting and self-programming and is capable of automatically performing a sequence of logical operations similar to the mental processes of humans—equipment which can correct the errors which occur in the course of operation and can choose among several predetermined

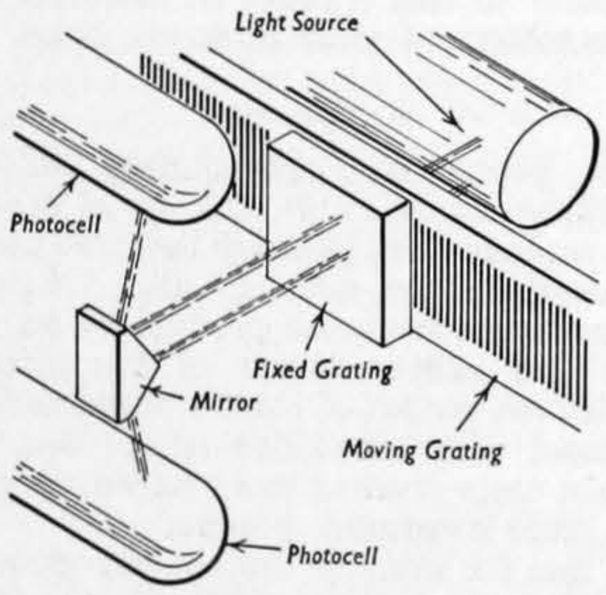


Fig. 8—Method of converting slide motion into count pulses ; electronically controlled milling machine —Ferranti

plans of action. These recent advances constitute the first stages of what coming generations will regard as the second industrial revolution.

[13] "New Methods of Radio Production," J. A. Sargrove, *Proc. Brit. I.R.E.*, 1947, Vol. 7, page 2.
"New Techniques for Fabrication of Airborne Electronic Equipment," R. K. F. Seal, *Proc. I.R.E.*, 1955, Vol. 43, pages 4–11.

It is now becoming possible to modify production machines for automatic operation by replacing the operator and adding material handling devices. Man's function at present is to tend the machine ; he positions raw stock, inspects and removes the workpiece ; when trouble arises he stops the machine, ascertains the cause, and corrects it. He records the number of pieces machined and rejected and uses his senses of smell, sight, touch and hearing to ensure correct operation. In fact, he acts as an overall control. If we couple existing production machines with material handling devices, add appropriate sensing devices and a control mechanism to do the work of the operator, then we have complete automation.

A machine which fabricates a product, inspects it and, if incorrect, returns it to the fabricating machine for further operation until it meets a given specification is truly automatic—one example is a piston-fabricating machine which repeats the machining operation until the weight of each product lies within specified limits ; another is the automatic control of strip thickness in modern steel strip mills where the speed of passage precludes manual adjustment of the rolls to compensate for variation in the properties of the incoming material.

The essential "role" of electronics in the development of the fully automatic factory is, therefore, the provision of reliable sensing devices and of some kind of overall controller or computer. In most cases the controller is comparatively simple ; it is to be deprecated that an impression has been created by the popular press that it is the computer which provides the key to the fully automatic factory of the future and that all that is necessary is to build cheap computers. Automatic sensing devices and materials handling devices are in most cases far more important.

The factory of the future, and the near future at that, will consist of production and transfer machines with electronic sensing devices to control, inspect, count, sort, and pack the product ; these modern robots are the substitutes for repetitive human labour ; they can observe events with greater delicacy than the human senses ; they can work at much higher speeds ; they can leave a record of what they have done ; and they "never get sleepy no matter how late they may have been up the night before." In consequence, they can relieve man of much of the monotony inherent in mass production, they can ensure greater uniformity of the finished product, they can save raw material, and they can increase output because the working day can be indefinitely extended.

In the fully automatic factory of the future the information generated by the production processes will be gathered automatically from these processes. It will be possible for a central computing mechanism to keep a continuous running record of each part that is passing through the plant. If the individual machine-control circuits are connected to the information-handling circuits of the office, a running record can be kept of the position of each part in the production process and of the number of acceptances and rejections at each manufacturing stage ; if a machine breaks down, the production of other machines and the flow of product units between machines will be adjusted automatically by the computer to compensate for the disruption. With continuous monitoring by the inspection devices machine failures can be reduced. The computer will take cognizance of the fact that trouble has begun and either correct it or inform the maintenance staff of the location of the trouble ;

this will occur before the machine actually breaks down, or before many parts are spoiled, or before machining time is wasted on parts that will subsequently be rejected.

Production scheduling and production control will also be entirely automatic. Starting with the product output requirements, introduced into the computer on the basis of management decisions, the computer will automatically schedule the entire production processes of the plant and will take into account disruptions that occur in actual operation. By programming the machine with information now contained on parts lists, specification sheets, operation sheets, and other forms used in production control, it will be possible for the computer to determine the optimum runs for each production line, taking into account such variables as the cycle time of individual machines, machine availability, special requirements of certain components, and the probability that delays will occur at specific points.

Under the most progressive present systems of production control, parts lists and specification sheets are in the form of punched cards. These cards are processed by office machinery to determine the material requirements for production. With a computer, not only will parts lists be compiled but this information will be used also to determine the optimum scheduling of each production machine. Such automatic scheduling will be done in terms of criteria built into the computer's programme.

Once properly programmed a digital computer can automatically process a great variety of information and can take all necessary action in connection with its analysis. Using automatic typewriters and accounting machines it can be designed to perform all accounting and book-keeping functions of a business. If attached to the control of automatic-processing equipment it can monitor the operations of an entire manufacturing plant. By very rapidly "asking" a series of questions of each machine tool and each sensing device it can quickly correct errors which have occurred, or which certain combinations of events indicate will soon occur. With such computer control it is possible to extend the industrial use of the principle of "end-point control" —whereby a signalled change in the requirements of the end product automatically brings about the necessary changes at each point in the manufacturing process. Such control is now possible in a limited number of the already highly automatic process industries, such as oil refining. By use of computers it will be possible to introduce end-point control in whole, or in part, to many other industries.

Digital computers will provide a means of automatically governing the operation of much of our manufacturing equipment. Where processing equipment can economically be connected to permit a continuous flow of product units, entirely automatic plants are possible ; in many more cases, portions, but not all, of the operations of a business can be put on an automatic basis. If used with insight and ingenuity, computers will permit relief from the most repetitive form of human work. They will make possible more rapid and less wasteful methods of increasing our productivity. By virtue of their great speed and ability to handle simultaneously many variables they will permit many tasks to be performed which until now could not reasonably be attempted.

"Automation," in the sense of the fully automatic factory, is just beginning to displace mental effort ; just as mechanical aids have very largely displaced man's physical effort and produced the first industrial revolution, so will electronic aids ultimately displace man's mental effort. It is this "intelligent" control of a complex process now made possible by such techniques which distinguishes them from all others and which legitimately can be called revolutionary.

This is the object which control engineers are trying to attain, and their success will represent one of the advances in technique which Sir Ben Lockspeiser said recently[14] must be developed if the Chancellor's hopes for a rapid rise in our standard of living are to be realised.

The author wishes to acknowledge his indebtedness to those industrial organisations and publishers who have given permission to extract material, and to Unilever Limited for permission to publish this article.

Agriculture

By S. J. WRIGHT, M.A.*

UNTIL well into the nineteenth century nearly all farm implements were made by local craftsmen working, more often than not, to the designs of individual farmers. There were innumerable types, each more or less confined to one neighbourhood, so that a distinguished French agriculturist of the period was led to observe that "in England there are above a hundred ploughs, all of them bad." One of the first men to set up a plough works from which a wider range of needs could be supplied was the Robert Ransome who was largely responsible for the all-iron plough, and who invented chill casting as a means of making self-sharpening plough shares. Other implement works followed, while the growth of agricultural engineering as a distinct industry was accelerated by the spate of new farm appliances that arose later in the century. This was a Golden Age of agricultural invention, partly as a result of competitions organised by such bodies as the newly formed Royal Agricultural Society, and partly because of the unceasing demand for labour-saving machines that arose from the opening up of the prairie lands of North America.

But the factories that were set up to manufacture these new machines in Britain were all situated in the Eastern Counties —as in America they were located on the threshold of the Middle-West—where the demand for their products was greatest, but where at the time little, if any, general engineering was carried on. And, whether or not as a result of this geographical divorce, there was, for a very long time to come, a sharp and discernable difference—in design, materials and construction alike—between the products of the implement factory and those of engineering proper. Perhaps it is only fair, however, to mention another reason—that mechanisation in agriculture is beset with the peculiar economic limitation that machines hardly affect actual production processes at all and cannot change their time table. Given a reasonable standard of husbandry to start with, for example, the mechanisation of corn growing will neither raise yields nor speed up growth ; while, however costly the harvesting equipment may be, it can be used only for five or six weeks in the year. For reasons like this agricultural machines have always tended to be cheap and effective, rather than elaborate or even efficient in the ordinary sense, and perhaps this is why materials and manufacturing methods which were outmoded in other industries lingered in agricultural engineering for so long.

Nevertheless, as this article is concerned to illustrate, most of the barriers between agricultural and general engineering have, in fact, been removed almost within the last decade. One side of the story, which needs to be told in some detail if the influences at work are to be understood, concerns the evolution of farm motive power from the steam ploughing with windlass and cable which John Fowler and Robert Ransome's descendants contrived in the 1850s, through the "oil-engined agricultural locomotive" that appeared with the turn of the century, to the ubiquitous farm tractor of to-day. Another aspect may be illustrated by the developments, largely independent of the tractor, that have arisen in the conservation and storage of crops on the farm. Finally, there are the new links with engineering, too numerous for more than brief mention, that have arisen from such factors as the spread of rural electrification, new techniques for processing crops between farm and consumer, and new scientific discovery on the control of weeds and pests.

The designer of the first oil-engined agricultural locomotive was so careful not to flout tradition that he gave it a smoke-stack, and concealed his engine with what was to all appearances a steam boiler! Twenty years later, the farm tractor was still little more than a slow-moving stationary engine mounted, together with a crude transmission, on a heavy cumbersome chassis.

The first break with this kind of outlook came, almost dramatically, in 1917 with the tractor which—it is said at the direct instigation of Mr. Lloyd George—Henry Ford I designed and produced to assist our food production campaign. This tractor, powered by a relatively high-speed, multi-cylinder engine, with no chassis other than that provided by the engine and transmission housing, and lighter by far than any of its predecessors, was widely criticised on its first appearance as being quite unsuited to agriculture. Nevertheless, from 1920 onwards the design was so widely imitated that practically every tractor that has come into large-scale production since has followed the same general pattern. Moreover, the actual model itself, manufactured first in the U.S.A., then in Ireland and finally in Britain, survived with very little essential change to bear, in the second world war, the brunt of yet another food production campaign.

This tractor was probably the first agricultural appliance ever to be designed without reference to what farmers might think it should look like : the first in any modern sense—and as a natural consequence of being designed by the man who had already set the motor industry on its way—to be "engineered." More significantly the tractor marked the first step in the liaison between agricultural engineering and the motor industry, which, though it was not to come to full fruition for another quarter of a century, has now changed the whole pattern of farm mechanisation.

Between the wars, while tractors on British farms were rising in number from the 2000 or 3000 left over from wartime food production to around 50,000, they were used for the most part alongside horses,

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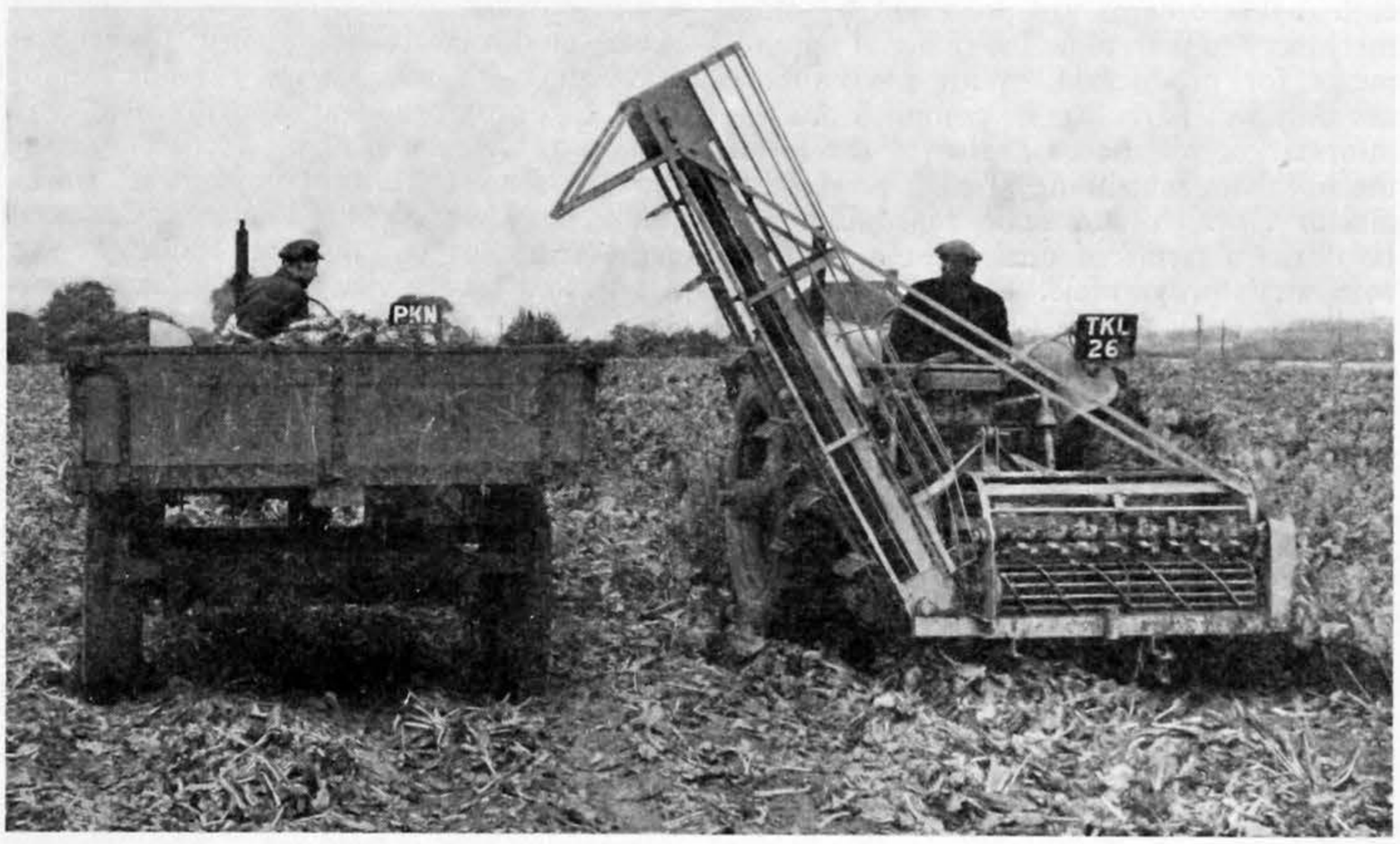
[14] In a speech entitled "When Industry and Science Get Together," given to the Institute of Directors in November, 1954.

and mainly to assist or replace them in the heavier work. Provided that the job was one in which greater power could be used to good effect a man with a tractor could accomplish as much as three or four men with pair-horse teams, and if the tractor cost more to buy and operate, this was offset by the saving in wages. But horses were still there for the lighter work ; nor in the 'twenties did it cost much to keep them. Corn prices were low and there was plenty of understocked grassland ; while, as it used to be said, horses bred on the farm for sale to the town soon ran into money. In fact, by displacing horses from the roads, the motor industry itself did much to change the economics of horses on farms. Two major developments of the period were the power take-off with which the tractor engine could drive mechanisms, like those of the mower and binder, independently of land wheels, and the low-pressure pneumatic tyre which made tractors more mobile both in getting about the farm and for transport work. By and large, however, there was no real indication up to the outbreak of World War II that tractors would ever displace horses from farming as completely as they are doing now ; nor had they yet done anything to reduce the great amount of direct hand labour still necessary not only in many aspects of crop production but also for innumerable farm chores.

What has happened since the war is the result of many different influences, perhaps the biggest single one being that of the younger generation of farmers' sons and farm workers who, as the result of their experiences in the Services or elsewhere off the farm, had become machinery-minded. Like the American farm worker whom the late C. S. Orwin used to tell about twenty years ago, they were no longer content to be " chambermaid to a pair of mules." If they were to be kept on the farm the farming must be mechanised. Moreover, men who are accustomed to control machines in their main work take unkindly to hand work in between, or in the off season ; while shortcomings in this respect are accentuated by the higher statutory wages now payable. In consequence there has been a general urge, not yet fully satisfied, to use mechanisms and mechanical power for everything in farming, for all the everyday chores as well as for the cultivating, sowing and harvesting.

For those who could see ahead immediately after the war there was foreshadowed a demand for all kinds of equipment outside the normal range of the implement maker : for loading and handling farm produce and materials ; for such tasks as trimming hedges or cleaning ditches ; for preparing and mixing feeding stuffs. Moreover, very often looking to farm mechanisation for new outlets for their energies, there were the many factories outside agricultural engineering that had been expanded or brought into being to make munitions. By this time tractors had come into everyday use on most large or medium-sized farms and it was natural for designers to regard them, not only as the power units which would operate their new devices, but also, in many instances, as the basic structures on which new equipment could be mounted. In the meantime, even with the traditional ploughs, cultivators and harrows, a new conception of equipment that would be integral with the tractor instead of simply being hauled by it had arisen from Mr. Ferguson's unit principle implements with hydraulic lift. Even before the war enough tractors embodying this principle had appeared to whet appetites for more, and in their plans for new post-war models most tractor manufacturers in both Britain and the U.S.A. were thinking on similar lines. Particularly in Britain this meant that tractor and implement designers could no longer work—as they had largely done hitherto—in isolation from one another, leaving their respective products to be matched up only by the farmer in the field. Whether in co-operation with old-established implement makers, or independently, tractor manufacturers had necessarily to interest themselves in implement design, while in their new models they had also to pay some regard to all the new appliances which were likely to be attached to them. The result has been a happy one for all concerned : the age-long experience of the traditional implement maker has been wedded to the design and production know-how of the motor industry; a great deal of new manufacturing ability has been brought to the service of farming ; and to repeat a phrase already used, the barrier between agricultural and general engineering has virtually disappeared. There have been three major consequences, the first being that most traditional implements have acquired an entirely new look, partly from the elimination of self-lifts and general cleaning up of design that followed automatically from mounting them on the tractor, and partly from the use of a wider range of materials and manufacturing methods. Secondly, there has emerged an entirely new and extensive range of equipment for loading, digging, earth moving, and so on, which has not only brought into farming many appliances that were once available only to civil engineering, but has also taken the nominally agricultural tractor into fields of activity far removed from the farm. Finally, although, apart from restyling, general appearance has altered very little, the functional attributes of the tractor have changed entirely. It is now literally a maid of all work, able to travel slowly or fast as required, able to operate economically in light work as well as heavy, and able, through its external hydraulic services, to operate mechanisms of ever-increasing variety. One very notable advance, with potential repercussions well outside agriculture, has been the development of the low-cost high-speed diesel engine with power and torque characteristics so well suited to the varying loads of farming. Diesel engines designed originally for farming are now being used to cheapen road transport ; tractor engines have even been built into production motor cars ; while, more recently still, the evolution of very small air-cooled diesels for an almost infinite range of applications owed its inception mainly to agricultural needs.

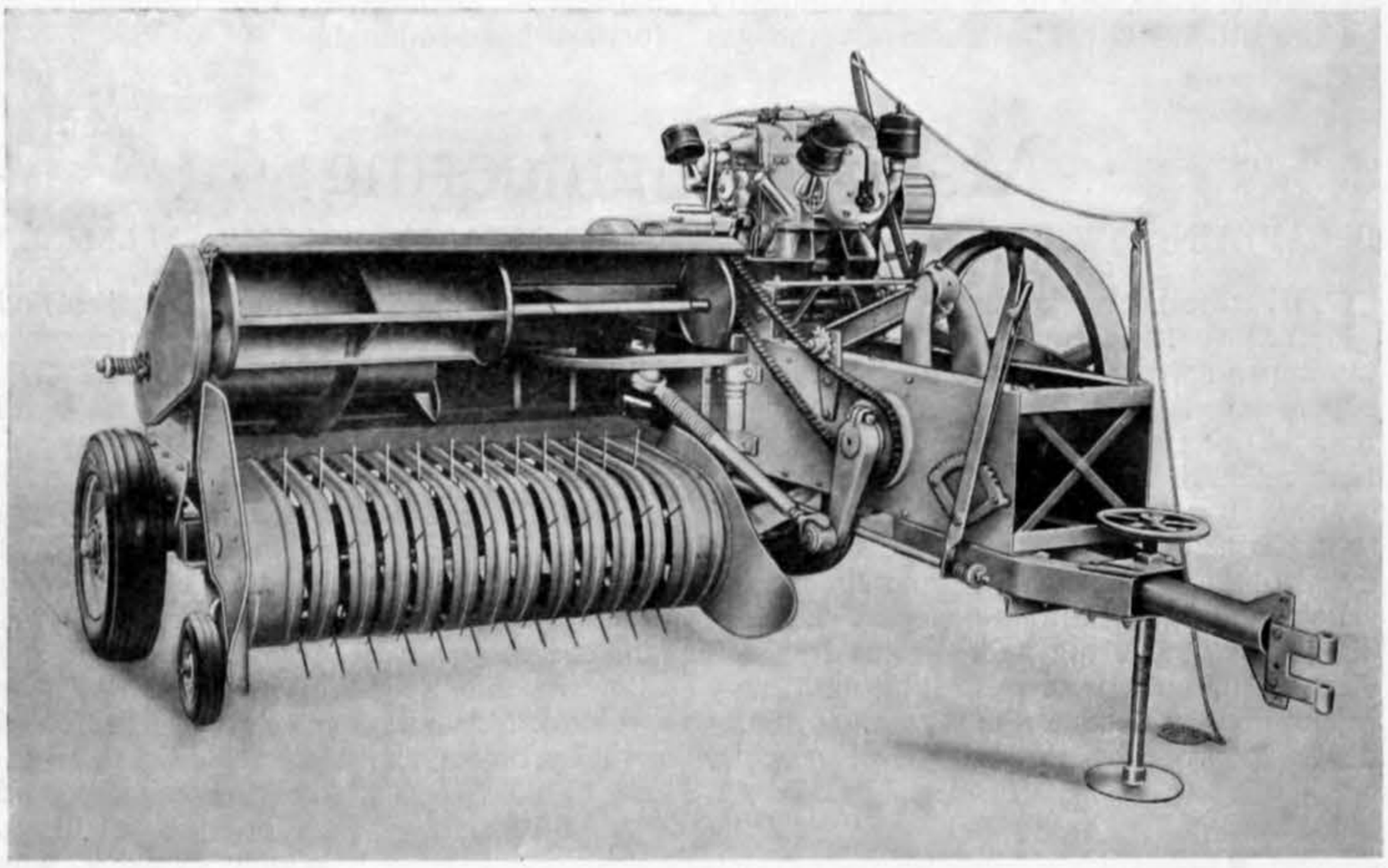
Quite another direction in which recent farming progress has involved new engineering enterprise is crop conservation and storage. One side of this arises from the growing popularity of combine-harvesting, and another from the need to reduce imports of feeding stuffs by making better use of our own fodder products. Two of the major inventions of the nineteenth century were the threshing machine and the reaping machine, and it was natural enough in the long run that the two should be combined so as to eliminate intermediate handling by cutting and threshing grain in one operation. The original demand for this arose mainly from the prairie countries, and it was not until the 1930s that combined harvester-threshers began to come into use here. But in our climate grain at harvest time was very often not dry enough to be safely stored ;



Tractor-operated sugar beet harvester designed by G.W.B. Farm Machinery, Ltd. The machine tops the beet lifts it from the ground and conveys it to a vehicle running alongside

so the introduction of the combine, as it is now commonly called, brought with it a need to develop farm grain driers. Until 1939, when there were less than 200 combines on British farms, each had its own grain drier ; but, through shortage of materials, the two or three thousand additional combines that came into use during the war had generally to manage without them. Even with this greater number of machines the proportion of the whole grain crop that was threshed in the field was quite small ; and through the good offices of local millers, and with some help from Government-sponsored grain drying plants operated by county war agricultural committees, all the combined grain was handled without serious loss. Since the war, however, the demand for combines—not only to save labour but to reduce the weather hazard of the corn harvest—has so accelerated that it now seems not unlikely that the machine will soon be as universally used as the reaper-binder before it. This has brought the new problems arising from a big proportion of the total grain crop coming on to the market immediately after harvest—instead of being stored in the stack and threshed during the winter—and recent government policy has aimed, by price

differentials, at giving farmers an incentive to provide their own storage for threshed grain. In particular, this has brought the science of pneumatics right on to the farmer's doorstep in connection not only with the actual drying but also with the movement of grain through the installation as a whole. The drying of grain is not simply a matter of getting rid of excess moisture as quickly and cheaply as possible ; if the malting qualities of barley, the baking qualities of wheat, and the germination of seed grains of all kinds are not to be impaired, there must be close control of temperature and also of the rate at which moisture is removed. Problems of air flow arise even with the continuous drier in which heated air is blown through a relatively thin sheet of grain which is moving continuously meanwhile ; and, to a greater degree with batch driers in which similar sheets of grain are stationary during the drying. More recently, however, the incentive to provide storage as well as drying facilities has brought a new method into prominence in which instead of being dried the grain is " ventilated " with cool air during bulk storage in bins. Here, particularly just after the grain is first put into bins, the question of air flow may be very critical indeed, for pockets of damp grain may later be detrimental to the whole mass. One way of avoiding risks is a periodical transfer of the whole mass of grain from one bin to another so that it gets thoroughly mixed in the process. According to the particular layout—which is very often dictated by existing farm buildings—this and other transfers of grain from one point to another may be done either mechanically or pneumatically, while in the latter case the avoidance of mechanical damage from impact is yet another factor to be looked after. A great deal of experimental work on all this has been done, notably at the National Institute of Agricultural Engineering, and a great deal of engineering ingenuity put into the design of drying and storage plants. The construction of storage bins alone—involving, as it may do, materials as diversified as wood, breeze blocks and sheet aluminium—has brought farming new contacts with engineering industries. The instrumentation side of drying is also quite important : in connection with the measurement and recording of temperature ; the automatic control of air burners and air intakes ; and the measurement of moisture content in which physical, chemical and electrical methods are all used. The conservation of grass and other fodder crops is a more diversified subject with the final outcome still very much in the balance. The traditional method of conserving grass for winter feeding—and the one still most widely practised by farmers—is ordinary hay-making in which the grass is dried, from its original moisture content of perhaps 80 per cent to about 14 per cent, by the natural agencies of sun and wind in the field. There have been notable advances in hay-making machinery but these, like the combine, are for the most part straightforward developments from 19th century inventions and need not be discussed here. One newer line of development that is worth brief mention, because it has a bearing on what follows, is that of machines which will bruise or crush the grass immediately after cutting so as to accelerate natural drying. The basic difficulty of hay-making in our uncertain climate is that it is so liable to be interrupted by unfavourable weather that, more often than not, the resulting hay has a much lower nutritional value than the grass from which it is made. Moreover the one food element that every stock-rearing farmer would like to provide for himself is protein ; and while, if it is cut when young and green, grass has a high protein content, it is notoriously difficult to make into hay from this state and is normally left to grow longer, losing much of its protein meanwhile. Correspondingly the basic difficulty of all alternatives to hay-making is that they involve collecting and transporting from the field, not only a weight of material equivalent to that of the hay, but also the weight, four times as great, of the unwanted moisture. One such alternative is silage making in which the grass, which can be cut while the protein content is still at its maximum, is put while still green into pits, stacks or silos where, given careful enough control, a process of fermentation not only preserves it but ensures that most of the original feeding qualities are retained. But silage is heavy and generally unpleasant to handle and, although some of the tractor attachments mentioned earlier have made the task easier, most farmers and farm workers would prefer something different.



Pick-up baler for hay or straw, built by Bamfords, Ltd. This machine is hauled by a tractor and powered independently by a twin-cylinder oil engine. It can handle eight 60-lb bales a minute

Interest in artificial drying as an alternative to both haymaking and silage began twenty years ago, when experiments at Cambridge showed that, in this way, ordinary lawn mowings could be turned into a high-protein concentrate. The physical problems of collecting and transporting grass for drying are similar to those of silage-making and involve much the same equipment in the field. The agricultural problem, with anything but a small drier, is to maintain an even supply of grass. In May and early June there is a flush of grass heavy enough to overload even a large plant, while for several weeks afterwards the rate of growth is generally so far reduced that it is difficult to keep any plant working economically. In the drying itself, problems of air flow are even more critical than in grain drying, not because there is ordinarily any great danger of spoiling the product, but for the economic reason that, with a much greater weight of water to be removed, it is essential that every cubic foot of heated air should carry off its full quota. The earliest farm plant, and the one still most common for the production of relatively small quantities of dried grass for consumption actually on the farm, was the simple tray drier, in which air heated by being mixed with the gaseous products of combustion from an oil or coke-fired furnace is blown through the perforated bottom of a tray on which a layer of grass has been spread by hand. For uniform drying the grass generally needs to be turned over or transferred to another tray at a halfway stage ; so that the method has a relatively large labour demand, and is not highly efficient from the standpoint of moisture removal per pound of fuel. Larger farms, and particularly those which aim at providing dried grass for sale as well as for their own use, generally use conveyor driers which use recirculation of air to improve thermal efficiency and on to which the grass is fed and tedded mechanically. Finally, there are the " factory " plants, very often using grass grown under contract on several surrounding farms, which use high temperature driers through which previously chopped grass is carried by the air-stream itself and dried almost instantaneously. Mention should also be made of a compromise process, somewhat analogous to the ventilation of grain in bins, which has found some favour, particularly in the north of England. In this, after wilting or partial drying in the field—and this can be done without much risk from bad weather—the grass is put into barns and finished off by ventilation with air which is heated, if at all, only sufficiently to lower the humidity. Grass drying generally involves much the same engineering problems as grain drying : all of them intensified by the different nature of the material ; the greater need for thermal efficiency ; and, at least with some types of drier, the much higher temperatures involved.

The most recent development in protein conservation provides a still more striking example of the incursion of engineering into agriculture because it tackles the problem in entirely new and mechanical fashion. Briefly, the principle behind it is that, provided the cell structure of green crops can be thoroughly broken down, the greater part of their protein content can be expressed in juice : and that the solids in this can afterwards be coagulated by moderate heating or, more slowly, by settling alone. The worm mechanism used for rupturing the cells and expressing the juice bears some resemblance to that used for the extraction of vegetable oils from seeds, but has two main differences. The

worm itself has a tapered profile with diminishing pitch and tooth depth so as to exercise a wringing, as well as pressing, action ; while instead of being expelled through the sides of the worm chamber, the juice filters back through the material to emerge near the larger end of the worm. Following coagulation and the squeezing-out of surplus moisture from the resulting sludge in a simple press, there are two end products. One of these is a reasonably dry " cake " with a protein content of 40 or 50 per cent ; while the other is a fibrous residue, nominally suitable for feeding as roughage, with about 8 per cent of protein and, presumably, much of the original carbohydrate content. This is essentially a farm process because of the high cost of transporting green material, and because the outcome will depend largely on ability to make good use of the fibrous residue. Actual application on the farm is still very much a matter for experiment and trial ; but, if it proves successful, the process will represent one of the most radical departures from traditional practice yet seen in everyday farming.

In more specialised branches of agriculture other radical departures from traditional practice have arisen already from the extended use of electricity. There are, of course, innumerable instances on the farm in which electricity, without substantially changing methods, provides a more convenient form of light, heat or power : for the safe lighting of farm buildings ; for the operation and automatic control of pumping sets and feed grinding installations ; and in connection with the ventilation methods of drying grain and hay. In dairying, too, the supreme virtue of cleanliness has brought electricity into every phase of milk production, from cow to bulk container, and has given rise to a completely new branch of the equipment industry. Apart from all this, however, electricity is introducing new methods in both pig and poultry husbandry as well as in the side of horticulture that is concerned with producing out-of-season crops. With both forms of livestock infra-red heating is being used to reduce infant mortality ; with pigs it is being used also to give the greater weight for age on which economical production depends ; while, by controlled lighting, the adult hen is being deluded into laying more eggs. Electricity in horticulture is mainly concerned with soil heating, the higher cost of heat itself being more than offset by the fact that with buried low temperature cables it can be applied, without need for the permanent installation of piping or anything of the kind, wherever it is needed. Again, with such crops as lettuce, artificial daylight is being used to promote winter growth.

Apart from fresh fruit and vegetables, few of the products of agriculture reach the consumer in anything like the form in which they leave the farm. Indeed, some, like wheat and barley and hops, are very largely only the raw materials of other industries like milling and brewing. One instance of the kind in which there has been a very close inter-action between engineering and farming is sugar beet. In this country the beet sugar industry is of comparatively recent origin ; and, in view of the great efforts being put into the development and manufacture of beet harvesters and other labour-saving machines, it is strange to recall now that when the crop was first given official encouragement in the 1920s, one main object was to check rural unemployment. In relation to world prices sugar made from sugar beet, wherever it is grown, has always been up against the difficulty that it can hardly compete on level terms with cane-produced sugar. On the other hand, the one justification for the crop in Britain—which the second world war served only to emphasise—is that it produces more human food an acre than any other. To-day, however, thanks very largely to what has been done, mainly in the field of chemical engineering, to improve processing techniques—by lowering fuel consumption, economising labour, and raising the sugar extraction ratio—the disadvantage of beet in relation to cane is smaller than ever before. Indeed, if what the industry has also done to give beet-growing farmers a cheap and valuable feeding-stuff in the shape of dried, and sometimes molassed pulp, is also taken into account, it is doubtful whether overall disadvantage exists any longer. Another off-the-farm aspect of agriculture which engineering developments have altered materially, with benefit to producer and consumer alike, is the marketing of fruit and vegetables. It would be difficult to estimate, for example, just what the canning that is now done in or near our own countryside means to the farming industry on the one hand, and to the tinplate industry on the other. Other instances are the gas storage and controlled ripening of fruit, the deep freezing of vegetables, and the refrigerated transport of meat. Finally, there are the new links with engineering that are arising from new scientific discovery on the control of weeds and pests.

Throughout this story, the one thing that has hardly altered at all is the actual succession of operations—with plough, cultivator and harrows—with which our fields are cultivated. From earliest days of steam men have dreamed of applying mechanical power directly to soil cultivation, instead of simply to the pulling or carrying of existing implements, yet by and large traditional methods have persisted. In the last analysis, however, these methods are concerned so largely with weed control that with the new selective weed killers now becoming available, the whole basis of cultivation may be altered in the future. In the meantime, what is to be marvelled at is the speed with which once a new herbicide has been discovered—generally in a field laboratory far removed from any factory—one or other branch of engineering makes it readily and cheaply available to the farmer. There are indeed no longer any barriers : engineering and agriculture go forward hand-in-hand.

Marine Engineering

By CAPTAIN (E.) W. GREGSON, R.N.R., M.Sc.(Eng.), M.I.Mech.E., M.I.N.A., M.I.Mar.E.*

THE editorial in the first number of THE ENGINEER, in January, 1856, propounds the aims and objects of the founders of the paper and their intention of covering all branches of engineering—a policy which has been maintained throughout the succeeding century. It is, however, particularly gratifying to a marine engineer to find that, on turning over to the next page, the first descriptive article and illustration concerns a ship. True it was but a tug built for the Regent's Canal Company, with propelling machinery resembling a locomotive ; each cylinder drove a propeller through bevel gearing. The design in question qualified for the premium of £100 offered by the Canal Company for the best type of vessel for their local London services. Perusing the pages of the January, 1856, numbers, we then find the first mention of an ocean-going steamship in a description of the American-built " C. Vanderbilt " ; the description ends with these prophetic words : " . . . and apparently but little reliance will be placed upon her sails." But sails remained as auxiliary to steam for many years, not for security of service, but to take advantage of favourable winds and so reduce the demand on fuel. The steamship had to give up space and allow for the weight of its machinery plus its bunker requirements : this represented a vital problem, as it meant sacrificing cargo-carrying capacity and therefore earnings. Which explains why the sailing ship persisted as an economic entity right up to the turn of the century on the long runs to the West Coast of South America, to Australasia and to the China seas.

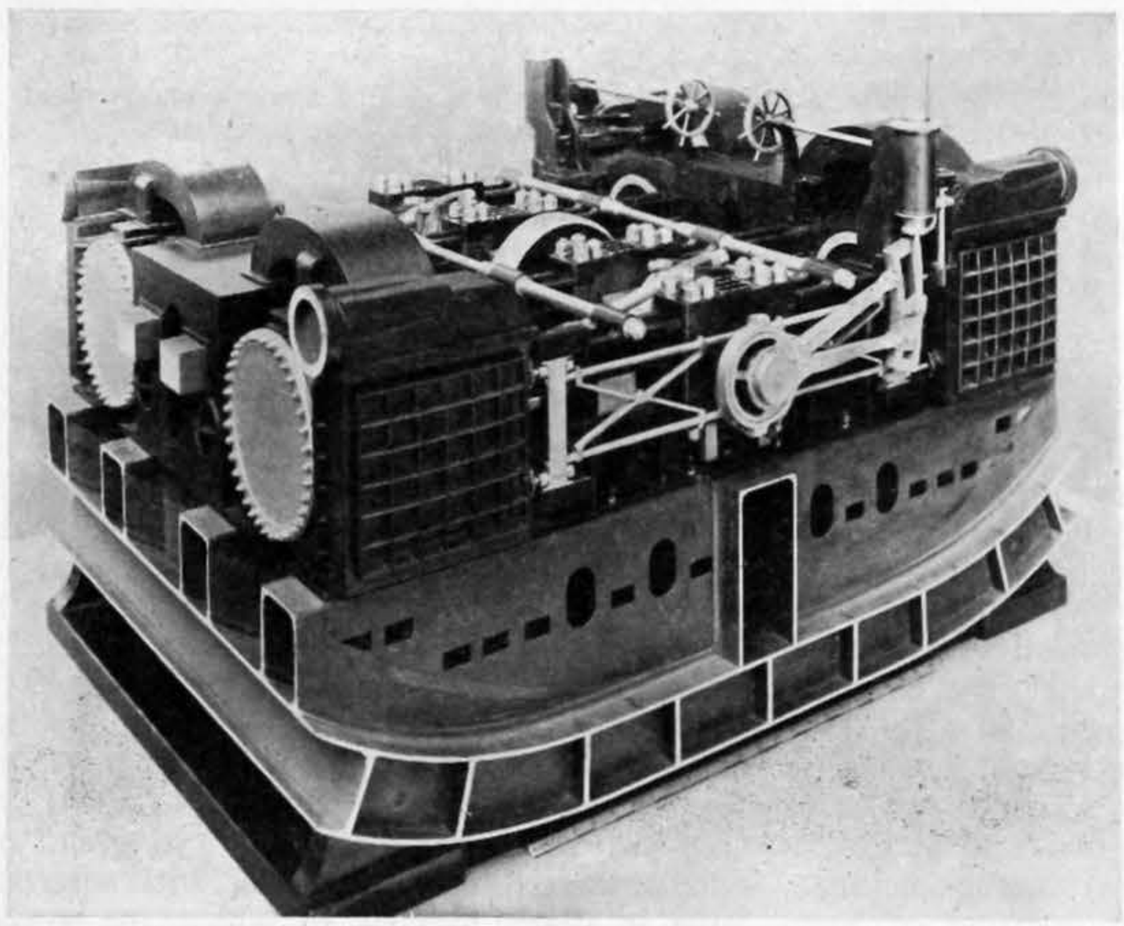


Fig. 1—Set of engines for S.S. " Great Eastern " (1858) driving propeller. This ship also had paddle engines. This Crown copyright photograph of a model is reproduced by courtesy of the Science Museum

COMING OF THE INVERTED ENGINE

The machinery seen in ships at sea in the eighteen-fifties (Fig. 1) covered a varied assortment of designs. The names of Napier, Penn and Maudslay appear frequently in references to marine propulsion and they and their contemporaries designed and constructed oscillating, trunk piston, side lever and many variations thereof. All these engines were slow-running long-stroke machines, so when used for screw propulsion speed increasing tooth gearing had to be fitted. In 1856 H.M. Navy was using the horizontal trunk piston type of engine almost exclusively.

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The inverted engine (" built on the idea of the Nasmyth steam hammer ") came into being in the middle 'fifties, and two early ships so fitted were " Thunder " and " Laconia," in each case the engine consisting of twin cylinders of shorter stroke than maintained with all the earlier types of engines, thus allowing for engine speeds commensurate with propeller requirements. Incidentally, " Thunder " carried 100 deg. Fah. of superheat although only working at 14·5 lb per square inch. Excepting for paddle propulsion, the inverted engine quickly displaced all other designs. The oscillating engine took over the powering of paddlers as earlier designs were discarded, to be replaced as steam pressures increased by diagonal engines of the type well known to-day, in, however, a class of vessel which is rapidly disappearing (Fig. 3). The modified beam engines of the U.S.A. rivers remained in their traditional form right up to a comparatively recent date.

Compound Engines

The outstanding development of the eighteen-fifties was the compound engine of John Elder, whose name will always be remembered in the annals of marine engineering. A truly great engineer, Elder possessed great powers of application and the advantage of the compound engine was demonstrated in no small way when the Pacific Steam Navigation Company's " Callao," "Lima" and "Bogota" were re-engined by Elder's firm and cut their fuel consumption by something to the order of 40 per cent compared with the admittedly old engines. Actually the first steamer to be fitted with a compound engine was " Brandon," and she had been in service some two years before THE ENGINEER made its debut. Compared with contemporary designs of engine of the single-expansion type, the compound offered over 25 per cent reduction in specific fuel consumption, so it is small wonder that Elder's invention marked an important phase in the development of the marine engine. By increasing its range of action before demanding bunkers the steamer was now able to compete with sail on voyages which up to then had been considered appropriate only for sail. Elder gave some interesting comparisons of performance in papers read before the British Association in 1858 and 1859 and refers *inter alia* to ships with older machinery taking over 4 lb of " best Welsh coal " per indicated horsepower-hour, compared with less than 3 lb with the new type of engine, and figures as low as 2 lb of coal per indicated horsepower-hour were quoted as expectations.

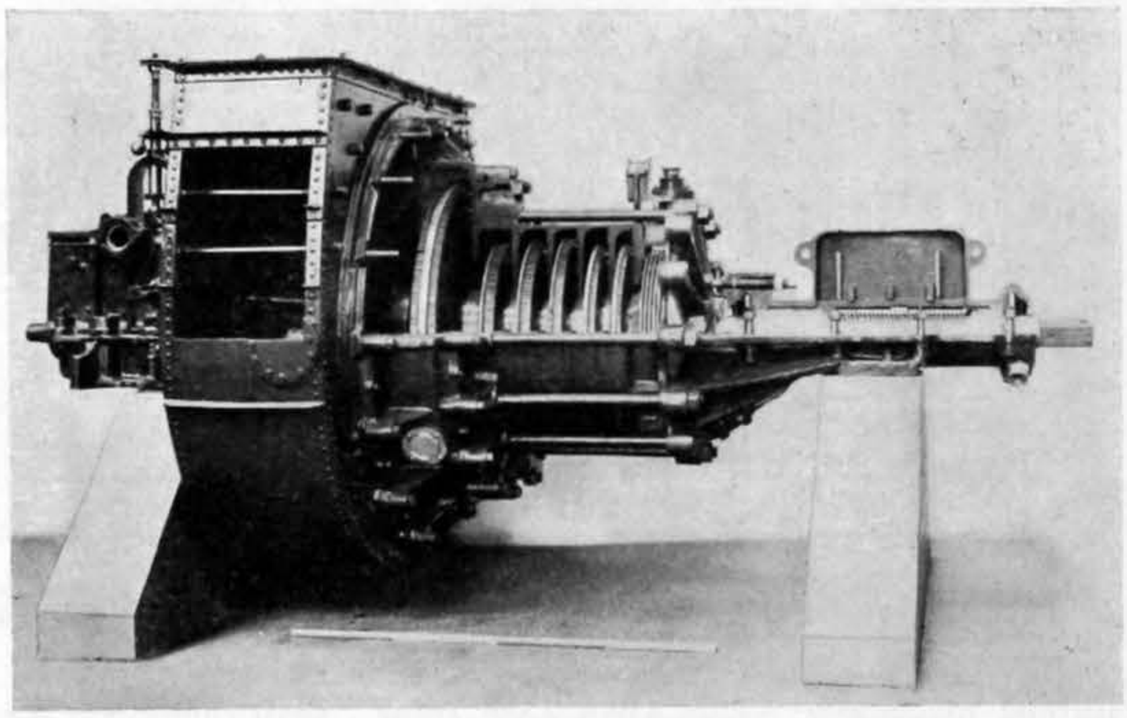


Fig. 2—Original turbines of S.S. " Turbinia " (Parsons Marine), 1894. This Crown copyright photograph is reproduced by courtesy of the Science Museum

Boilers, Condensers and Superheat in the " Fifties " and " Sixties "

At the time our story commences steam pressures were seldom higher than 30 lb per square inch ; jet condensers were in common use and boiler design was extremely elementary. Materials, apart from bearing metals, were limited to cast and wrought iron. But it was the boiler which was the real stumbling-block to progress : salt water feed resulted in heavy deposits and scale in spite of frequent and heavy blowing down and accidents were only too common. The development of the surface condenser enabled the new compounds to function at some 60 lb pressure, but the early designs of surface condenser gave a good deal of trouble and it was not until the circulating water (instead of steam) was passed through the tubes that fouling was overcome. Fouling was due largely to the types of oil and tallow then in use for cylinder lubrication. It is interesting to note that the advantages of steam-jacketing were fully appreciated and, as already mentioned, superheating had come into practice. The trunk-piston engines of H.M.S. " Black Prince " and " Dee " in 1856 represented H.M. Navy's first use of superheated steam. Later on, as pressures and therefore saturated steam temperatures increased, superheating went under a cloud, but in the 'twenties of this century it returned to marine practice and has been highly developed since. H.M.S. " Constance " is believed to be the first naval vessel fitted with a compound engine and on a trial run from Plymouth to Madeira returned a coal consumption figure of 2·51 lb/i.h.p.-hour. H.M.S. " Arethusa " and a series of sister ships were fitted with compound engines when converted from paddle to screw propulsion.

The first ships of the Blue Funnel Line (in 1866) had single-crank tandem compound engines to reduce engine-room length and are reputed to have sailed from the Mersey via the Cape as far as Mauritius without refuelling ; possibly, however, one hold was allocated for additional bunkers on the outward run. The opening of the Suez Canal in 1869 reflected immediately on the increased use of steamships for Eastern and Far Eastern trade. " Canton ", built by Wigham Richardson in 1860, was fitted with Scotch boilers and a two-cylinder compound engine operating at 80 lb per square inch—well in advance of normal practice at this period—and returned a coal figure of 2·31 lb/i.h.p.-hour on her maiden voyage.

Boilers were gradually being improved in design and the Scotch type of multitubular boiler was coming into service. The Belleville water-tube boilers were tried in the Navy as far back as 1860. The way of the water-tube boiler was beset with operational difficulties and high maintenance owing to feed conditions and, oddly enough, the earliest water-tube designs to go to sea were peculiarly susceptible to bad feed conditions. (Incidentally, H.M.S. " Thunderer " was the last capital ship to be fitted with rectangular boilers at 30 lb pressure, and that was in 1872). The later designs of Yarrow, Thornycroft and Babcock and Wilcox produced boilers which really faced up to marine requirements. But there was a long way to go before the Merchant Navy became water-tube-boiler-minded and the factors that helped most—apart from the urge for space and weight reductions—were the steady improvements in condenser construction and materials.

Triple and Quadruple Expansion

Dr. A. C. Kirk, who followed Elder at the (now) Fairfield Yard was responsible for the next major milestone in engine development. He worked on ideas already proposed by his predecessor and produced the triple expansion engine, giving lower steam rates per indicated horsepower-hour than the compound and calling for boiler pressures in excess of 100 lb per square inch. One of the earliest examples was the machinery of " Aberdeen," built for the Australia run where sail competition was dominant. Her engines worked at an initial pressure of 125 lb per square inch. The writer remembers a description of the triple expansion engines of " Arizona "—a ship built soon afterwards—which figured in Rankine's text-book, a copy of which was handed down to him in his boyhood in a very well-thumbed and somewhat tattered condition, but which formed one of his most treasured possessions. Incidentally, MacQuorn Rankine—a man of great intellectual stature who did much to guide contemporary thought and development—was the outstanding figure on the academic side of engineering in the middle of the nineteenth century. The triple expansion engine has persisted until today, but the advantages accruing from more fully expanding the steam before it entered the condenser brought forth the quadruple expansion engine in 1884 ; ten years later one of the most advanced quadruples (before the mighty Atlantic liner engines of the turn of the century) was fitted in " Inchmarlo "—built in 1894 with engines having split l.p. cylinders and working on a 5-crank arrangement. She functioned at 225 lb per square inch with 100 deg. Fah. superheat and the ship is credited with a performance of 1·15 lb of "best" coal per indicated horsepower-hour. Towards the close of the century opinion varied between the merits of a 4-crank triple (with split l.p. cylinders) and a 4-crank quadruple, while the straight 3-crank triple still possessed a host of adherents. The method of assessing fuel consumption against indicated horsepower-hour (a readily ascertainable quantity, measured from indicator diagrams) undoubtedly clouded the issue as, if performance had been based on a brake horsepower-hour basis, it is probable that the increased mechanical losses of the additional cylinder and its motion and valve gear would have reduced the gross thermodynamic gain considerably. The application of the Yarrow-Schlick-Tweedy system of balancing did much to increase the mechanical efficiency of the 4-crank triple and so widen its usage, and it is undoubtedly a better all-round engine than the quadruple.

The engines of the late 'nineties and early twentieth century were indeed striking examples of the art and craft of the marine engine designer and builder, and McAndrew's description thereof—as voiced by Kipling—gives some measure of the perfection of rhythm which attended their operation.

In the Royal Navy, H.M.S. " Diadem," built in 1898, had two sets of 4-crank triples operating at 300 lb pressure and H.M.S. " King Alfred," built in 1900, had similar engines of increased size capable of developing 30,000 i.h.p. on two shafts.

Engines for the Atlantic liners were increasing in power and the last ship to be completed by Harland and Wolff in 1899—"Oceanic"—had two sets of 4-crank triples developing 28,000 i.h.p. on two shafts. German-built liners entering the New York service in the early days of this century had even larger engines, those of "Kaiser Wilhelm II." giving 40,000 i.h.p. *in toto* on two shafts. Each set of engines consisted of a double quadruple engine with the h.p. cylinders in tandem.

The Steam Turbine

We leave the development of the multi-expansion engine for the time being to turn to a competitor which entered the marine field at the close of the nineteenth century—the steam turbine. Curtis in America and Rateau in France were developing impulse-type turbines for land application, and Charles Parsons was pressing on in England with his reaction machine, and it is due to the genius and dynamic energy of Parsons that the steam turbine was first applied to marine propulsion. The story of "Turbinia" is one of the best known epics in marine engineering: how in 1897, at the time of the Naval Review at Spithead to celebrate Queen Victoria's Diamond Jubilee, the little "Turbinia"—with Parsons and his colleagues aboard—ran up and down the lines of naval vessels at (then) unheard of speeds (Fig. 2). The Navy immediately took notice of this entirely novel system of ships' propulsion and two destroyers—"Viper" and "Cobra"—were built to try out the Parsons turbine. Ill-fate brought each vessel to an untimely end, but not through any machinery defects, and these experiments settled the future policy of the Royal Navy. The advent of "Dreadnought" in 1906 marked the beginning of a new phase in naval development and construction, and on the propulsion side she was fitted with four sets of Parsons turbines, and Babcock boilers—following the recommendations of the Boiler Committee in 1901 when Yarrow and Babcock and Wilcox were accepted as basic types for naval work. The former were at first applied to the lighter ships—destroyers and cruisers—and the header-type to the heavier vessels where their increased weight over the 3-drum design was still acceptable.

The first application of the steam turbine to the Merchant Navy was in 1902, when "King Edward" was built by Denny's for the Clyde Coast service. Two of the railway companies ordered similarly propelled vessels, "Queen" for the Dover/Calais service and "Brighton" for the Newhaven/Dieppe run. Remembering that cross-channel packets have the highest power/displacement ratio of all merchant ships, the advantages of turbine machinery with its reduced weight were outstanding. Turbine drive rapidly became standard practice for all the railway steamer mail routes and, benefiting by naval experience, the adoption of water-tube boilers—Yarrow and Babcock and Wilcox—in order to effect further reduction in machinery weight followed. These developments enabled higher powers without increased draught—the latter an important consideration in certain of the terminal ports. It must be remembered that at this period most cross-channel services were highly competitive and, in fact, service speeds were higher in the early days of this century than normally obtain to-day. The Laird-built vessels for the City of Dublin S.P. Co.'s Holyhead/Kingstown Irish mail service represented, with their competitors the Denny-built L.N.W. Railway Co.'s ships on the Holyhead/Dublin run, the highest development of the reciprocator for these fast ships prior to the adoption of the turbine.

Following experience in home waters the turbine was then considered for blue water tonnage; as already stated the large transatlantic liners of the early 1900s were fitted with truly massive reciprocators, and the turbine offered great inducements.

The Cunard undertook a classic experiment by placing with Clydebank an order for "Caronia" with reciprocators and a sister ship "Carmania" with turbines on four shafts—two shafts with h.p. turbines exhausting to l.p. turbines on the other pair, and astern blading on one pair of shafts only. Whereas both ships were outstanding successes on the Western Ocean run "Carmania" demonstrated the advantages of

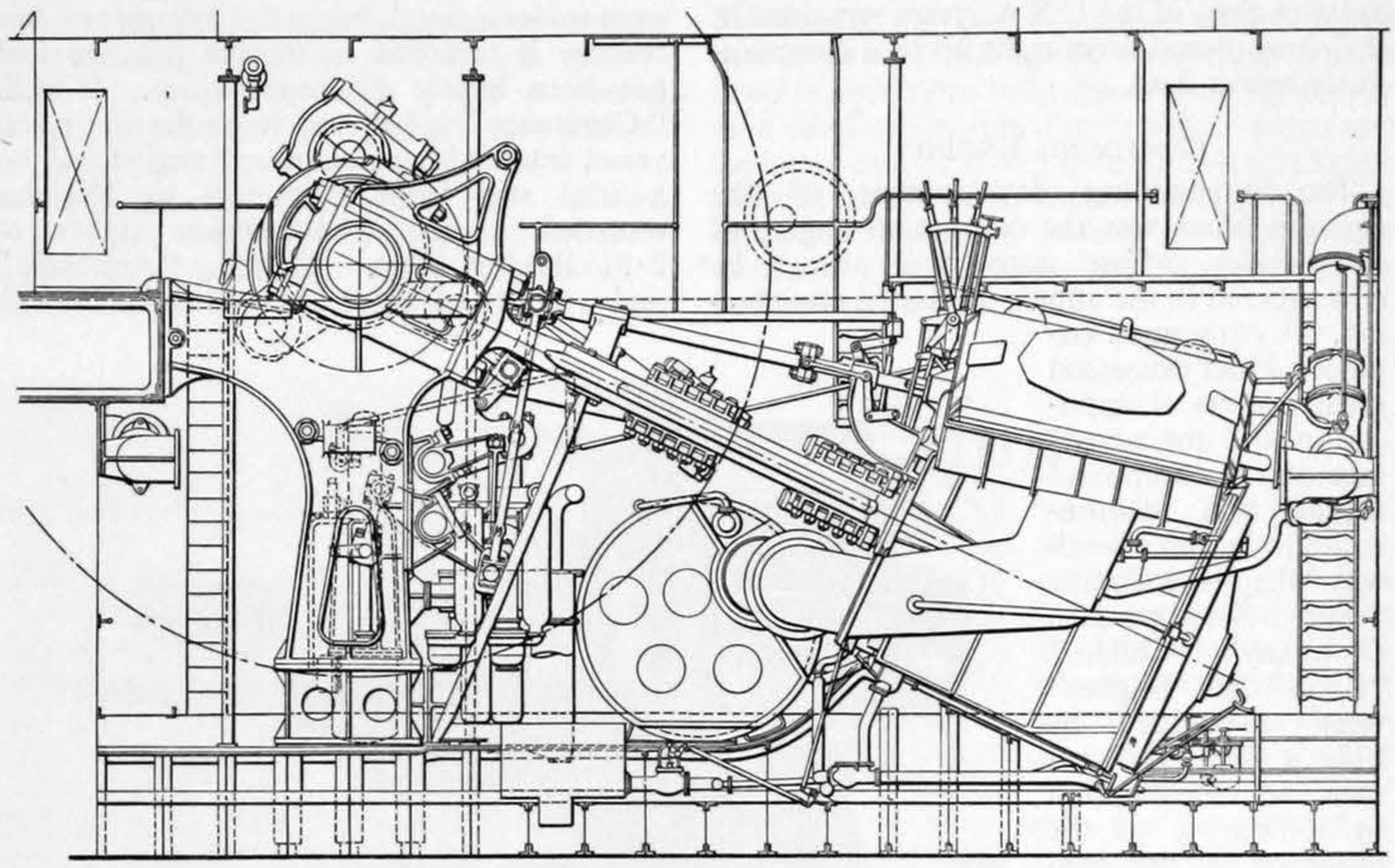


Fig. 3—Three-cylinder compound engines of P.S. "Empress Queen" (Isle of Man Steam Packet Company). Developing 11,000 i.h.p. these were the highest powered paddle engines ever built (Fairfield, 1897)

turbine machinery. The Allan Line (now Canadian Pacific) was also early in the field with turbines for its Liverpool-Canadian service. Then followed those two famous vessels "Lusitania" from Clydebank and "Mauretania" from Swan, Hunter's, the latter with turbines built by Wallsend Slipway under the eagle eye of another of the great figures in marine engineering development, Andrew Laing. And so the steam turbine steadily became the accepted method of propulsion for all vessels involving high powers, the reciprocator filling the needs of lower powered ships; certain steamship lines, however, carried on with reciprocators for medium powers until their post-Great-War programme. Incidentally, the non-contaminated exhaust of the steam turbine freed the water-tube boiler from one of its greatest bugbears.

Exhaust Turbine Development

A contemporary development for high-powered ships comprised two sets of triple-expansion engines on wing shafts and a centre screw driven by a l.p. turbine taking its steam from the reciprocators and so enabling better use to be made of the steam in the l.p. and vacuum range; manœuvring was carried out on the reciprocators alone, cutting out the turbine when going astern. The first ship so fitted was "Otaki," of the New Zealand Shipping Company, built by Denny's; she went into service late in 1908. But the system was especially developed by Harland and Wolff and "Laurentic," of the White Star, which entered service early in 1909, was the pioneer of many Harland and Wolff-built ships to adopt triple-screw "mixed" prime movers. The most famous ship with combination machinery of this type (Fig. 4) was "Olympic," followed by two sisters. The two four-crank triples of "Olympic" each had a service indicated horsepower of 17,000 and the l.p. turbine—taking steam from both sets of engines—developed 17,000 s.h.p. "Olympic" entered the transatlantic run in 1911 and was throughout her career a great success. She possessed the outstanding virtue of ample power in hand to meet her service requirements.

The Geared Turbine

All these early turbine-propelled vessels were direct driven, turbine and propeller shaft running at the same speed, and Parsons realised that to obtain a substantial increase in overall efficiency it was necessary to reduce the slip due to fast-running propellers and at the same time increase the efficiency of the motive unit by running at high blade speeds; the arrangement hitherto was a compromise militating against high efficiency. Parsons therefore developed the idea of reduction gearing and first tried it out in the re-engined "Vespasian" in 1908, with appreciable increase in fuel economy. Then—as ever—the railway companies were well in the van of progress and the Fairfield-built "Normannia" and "Hantonia," for the Southampton/Havre service of the L.S.W.R. Company, were the first two passenger/mail vessels to be so fitted. It is of interest to remember that "Normannia" remained in service until some three years ago, when replaced by a new vessel of the same name.

The natural sequel to the success of single-reduction gearing was to get a wider differential between turbine and propeller shaft speeds without excessive diameter of the main wheel by the introduction of double-reduction gearing. The first ship to be fitted with this type of gearing was "Somerset," but the early installations did not always meet with success and were often very noisy. It was realised that very accurate gear-cutting technique must be available before this development could be used for marine purposes, and in due course improved gear-cutting brought double-reduction gearing back into service and it is now adopted on

a wide scale. The modern gear-cutting machine is indeed a masterpiece of the machine tool art.

The Diesel Engine

So far we have surveyed the story of steam; in 1912 the diesel engine (Fig. 5) went to sea in "Selandia," of the East Asiatic Company, followed by "Jutlandia." Experience had already been gained in a few lower-powered ships, but these two cargo-passenger liner types of vessel really put the heavy oil engine into the marine field. "Selandia's" two engines, four-cycle, single-acting, eight-cylinder units developing 2480 b.h.p. together, were built by Burmeister and Wain; "Jutlandia's" were constructed by Barclay, Curle. The 1914–18 war held back developments on any large scale in Great Britain, but meanwhile Danish, Dutch, Swedish and Swiss firms of world repute were forging ahead and many of our shipyards in due course operated under licence from these companies. It is interesting to note that the original engine patented by Diesel was to use coal dust and not oil, but the inventor never got far on solid fuel. By the early 'twenties the oil engine was well established in the British merchant service. Early in the field was Harland and Wolff, which had taken out a Burmeister and Wain licence before the war; subsequent Harland engines designed and built on underlying Burmeister and Wain principles have included the largest marine diesels ever built. Sulzer, Werkspoor, Polar and other types were built by British shipyards and Doxford had steadily developed its own design of opposed piston, two-stroke engine, and that firm and its licensees probably produce the largest number of medium-sized engines in Britain, particularly for cargo vessels. Names which will always be associated with marine oil engine developments in the British Isles are C. C. Pounder, of Harland and Wolff, and K. Keller, of Doxfords.

The marine oil engine was a highly efficient prime mover right from its inception. Although specific fuel consumption has been improved during the years, developments have been largely by way of reducing weight and space and maintenance costs, which latter were heavy with the earlier engines. Successive developments include the change-over from air to solid injection, the adoption of supercharging and improved scavenging arrangements, the use of more appropriate metals for cylinder liners and pistons, and the wide adoption of fabricated entablatures to replace castings and so save weight. Many of the early engines worked on the four-stroke cycle, and double-acting designs of high power came into service; examples of these engines are still running in the Cunard's ex-White Star "Britannic" and "Georgic." But the two-cycle engine—simpler and of lighter specific weight—gradually took the field and here again powerful double-acting engines were fitted aboard large vessels. Typical of these double-acting, two-cycle engines are those built by Harland's for the Union-Castle Company's "Capetown Castle" and her two sisters; these ten-cylinder engines develop 16,000 s.h.p. each, i.e. 32,000 s.h.p. per ship.

Higher Steam Pressures and Superheats

In the 'twenties it really looked as if steam was on the decline and would become submerged by the diesel for all but very high powers where the lighter-weight steam machinery could still hold its own. But steam took up the challenge and the adoption of higher pressures and superheats, improved cycle conditions (multiple bled-steam feed heating, &c.) and ancillary equipment for boilers such as air preheaters and/or economisers, made great strides. Sir Charles Parsons and his colleagues and friends were again in the van of progress, and "King George V" was built and engined for the same company that owned "King Edward," to establish modern steam conditions at sea. The first large liner to incorporate high pressure steam for propulsion was the Holland-America Line's "Statendam," built and engined by Harland's. This ship, which went into the transatlantic service in 1929, was an outstanding success and set a standard for what steam could achieve: incidentally, her auxiliary load was carried by diesel-electric generators—a system largely used at the present day.

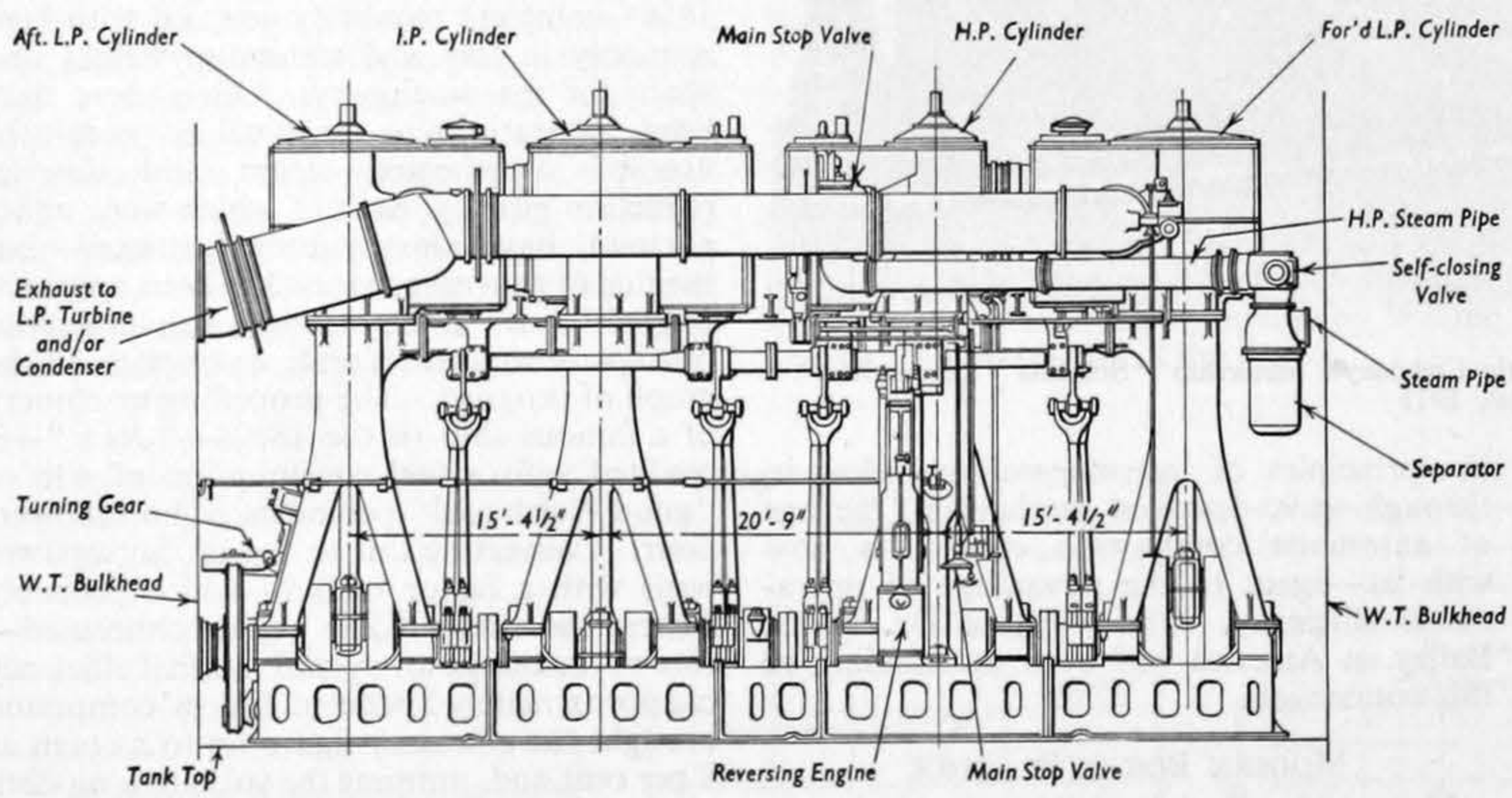


Fig. 4—A set of four-crank triple-expansion engines of the White Star Line's triple-screw S.S. "Olympic" (Harland and Wolff), 1911. The illustration is redrawn from an original in a lecture by C. C. Pounder (Belfast Association Engineers, March 3, 1948)

Oil Firing

In the 'thirties a galaxy of noble and modern vessels was built for many diverse services and with these vessels oil-fired water-tube boilers operating with steam conditions of 450 lb per square inch, coupled with a final steam temperature of 750 deg. Fah., became standard practice. Incidentally, all the older large liners were converted to oil fuel in the 'twenties, ships like "Olympic," "Aquitania" and "Mauretania" coming under this category, but still running on saturated steam from their original Scotch boilers. The liners of the 'thirties all adopted water-tube boilers with great savings in weight and space, and included "Empress of Britain," of C.P.S., new vessels for the Orient and P. and O. (the engineering masterpieces of James Callender of Vickers-Armstrongs), the Clydebank-built "Queens" of the Cunard, followed by the new "Mauretania," built by Cammell Laird's, and "Andes," from Harland's, for the Royal Mail Lines—the latter with steam at 500 lb superheated to 800 deg. Fah. At the same time the United States and Continental yards were building large liners embodying the principles of modern steam.

Back-to-Coal Experiments

In the 'twenties and early 'thirties experiments were tried out at sea on burning pulverised coal in order to reduce manpower and attain higher combustion efficiencies than could be obtained by hand-firing, as at that time coal was still an economic fuel for lower powers, or, again, for short cross-channel runs. These experiments also extended to colloidal fuel but for a variety of reasons inherent to marine practice they were not a success. Firing by mechanical stokers was then tried out and proved highly successful when associated with water-tube boilers, but the coal era was on the decline as far as ship propulsion was concerned and oil was steadily gaining favour with its outstanding advantages in simplified bunkering, ease of storage and simplicity of control for high-efficiency operation. World War II and subsequent events have practically banished coal from sea except for certain classes of low-powered ships.

Modern Practice

With improved alloys now available the latest practice in high-powered vessels has centred on 650 lb/850 deg. Fah. at the superheater stop valves, and British-built installations are now at sea involving a 900 lb/900 deg. Fah. cycle. Descriptions of many of these vessels have appeared in articles in The Engineer within the last few years and so hardly come within the orbit of a historical survey. The writer believes the first of the 650 lb/850 deg. Fah. cycle liners were the Belfast-built "Pretoria Castle" and "Edinburgh Castle" for the Union-Castle Line. It is of interest to remember that when the turbine was first entertained for sea service by Parsons it was an all-reaction machine: the impulse designs took up the challenge, and in Great Britain Clydebank were the protagonists of the Brown-Curtis turbine, with which the name of Stephen Pigott will always be associated. Gradually the designs of marine turbines began to merge and for modern tonnage the general practice is impulse for the h.p. and reaction for the l.p. stages, the intermediate blading varying between the two systems. Astern running is invariably carried out on impulse wheels. All-reaction and all-impulse ahead designs are, however, still favoured by some owners. More advanced steam conditions may be used and in fact are in limited service, but the law of diminishing returns is an important factor. It must be remembered that with few exceptions marine machinery is of much lower power than maintains in land power station practice, and scale effect has a big influence in determining optimum economic steam cycle conditions.

Turbo-electric and diesel-electric drives have found limited application, some of the outstanding examples of the former being in the Furness-Bermuda liners "Monarch of Bermuda" and "Queen of Bermuda"; in the P. and O. Company's "Viceroy of India," "Strathaird" and "Strathnaver"; in the 1946 "Beavers" of Canadian Pacific, which utilise steam conditions of 850 lb per square inch superheated to 850 deg. Fah.

and reheated at 160 lb per square inch to 850 deg. Fah.; and in a number of modern tankers.

Survival of Reciprocators

The complete success of turbine machinery has not, however, eclipsed the steam reciprocator, which still finds economic application in the lower ranges of power, say, 3500 s.h.p. downwards. Modern developments include the application of the Bauer Wach system exploited in this country by Swan, Hunter and their associates, and which covers a low-pressure turbine geared into the main shaft through an appropriate coupling. Fuel economy to the order of 25 per cent over the straight triple is afforded by this system. The name of P. L. Jones, of Swan, Hunter will always be associated with this development in heat engine technique. Another system is the North Eastern Marine intercylinder reheat engine, which owes its inception to the work of Harry Hunter. A third method of improving the efficiency of the reciprocator is by interstage steam compression driving the compressor by an exhaust steam turbine. This system was developed by Gotaverken in Sweden.

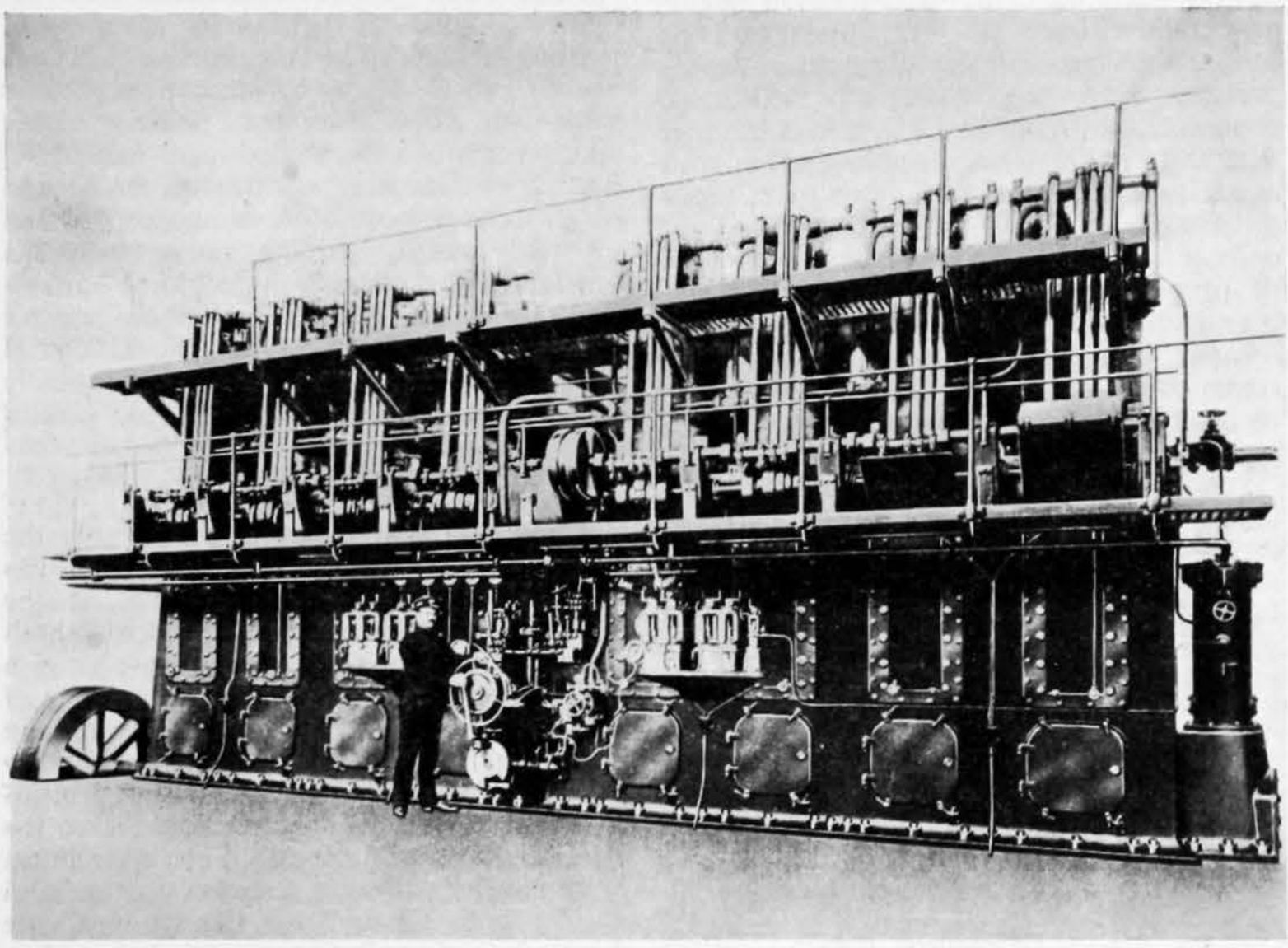


Fig. 5—One set of diesel engines of the East Asiatic Company's motorship " Selandia " (Burmeister and Wain), 1911

Ancillary Equipment

Another outstanding technical development towards the end of the first world war was the Michell thrust to replace the multiple-collar thrust which had been used for years and which—with the higher powers now obtaining—became inordinately large, bulky and complex. One of the earlier vessels to be fitted with the Michell thrust was the cross-Channel steamer " Paris," and H.M. Navy very quickly took advantage of this innovation, the destroyer " Leonidas " being one of the first naval vessels to be so equipped.

The whole of our story is linked in by inventions and developments of ancillary equipment as well as the main engines themselves. James Howden endeavoured to introduce forced draught for boilers as far back as the 1860s but, confining his efforts to undergrate air, met with little success. When the matter was reviewed in the early 1880s with a split and controllable air stream and associated with a tubular air preheater in the flue gas discharge, immediate success was attained and boiler efficiencies improved to the order of 15 per cent. This reflected directly on fuel consumption. The Weirs added their quota to improvements in marine propulsion, and apart from their feed pumps they, contemporaneously with Professor Elliott, expounded the thermal advantage of a bled-steam cycle associated with the boiler feed system. The firm of Weir was also a leader in the introduction of the evaporator at the turn of the century, and at a later date it developed the closed feed system, which is now in standard use to maintain optimum feed conditions for high-pressure boilers.

The last twenty-five years have seen a great advance in instrumentation, thereby enabling accurate records to be logged and conducing to efficiently maintained operation. Using the principles of instrumentation linked in through servo-operated mechanism, the age of automatic combustion control is now with us—again to the advantage of operational efficiency. The work of Dr. E. G. Bailey in America has been outstanding in this connection.

Modern Boiler Practice

Near-perfect feed conditions coupled, with oil firing, have completely revolutionised marine boiler designs within the last twenty-five years. Small tubes are now permissible and detailed study of circulation problems has enabled the boiler designer to reduce size and weight to a fraction of what it was less than a generation ago. Babcock, Foster-Wheeler and Yarrow (to put these names in alphabetical order) dominate the marine field and in all cases small tubes, with a varied degree of water-cooled furnace according to ratings, are standard present-day practice.

Research and Development

Progress in the metallurgical field has been a dominating factor in marine engineering progress, whether steam or diesel. The limiting factor in the development of the heat engine is metallurgical and, indeed, the metal theme runs right through the picture—down to bearing metals and condenser tubes. Science and research have played a notable part particularly during the last quarter of a century, and the fundamental work carried out in the applied science departments of universities and technical colleges has been followed by applied research in industry and by bodies such as the National Physical Laboratory, the British Shipbuilding Research Association, and by the Parsons and Marine Engineering Turbine Research and Development Association—Pametrada, for short. The equipment in the latter's research station at Wallsend-on-Tyne now allows, *inter alia*, for full power testing of marine turbines ashore—hitherto impracticable in this country, although practised in the U.S.A. at the Naval Research Station at League Island since the 1920s. Testing of reciprocating engines—steam and oil—has always been possible at sea by indicating, and oil engines could be shop tested against a dynamometer (thus correlating i.h.p. and b.h.p.), but turbines could not undergo other than light steam shop tests until the Pametrada station was available. Investigation of gearing under full load conditions is now practicable—and it is a long road from the cast iron gears of the slow-running engines of 1856 (when the problem was gearing up to propeller speeds) compared with the examples of to-day, with pitch line speeds to the order of 300ft per second and a loading of 1200 lb per inch of tooth face of primary pinions. And, of course, all these advances were only possible as the art of machining progressed, and the machine tool is one of the keys to modern practice.

Some Comparisons with 1856

Looking back over the century we can certainly claim spectacular achievement in the art of marine propulsion. The requirements to be met still remain as they did in 1856—complete reliability coupled with high economy in fuel and minimum weight and space for the machinery. Often there have been frustrations to technical advance—the use of superheated steam and double-reduction gearing, each of which went under a cloud, have already been instanced—but the line of general progress has been upwards. Maybe " line " is the wrong word, as a series of steps is a more accurate description of the graph of progress. The propelling machinery of a famous ship in the 1850s—" Asia "—is credited with a fuel consumption of 4 lb of " good Welsh coal " per indicated horsepower-hour. Converting this to a shaft horsepower basis with a factor of 0·9—which probably flatters the cumbersome engine concerned—this works out at an overall thermal efficiency of approximately 5 per cent. Elders' compound brought the efficiency figure up to as high as 8 per cent and, jumping the years to a modern oil-burner consuming 0·53 lb of fuel per shaft horsepower-hour, the efficiency figure is of the order of 26·5 per cent. The marine oil engine of to-day has an overall thermal efficiency of 37 per cent.

Elders' compounds gave an all-in machinery weight of 4·7 i.h.p. per ton and the triples of the 1880s 6·0 i.p.h. per ton. Converted to shaft horsepower on a 0·9 factor these figures become 4·2 and 5·4 respectively. Early direct-drive turbines with Scotch boilers are credited with 14 s.h.p. per ton. Compare these with two fairly recent cross-channel packets with oil-fired water-tube boilers and geared turbines, where the shaft horsepower per ton of machinery weight in working conditions runs out at 19 and 41 respectively. True, the latter is rather special for merchant service, as in order to develop the required power on a limited draught, the propeller speed is 385 r.p.m. H.M. Navy calls for a much greater power/weight factor than maintains

in the Merchant Navy, coupled with high efficiency to enable runs of long endurance to be carried out. The result is that the Royal Navy adopts the most advanced steam machinery which it is practicable to combine with the requirements of complete service reliability.

Future Possibilities

The general situation regarding the conception and practice of our subject matter was in a highly interesting state of development in 1856. In 1956 we find ourselves in exactly the same state, as the gas turbine has already gone to sea in the Shell Tanker Company's "Auris" sponsored by John Lamb, and we can definitely look forward to developments in connection with this new prime-mover. And beyond the gas turbine THE ENGINEER has already noted a still more advanced system of marine propulsion—the use of nuclear energy at sea aboard the U.S. submarine "Nautilus." And so we go on as generation succeeds generation—always aiming for the stars but as good realistic marine engineers keeping our feet well planted on the deck, as no advance in technique can be tolerated unless associated with reliability in service.

The operation of modern marine machinery calls for a high class of personnel, and marine engineering demands appropriate professional qualifications based on the combination of technical study and practical experience for all senior engineer officers afloat.

Auxiliary Machinery

Our survey would not be complete without a brief reference to auxiliary machinery, which has seen great changes in the course of a century. In the early days of our review most engine-room auxiliaries were operated from the main engine, and in fact this continued for many years and still applies to many reciprocating steam units. A century ago, ship auxiliaries were practically non-existent. Gradually the auxiliary load grew both on the ship side, and on the "hotel" side of passenger vessels, and additive auxiliaries appeared in the engine and boiler rooms. At first electricity was limited to lighting, but nowadays it has taken over practically all auxiliary services and generation is afforded either by steam driven sets—turbo-driven in all but the smaller classes of vessel with light electrical load—or by diesel-driven sets (which applies to steamships as well as motorships) and indeed in many steamships by a combination of steam and diesel, running the latter in port when the main engines and boilers are shut down.

Navigational and Ship Equipment

Modern navigational equipment has added its quota to the auxiliary load and the story of the development of the steering gear from hand operation to its present form of electric-hydraulic operation with telemotor control would form the basis of an interesting review. Cargo handling gear is becoming more and more electrified and the refrigeration plant becomes a major load in meat carriers and also in all classes of ships carrying perishables. The purely "hotel" load of a passenger vessel with its heating, lighting, galley, lifts, etc., can reach formidable figures. The cargo pumping equipment of a tanker involves power equivalent to a high percentage of main engine requirements to enable quick turn-round.

Conclusion

The writer has mentioned a few of the names associated with the design and construction of marine propelling machinery during the century: he has also noted the responsiblities of the sea-going engineer. Between the two comes the superintendent engineer and his staff; they have to select the most appropriate machinery the shipyards can offer for their services and theirs is the responsibility for continued maintenance in service. We have been fortunate throughout the generations in having men of knowledge, experience, judgment and wisdom to hold these positions.

Aeronautics

By H. G. CONWAY, M.I.Mech.E., F.R.Ae.S.*

BY 1856, aeronautics as a science had scarcely begun. In 1848 John Stringfellow had flown the first powered aeroplane in history, albeit a pilotless model, but none the less remarkable; Sir George Cayley, the "father of British aeronautics," had laid the foundations of the new science, the steam engine had paved the way for the internal combustion engine, and Congreve had made a weapon out of a Chinese toy—the rocket.

In the next forty-seven years progress towards the successful man-carrying aeroplane was slow. Lilienthal and others made gliders, Langley and Maxim built important, but unsuccessful, aeroplanes, but perhaps of greatest importance was the evolution of the gas and petrol engine by Lenoir, Otto and Benz, and its successful application to road vehicles. The Parsons turbine of 1884 is of particular interest in retrospect, although its effect on aeronautics was not felt for sixty years.

Then, on December 17, 1903, a really important milestone was reached—the first flight of a man-carrying aeroplane by Wilbur and Orville Wright, at Kitty Hawk.

Now, at the beginning of 1956, we look back on 100 years of aeronautical progress, a progress that was scarcely perceptible for the first fifty years, and which in the second half-century has been so great as almost to be incredible. In no other branch of engineering, or, indeed, science, not excepting nuclear physics, has progress been at such a fantastic rate.

It is worthwhile to recall a few simple statistics. The speed of manned aircraft has now risen to 1650 m.p.h. (Fig. 1*a*); the maximum altitude of manned aircraft has reached 79,000ft (Fig. 1*b*); the power of a single engine unit has risen to 15,000 h.p. (or a possible 25,000 h.p. if information on a Russian engine is correct) (Fig. 1*c*); while the specific weight per horsepower has dropped to the astonishing value of 0·14 lb per horsepower (Fig. 1*d*). The aeronautical industry is now one of the major industries of the world, in Britain in particular it being one of the country's important exporters (Fig. 2*a*); it was able to keep no less than 1·8 million persons in direct employment in Britain at the peak period of the war, and can to-day occupy more than 250,000 (Fig. 2*b*). The importance of air transport can be gauged by the fact that in 1955 more than 60,000,000 passengers were carried by commercial airlines throughout the world (Fig. 2*c*); this is the more remarkable when it is remembered that transatlantic air travel only began ten years ago, and now carries more passengers annually than do ships.

The engineer glancing at these diagrams will note that the most remarkable factor about most of them is the rapid rises in the last few years. The curves show that the rate of progress appears to be increasing; certainly there is no reason to suppose that it will slacken off. We may thus conclude

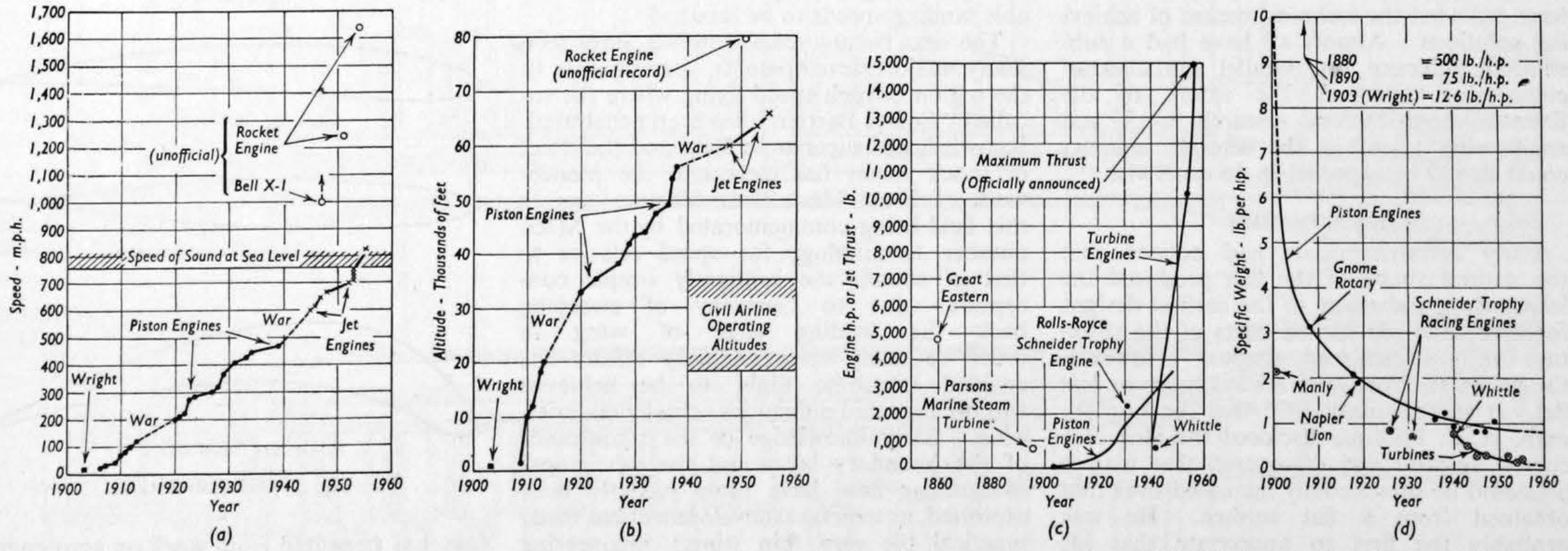
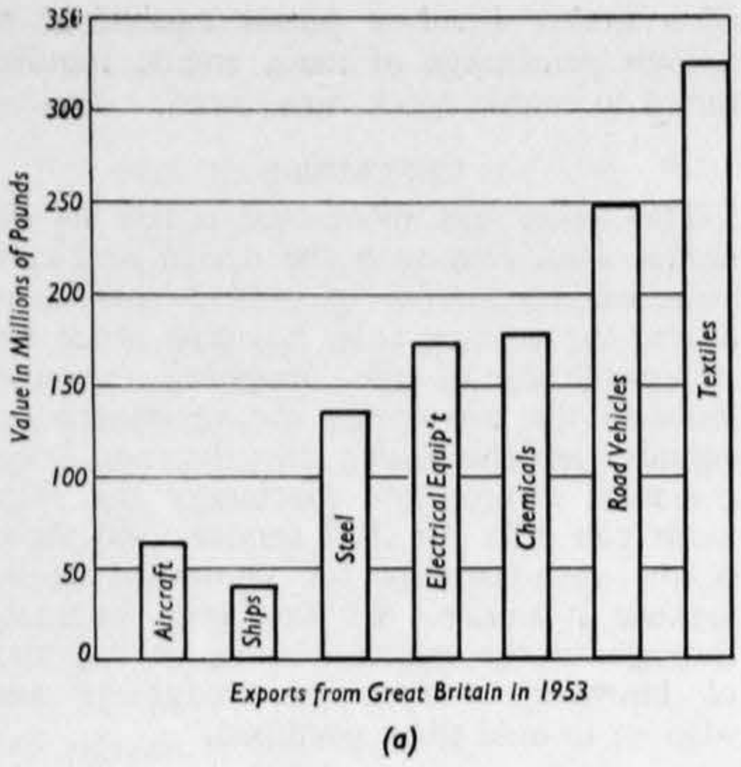
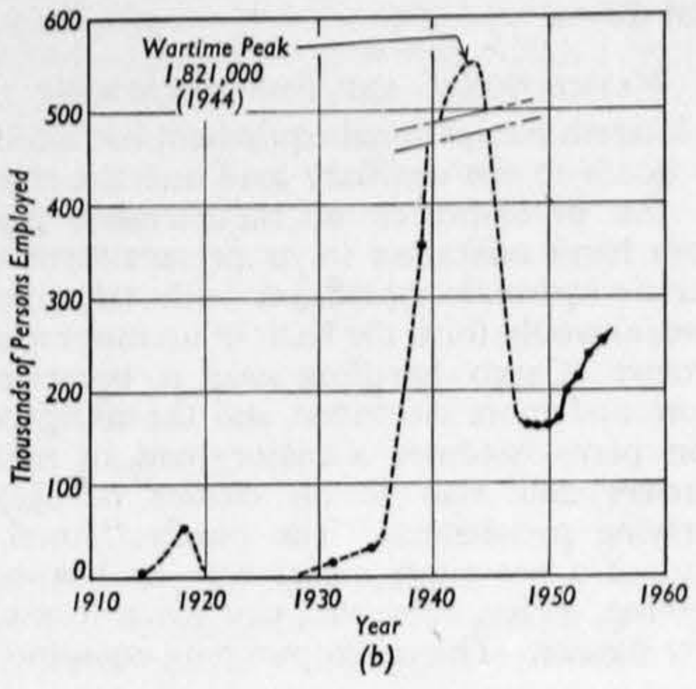


Fig. 1—(*a*) The progress of speed in air travel as indicated by the official speed record; (*b*) the progress of the official altitude record; (*c*) the development of engine power; (*d*) the progress of the reduction of engine weight

* Director and Chief Engineer, Short Brothers and Harland Ltd.





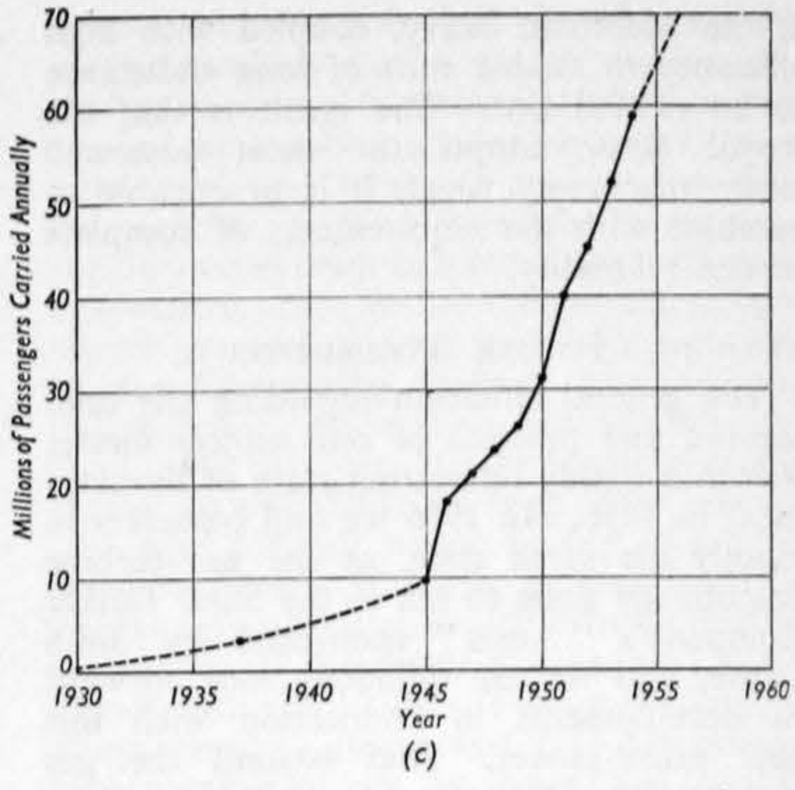


Fig. 2—(*a*) The aircraft industry in Britain as a major exporter, (*b*) employment in the British aircraft industry, (*c*) the number of passengers carried by the world's airlines

that by 1966 we will be flying at 3000 m.p.h. at 80,000ft, with engines of 30,000 h.p. and specific weights of 0·08 lb per horsepower, and that civil air transport will be carrying 90,000,000 passengers annually.

These introductory remarks serve to set the scene ; we do not wish to stage a historical pageant with Stringfellow, Cayley, Lilienthal, Manley, Wright, Bleriot, Lanchester, Prandtl, Ricardo, Whittle, Sanger and the others as the actors ; a few selected examples of progress in aeronautics and its impact on other branches of engineering may, however, be of interest.

Aeronautical development as a whole has been profoundly affected by developments in aerodynamics (theoretical aerodynamics, wind tunnels and tunnel research), propulsion (high-efficiency piston engines, jet propulsion, gas turbines, rocket power plants), high-performance materials (aluminium alloys, heat-resisting alloys), structural methods (all-metal stressed-skin construction, the theory of buckling or elastic instability of structures), control and stability (aerodynamic control surfaces, servo-mechanism theory, gyroscope devices), navigation systems (radar, v.h.f. radio, servo-mechanisms, gyroscope devices).

If defence demands have usually provided the incentive and the necessary finance (on a vast scale), it is these developments that have provided the technical means of achieving solutions. Almost all have had a substantial influence on parallel branches of engineering. Indeed, the extent of the financial contribution, research work and engineering talent in the aircraft industry could hardly be expected to do otherwise.

Aerodynamics

Early aerodynamicists had noticed that the natural shape of the fish produced the lowest drag and many of the earliest designs for aeroplanes illustrated parts of the structure with streamlined shapes. However, the lifting surfaces were always more or less flat. It was not until 1895 that the Englishman, H. F. Phillips, disclosed the idea of a curved aerofoil and discovered that with it lift could be substantially increased over that obtained from a flat surface. He was probably the first to appreciate that lift really arises from the increased velocity of the air over the upper surface rather than from the impact of the air on the lower, inclined surface.

In retrospect, it seems strange that early workers had not realised the significance of the curvature of the wings of birds, although the fact had been observed even by da Vinci. As F. W. Lanchester wrote in 1907 in his book *Aerodynamics*, " it is scarcely credible that so marked a peculiarity should have escaped observation for centuries."

Lanchester himself was one of the important workers in the field of theoretical aerodynamics ; Prandtl in Germany was perhaps of even greater importance although his work was not widely known until later. Most important of all in this early period was the building of the first effective wind tunnel by Eiffel in Paris in 1912, to be followed by others all over the world. Aerodynamic theory could now be applied to the design of practical aeroplanes.

The next major development, which took place after the first world war, was the introduction of wings with convex lower surfaces in place of the arched wings of the first successful aircraft. Aerofoil development in the wind tunnel had evolved shapes with adequate lift and yet much less resistance to forward flight than the early profiles (Fig. 3). The increased thickness of this type of wing enabled a proper structure to be introduced into it and paved the way for the elimination of the braced biplane.

Very considerable developments took place in the period up to about 1935 in the development of high lift devices, including leading edge slots and trailing edge flaps. All these enabled the lift co-efficient of the wing to be improved and often improved stalling characteristics. They resulted in faster flying due to higher wing loadings but enabled reasonable landing speeds to be retained.

The next twenty years, however, have seen many major developments, particularly in the region of high speed flying where the so-called " Sound Barrier " has been penetrated. Knowledge of supersonic flight and the effect of shock waves has increased, the pioneer work of Ernst Mach some 80 years ago in this field being commemorated by the Mach number terminology for speed relative to that of sound; the brilliantly simple conception—due to Germany—of sweeping back the leading edge of wing in order to delay compressibility effects has enabled transonic flight to be achieved without expected difficulties actually materialising. Early knowledge of the significance of the boundary layer and the advantages of laminar flow have more recently been exploited, as structural development has made practical the very thin wing ; engineering progress, particularly with turbine engines, where large supplies of compressed air are available, has enabled a start to be made on methods of augmenting the lift of a wing by means of sucking or blowing techniques over all or part of its surface.

All this work has naturally been of profound significance in the aeronautical field ; it has also had an indirect effect in many other branches of engineering, in some cases of some magnitude. For example, the design of turbine blading has been assisted by the understanding and theoretical knowledge of the flow of compressible fluids. The stage efficiency of a good steam turbine has now been increased to the relatively high figure of 88 to 92 per cent due to improved aerodynamic knowledge and the development of means of accurate manufacture of turbine blade assemblies.

A recent paper by F. Dollin* pays a generous tribute to aeronautical development. " The new approach " he says, " to the study of blading losses provided by wind-tunnel methods of testing is accompanied by a different mental approach to fluid flow problems. Steam turbine designers from the earliest days have been accustomed to thinking in terms of flow through nozzles, and blade passages, whereas modern aerodynamic thought considers the flow of fluid around aerofoils and other solid bodies. There is no doubt that the new outlook has given engineers a new awareness and has added greatly to our knowledge . . . ".

Similar if less spectacular advances have taken place in the design of fans. Axial flow fans are now produced with thin aerofoil blading and the design of centrifugal

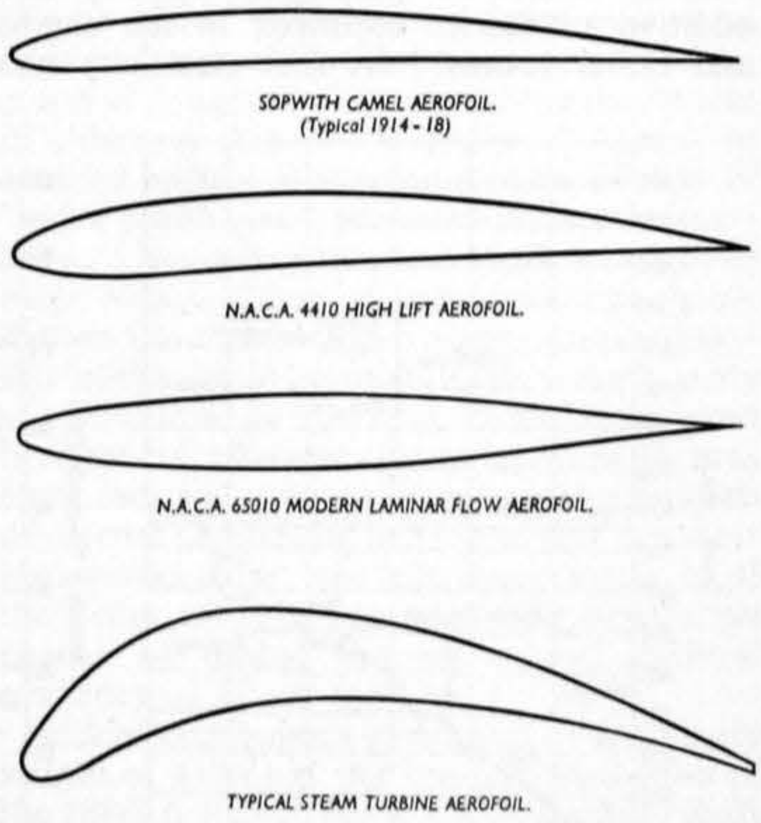


Fig. 3—Aerofoil sections

fans has benefited from work on aero engine superchargers and, later, gas turbine compressors.

The practice of streamlining rapidly moving vehicles such as motor cars or locomotives has become well established. It is now usual for high performance road vehicles to be tested in wind tunnels in the same way as aeroplanes are ; many railway trains, particularly in the U.S.A., have been similarly

* " Factors Influencing the Continuing Development of the Steam Turbine," Parsons Memorial Lecture, the Institution of Mechanical Engineers, October 29, 1954.

treated. The advantages to be gained from streamlining, even in the case of road vehicles travelling at not more than 60 m.p.h. are greater than is generally realised. A low drag car or bus can have a fuel consumption 20 or 30 per cent less than the same vehicle with a more conventional shape. The gains in the case of trains are not perhaps so spectacular but are nevertheless sufficiently worthwhile to justify the streamlining of most modern high-speed trains. The relationship between smooth air flow and noise level is beginning to be understood, and wind tunnels are now used to produce silent travel.

Modern bridge design has benefited greatly from aerodynamic research carried out in the U.S.A. and in this country. The failure of the Tacoma Bridge in the U.S.A. in 1940 will be recalled as a first example of a bridge which failed due to wind excited oscillations. Research in the wind tunnel has led to an understanding of the reasons for this phenomenon and has produced simple techniques for fairing or streamlining of the section of the bridge, so that oscillations are stable. It is now standard practice in the design of any long suspension bridge to submit models to wind tunnel tests to establish the safety of the design under wind loads. To quote from D. B. Steinman,† " A suspension bridge may be made safe in two ways. One is to stiffen the structure by bracing stays so as to prevent and to damp destructive oscillations, ... the more scientific approach is to apply aerodynamic principles to design bridge cross-sections which are fundamentally stable. The wind tunnel tests have produced the necessary data ; they show how the form and proportions of a bridge section, with suitable openings in its horizontal width, can be designed to give it stability in any wind. It is sounder and more economical to eliminate the cause than to build up the structure to resist the effect. Many suspension bridges have had to be reinforced in recent years to make them safe. . . . "

† " Bridges," *Scientific American*, Vol. 191, No. 5, November, 1954.

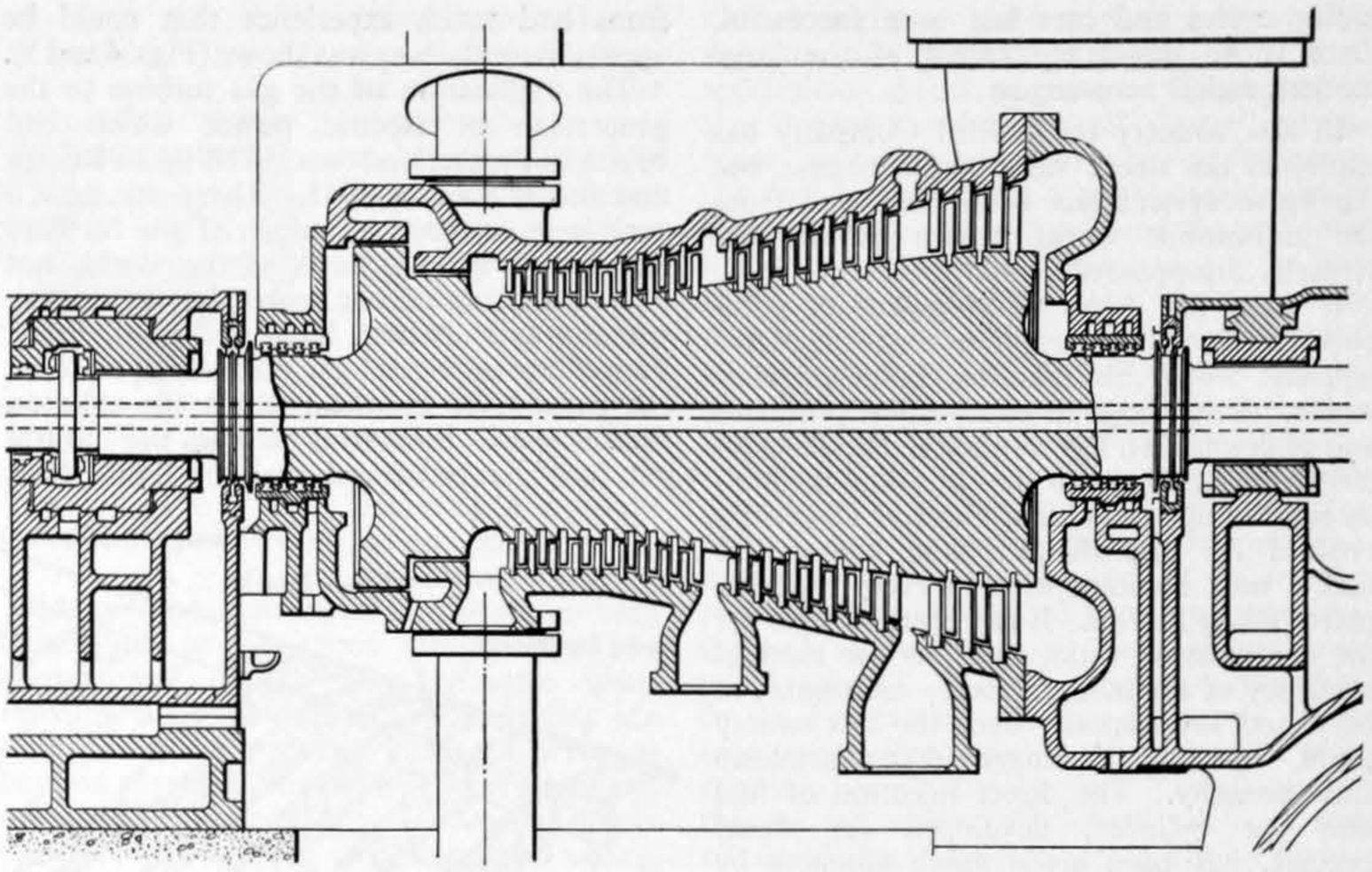


Fig. 4—Typical steam turbine for comparison with Fig. 5

In Britain similar work has been carried out at the National Physical Laboratory on models to prove the safeness of the proposed Severn suspension bridge. The technique has been extended to include the study of undesirable effects due to the proximity of one bridge with another, where instability might arise from buffeting or disturbed air flow between the bridges.

Propulsion

Until the advent of the jet engine it could be said that the aero engine had developed along lines differing less than might have been expected from the internal combustion engine of other spheres, such as road transport or marine propulsion. The small, comparatively high-speed engine used on commercial or passenger road vehicles was not of direct interest in the aeronautical field where engines of much greater power were required and where relatively low rotational speeds of the propeller were desirable. The development of compression ignition engines in the railway, marine and road vehicle fields was not in fact very much influenced by similar development work on the compression ignition engine for aeronautical use. Here the advantage in fuel economy was largely offset by the extra weight of the engine arising from the use of higher compression ratios.

Although the multi-cylinder V aero-engine has found its counterpart on road and rail vehicles, the air-cooled radial engine, which predominates in the aircraft sphere, is not used in other applications. The availability of large supplies of cooling air is obviously more or less restricted to aerial flight, and although air cooling of small engines on

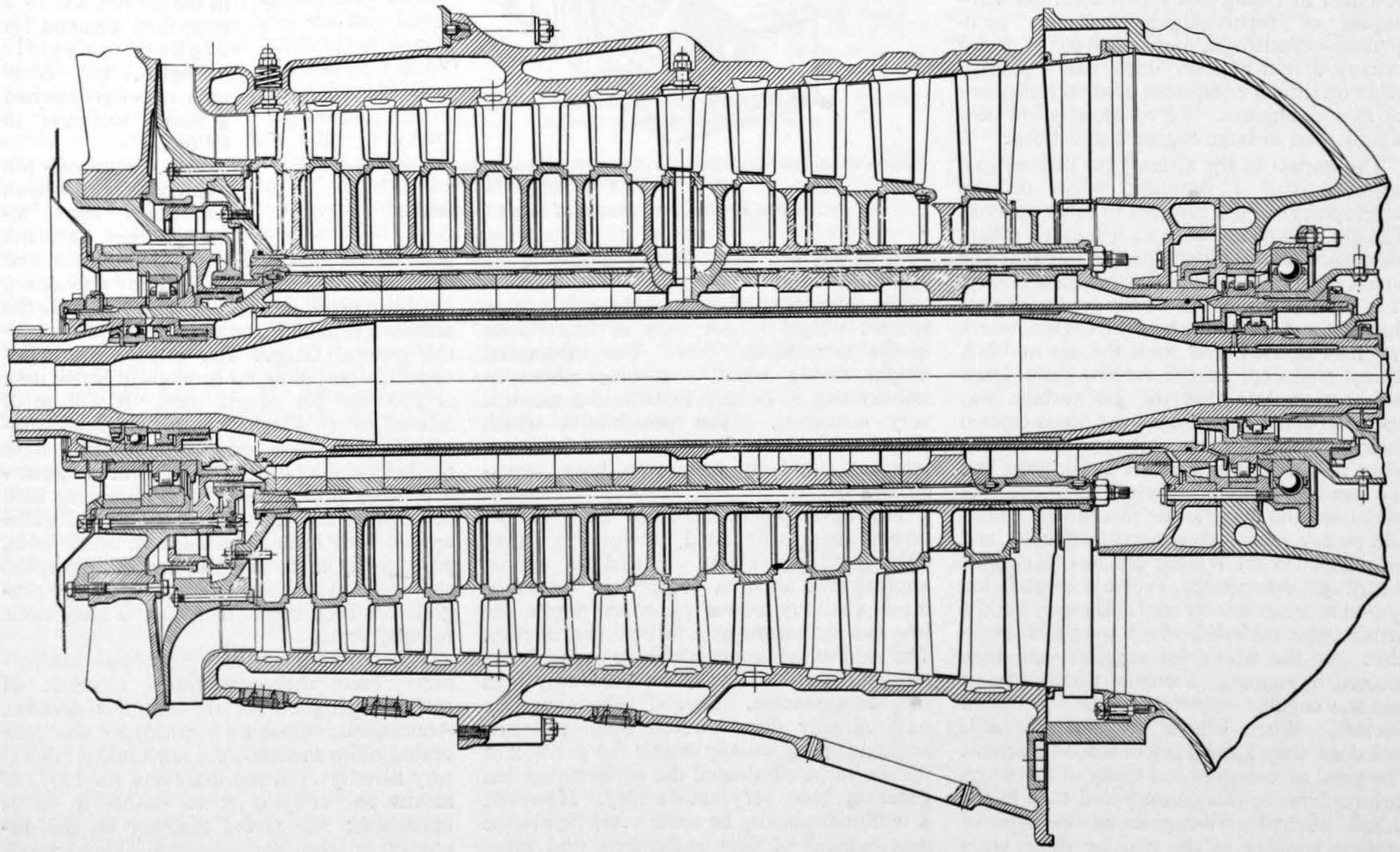


Fig. 5—Aero engine gas compressor

motor cycles and cars has been successful, there is no direct equivalent of the large modern radial aero-engine

In this country the Bristol Company has exploited the sleeve valve radial engine, but the valve system has been borrowed from the automobile world, where its use has virtually disappeared.

It is in the detail development of components for piston engines that the aeronautical world has had an influence elsewhere. Knowledge of combustion problems and of detonation has resulted in the development of high-octane or anti-knock fuels incorporating tetra-ethyl lead. Originally evolved for aircraft purposes, high-octane fuel is now commonplace in every roadside petrol filling station. It has been possible for the compression ratio, and thus the thermal efficiency of the modern motor car engine, to be raised substantially over the last twenty years, resulting in improved performance and economy. The direct injection of fuel into the cylinder, developed for diesel engines, has been given much stimulus by wartime use on aero-engines. The replacement of the carburettor by fuel injection on the ordinary road vehicle is a development which we may expect in the next few years.

As a result of the use of high compression ratios and high-octane fuels exhaust valve materials have been much improved and the use of hard inserts in the cylinder head is now commonplace on road vehicle engines. The widely used sodium-filled exhaust valve of the aero-engine has not yet, however, been used on road vehicles.

Bearing materials evolved for aero-engines have had some influence on similar materials used on the ordinary stationary or road engine. The earlier technique of applying a comparatively thick layer of white metal to connecting-rod and crankshaft bearings has given way to the use of shells with very thin coatings of bearing material of low friction.

Although supercharging of internal combustion engines for road vehicles has been confined to racing and sports cars, the techniques of supercharging used on aero-engines—centrifugal engine-driven or turbo exhaust-driven blowers—have had a parallel effect on similar equipment used on stationary or marine engines. Turbo blowers are now widely used in large engine installations.

The impact of the aircraft gas turbine has, however, had a profound effect on the development of gas turbines in other spheres. The gas turbine has been an inventor's dream ever since Charles Parsons showed that the steam turbine had become a practical reality. It is Whittle who deserves the credit for producing the first gas turbine jet engine, which ran first in 1937 and took the air in 1941. Many engineers in the turbine field knew before that date that the gas turbine was about to arrive and indeed the Swiss erected their first gas turbine electric generating plant in 1938. The aircraft application and the needs of war, however, provided the incentive, and Whittle the mechanical genius and perseverance against great difficulty and prejudice. What Whittle did was to make a centrifugal compressor, evolve a combustion system more or less by trial and error, build a turbine with materials which were then available, put the whole lot together and then succeed in running an engine which worked and was capable of sustaining the flight of an aircraft. When others saw what Whittle had done they knew they could do likewise. The great aero-engine and many of the steam turbine firms in this country and then in the U.S.A. all had aero-engines of one type or another running in the two or three years after Whittle's engine first flew ; the turbine firms had much experience that could be applied once the way was shown (Figs. 4 and 5).

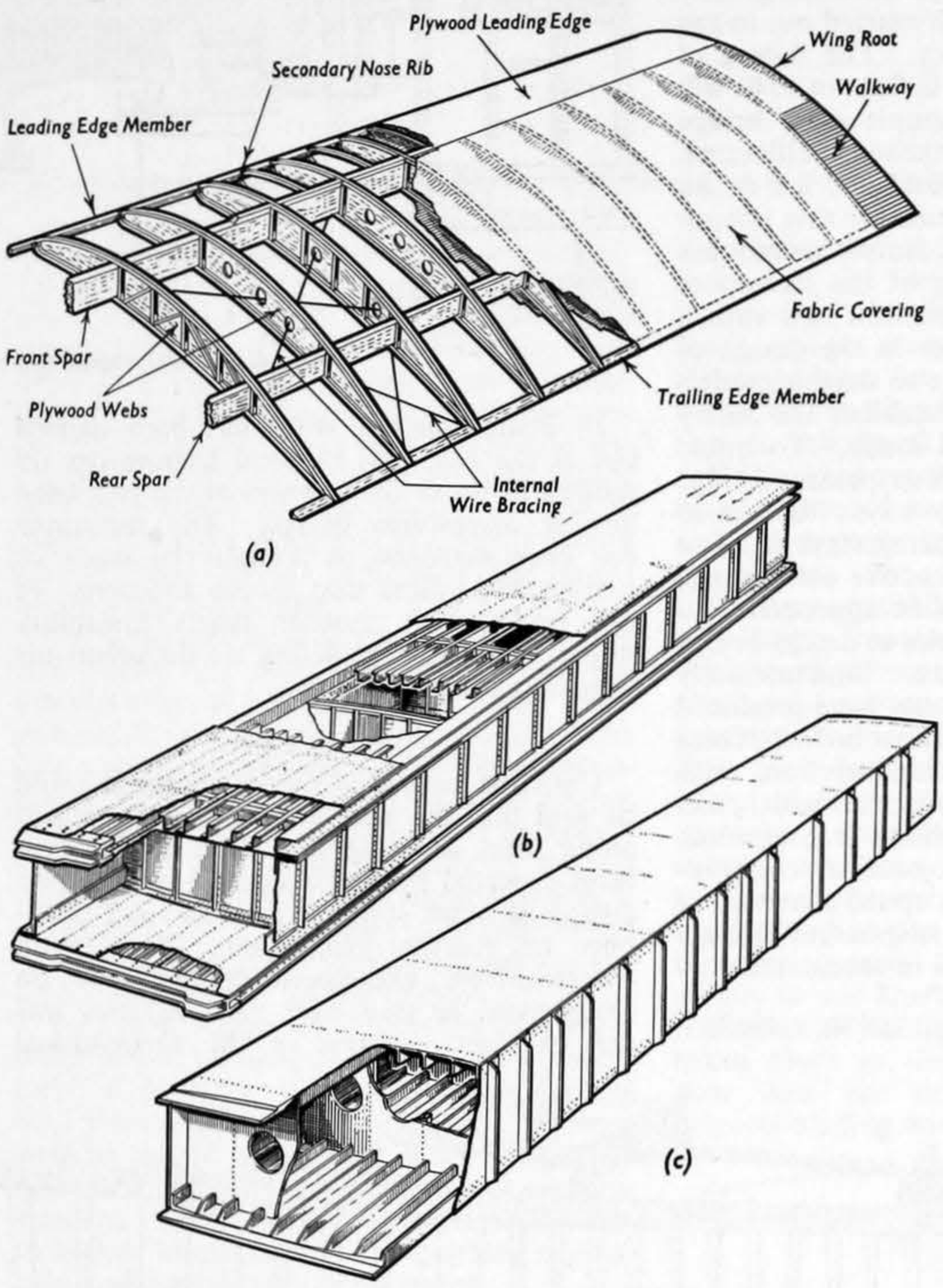
The application of the gas turbine to the generation of electric power which had begun in Switzerland was taken up in Britain and the U.S.A. in 1945. There are now a very large number of industrial gas turbines running in various parts of the world, not only generating electric power, but for railway traction and on both large and small ships. Few of the industrial gas turbines operate on the paraffin or kerosene which the aviation turbine uses. Industrial turbines use natural gas, peat or powdered coal, or liquid fuel, such as gas oil, where it is available at an appropriate cost.

The advantage of a gas turbine in its low specific weight is not only of importance in the aeronautical field. The substantial weight saving which a turbine allows in railway engine or ship installations make it very attractive. The possibilities which arise from its low maintenance cost due to an inherent simplicity have also been appreciated.

The development of large sizes of gas turbine has stimulated interest in small units for road vehicle use and for special applications, such as compressor drives or other auxiliary power purposes, where the low specific weight of a turbine is attractive. The road vehicle applications are probably the most difficult because of an inherently high fuel consumption. Several vehicle makers have already demonstrated small turbines, and since these usually enable the gearbox of the car to be eliminated the performance has generally been very satisfactory. However, it will undoubtedly be some years before the development of heat exchangers and other devices has brought the fuel consumption down to a commercially acceptable level.

In the case of the auxiliary drive units fuel consumption itself is usually of much lesser importance than light weight ; a reliable and reasonably priced unit would certainly find many applications in mines and civil engineering undertakings. Several units are now being produced with total weights of about 2 lb per horsepower (shaft drive) or 25 lb per kilowatt of generator output

The variable-pitch propeller is now a common feature of almost all modern aeroplanes, other than pure jets. Although the original proposals to use pitch variation were made for ships many years ago (practical tests had been made before 1856), the demands of aircraft led to the development of satisfactory engineering designs including governing systems in the early 1930s. This work has now found its way back into the marine world and several designs of V.P. marine propeller are available in this country and in the U.S.A. The detail design methods and the technique of remote control of the pitch are very largely based upon aeronautical practice.



(*a*)—Wooden frame, fabric-covered wing. (*b*)—Normal stressed skin wing construction. (*c*)—Integrally stiffened, machined wing.

Fig. 6—The development of aircraft structures

Materials

It is perhaps strange that in the development of structural materials other than light alloys engineering as a whole owes little to aeronautics. The need for saving weight in the air has led to a continued demand for higher specific strengths, but other industries have not had a strong incentive to follow.

One - hundred - ton steels have been known for many years, although they have not been widely used on account of high cost and difficulty of machining. Recently a tendency has been noted in the U.S.A. to heat-treat the same steels to 120 tons per square inch, where the general fatigue and impact properties appear, if anything, to be slightly better than at 100 tons per square inch. It will be of interest to see whether the use of these ultra-high-tensile steels expands. Aircraft have needed stainless steel in sheet form for structural work and for engine components such as jet pipes and exhaust manifolds. Parallel applications have been made in other fields, particularly in the construction of high speed railways. Apart from these steps, little progress has been made in structural alloy steels for fifty years.

The development of light alloys has perhaps been the outstanding example of material progress for the last few decades. Aluminium, whose own centenary was celebrated a few months ago, remained a laboratory novelty until the discovery (in 1907) of means for alloying it to enable it to be hardened ; this paved the way for the discovery of the high-strength alloys, which have made possible the all-metal aeroplane

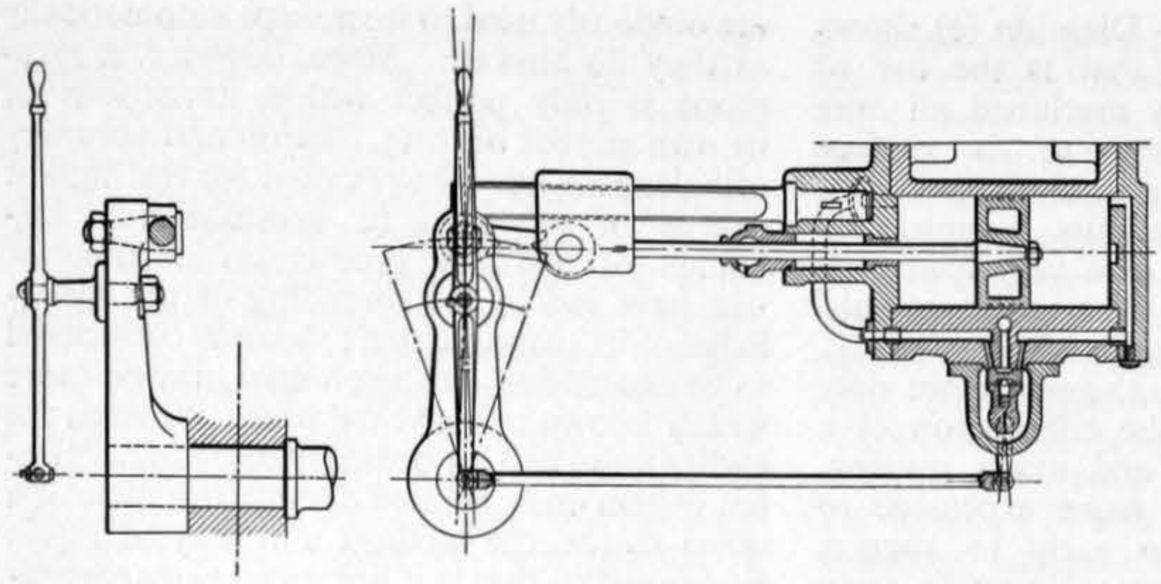


Fig. 7—Power boosters or servo mechanisms. Farcot's steam steering gear (1873)

of to-day. This in turn has resulted in an enormous expansion in the production facilities of the material, and has led to its widespread use for decorative, electrical, packaging and domestic purposes, as well as applications where its strength is important—in building and transport.

Early applications to the pistons of internal combustion engines where low weight and high thermal conductivity were advantageous, were stimulated by the needs of high-performance motor car engines as much as by aero-engines. The introduction of the earliest kind of high-tensile wrought light alloy (Duralumin) during the first world war, however, enabled aircraft designers, no doubt much stimulated by the use of this material in the Zeppelin airships, to begin to use the material. The first all-metal aeroplane (the Short *Silver Streak*) was produced in 1920, but as the proper use of light alloy requires the development and manufacture of the so-called stressed skin construction instead of the fabric-covered rib and spar method of the earlier aeroplanes, it was some time before all-metal aircraft became universal. To-day enormous productive capacity exists for rolling and extruding light alloy sheets and sections, while the stamping of forgings of several hundred pounds in weight is common.

The non-aeronautical engineer may sometimes wonder why, in spite of the very large productive capacity which exists in the world for producing light alloy, in spite of a substantial decrease in its price, and the activities of various development associations, there is not a wider use of light alloy in other spheres requiring stress-bearing as opposed to decorative material. In the automobile world light alloy is sometimes, but not generally, used for engine crankcases, and more frequently on bodywork, particularly on the more expensive cars. It is not used, however, for the many small fittings, levers and brackets, which could easily be stamped or cast and where substantial weight savings could be made. In the commercial vehicle world light-alloy bodies are sometimes used but by no means invariably. In rail transport, where weight saving is of equal importance, light alloy is the exception rather than the rule. In structural engineering bridges and hangars have been built in light alloy and stimulated no doubt by post-war conditions, large numbers of prefabricated buildings have been produced in the material. There is no sign, however, of a predominant place being taken in these spheres. The reasons for this are probably simple enough. In the structural and building spheres cost and, to some extent, the preference for traditional materials, are undoubtedly critical factors. In the transport field as a whole, apart from the cost factor, the most important criticism of light alloy is probably its low modulus of elasticity. It is comparatively unusual outside the aircraft field for structures or units to be designed with small margins of strength safety factor and with a great deal of accurate calculation. The substitution of a normal structural steel by light alloy will result in a reasonable saving in weight, but will also give a substantial reduction in rigidity; where extra material has to be used to compensate for the loss of rigidity, cost is increased, and weight saving becomes uneconomical.

Many miscellaneous materials have been stimulated to advanced development by aeronautical needs. The Nimonic heat-resisting alloys used on turbine blades are perhaps an outstanding example. Resin-bonded plywood, much used as a structural material for aircraft during the war, is widely used in other spheres, including small sailing craft. High-performance glues and adhesives for wood and for metal have all been able to make outstanding contributions outside

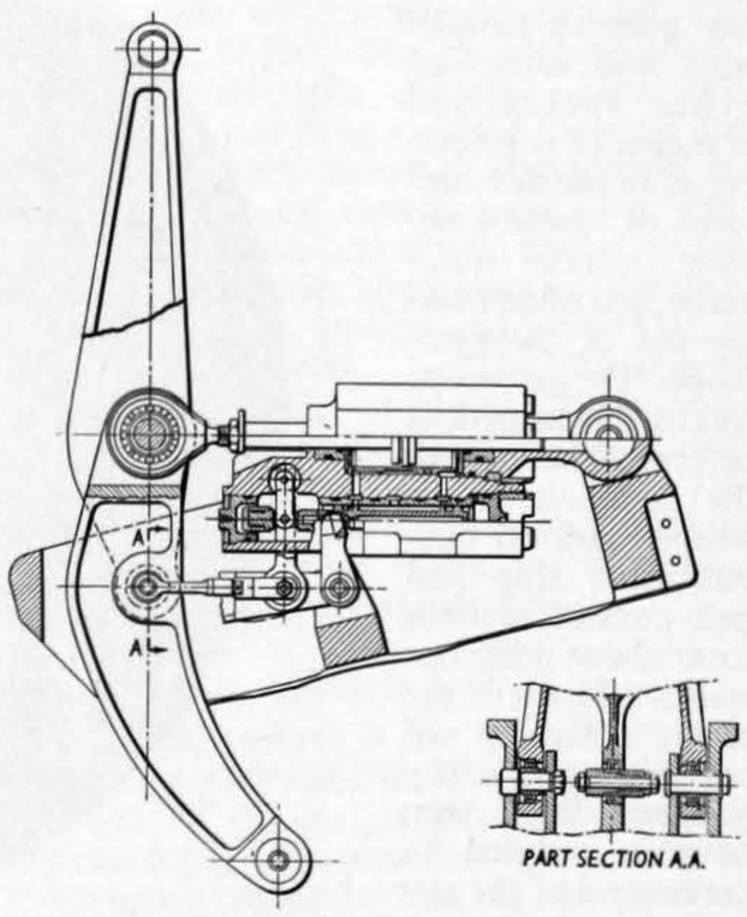


Fig. 8—Power boosters or servo mechanisms. Typical aircraft hydraulic flying control servo

their original aircraft applications. Artificial materials such as synthetic rubber, silicone, &c., are other examples. Rayon and nylon, long used on aircraft tyres, are now widely used on vehicle tyres. Lead and other bearing bronzes originated for the aircraft engine. Titanium, at present suitable only for aircraft use due to its high cost, may in twenty-five years' time be in the place that aluminium is to-day. Glass cloth and other high-strength structural plastics have been stimulated by aircraft needs.

Structures

Perhaps the most outstanding difference between the practices of the structural designer in the aircraft field as compared with those in other spheres, is in the much wider use of accurate calculation and confirmatory test. In the average engineering design office calculations are usually done by the draughtsmen themselves, or, in the case of bridge or building design, perhaps by one or two trained engineers who have specialised in the particular techniques of that industry. An aircraft design department, however, may have thirty stressmen for every hundred draughtsmen. Each drawing is stressed properly and the responsibility for each single component of the airframe, as regards its strength, is carried as a matter of legal responsibility by some senior engineer. A record of all calculations is kept in book-form, running, in the case of a large aircraft, into a series of large volumes.

Because of the necessity for accurate calculation of all sections to eliminate waste material and to save weight, classic simplified formulæ for the calculation of beams or struts have been replaced by more ambitious methods evolved over the years by such men as Southwell, Taylor and Timoshenko. In the last twenty years or so purely static calculations have been supplemented with dynamic or "aero-elastic" calculations—that is, full account has been taken of the effects of distortion and strain during flight, particularly to limit or control vibration or flutter.

It cannot be said that these practices have had a great effect in other branches of engineering, although there are signs that the principle of efficient use of material is accepted by some other industries. "Experience gained from aircraft structures," says a recent paper,* ". . . indicates that maximum efficiency and minimum cost go hand in hand with equality of strength of the structure as a whole and of the structural components." The structure of the modern high-performance car, for example, owes a lot to the aircraft structural design, although the design of the chassisless pressed steel body of the cheap mass-produced car is probably evolved more by practical trial than by calculation. The appreciation of the significance of wind effects on bridge design has already been mentioned; ambitious calculations have obviously to be made in the case of very large single-span roof buildings, where both wind and snow loads can be critical; lightweight railway coaches have also to be stressed properly rather than designed empirically.

The principle of the economy of material is perhaps the most important contribution to structural design technique that the aircraft industry has made. Because of the relative lightness of the structures and the use of thin, large-size elements, buckling or surface instability has been of much greater import-

*"The Use of Equal Strength Sections in Structure Design" by Kenedi and Harvey, Junior Institution of Engineers and Shipbuilders in Scotland, Paper 1136, Nov. 7, 1950.

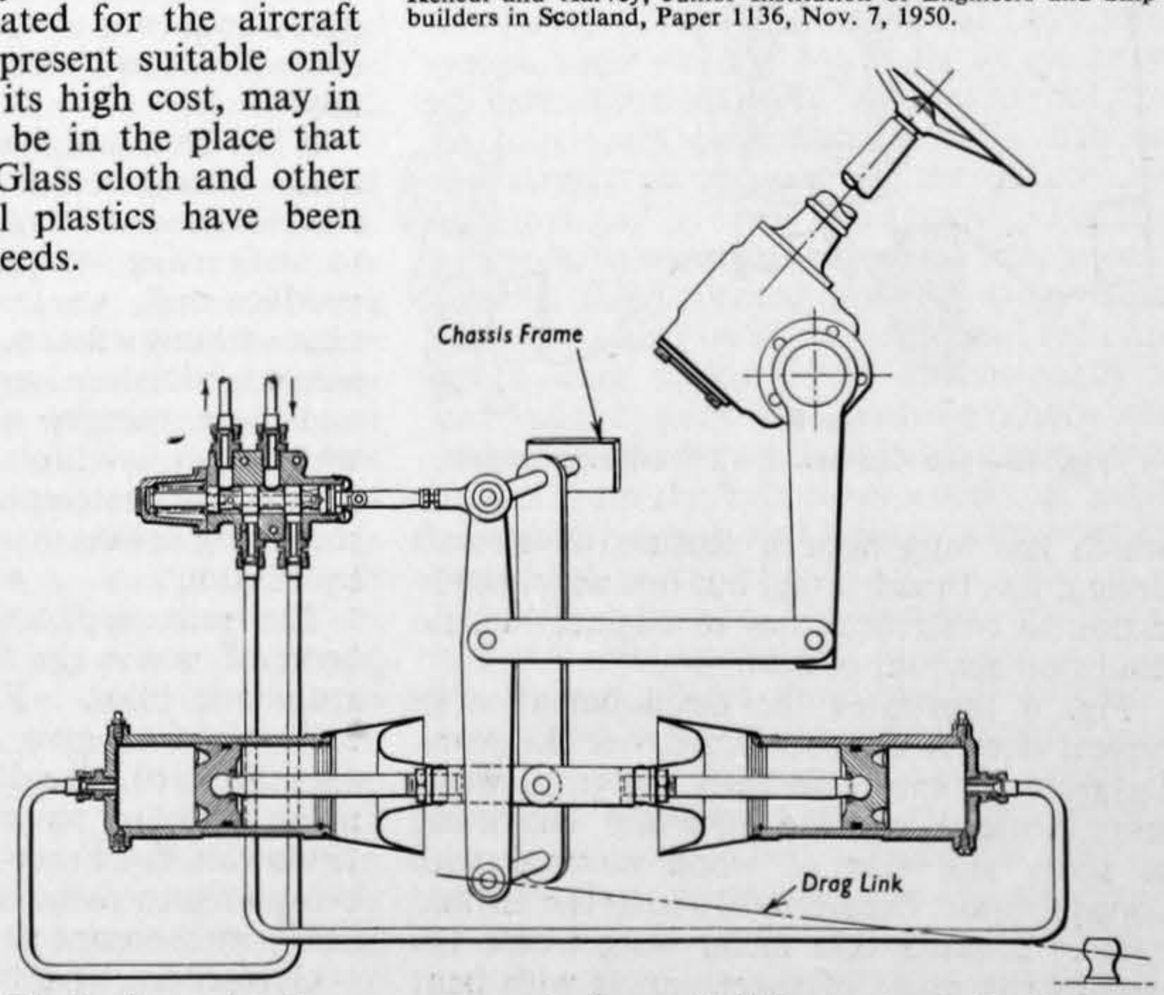


Fig. 9—Power boosters or servo mechanisms. Vehicle steering hydraulic servo

ance than in other spheres. The design technique has been to make use of extensive ribbing to stiffen or stabilise the main surfaces of the structure with the object of obtaining failure and instability about the same time. Extensive full-scale tests on all structures are carried out up to destruction and a structure which fails at too high a load is frowned on as much as one which fails too soon. This practice of destruction test,

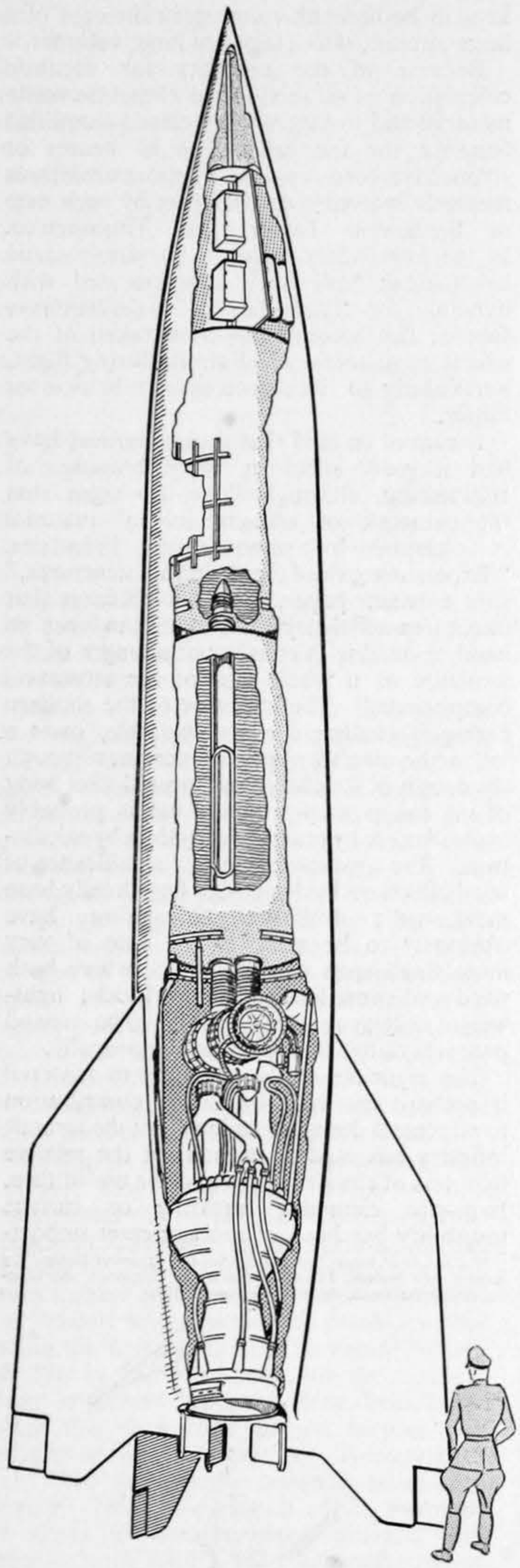


Fig. 10—The German "V2" ballistic rocket

which has long been a feature of aircraft design, has found some, but not wide, application in other branches of engineering, no doubt on account of cost.

Fig. 6 illustrates the development of a typical aircraft wing structure over the years. Diagram (*a*) shows an early design of wood and fabric wing, the structure consisting of spars and ribs of wood covered with doped fabric. Diagram (*b*) shows the normal type of stressed skin metal wing where the assembly is made of sheet panels with bent stiffeners riveted together, and riveted in turn to ribs and spars. Diagram (*c*) shows the latest development, that is the use of large slabs of light alloy machined all over with the complete contour of the surface of the structure, including all the longitudinal and transverse ribs and cut-outs. A wing made in this manner consists of a very few parts only, although the parts themselves are substantial and involve a great deal of work. The resultant structure is, however, not only lighter but, because of the elimination of a large number of pieces and much riveting, is not in practice any more expensive to manufacture. It is too early to suggest whether this process of machining to form will find a counterpart in other industries, although it could be said that the practice of flame cutting steel structures from large plates is already comparable. No doubt the large automatic profiling machines which are being developed for the aircraft industry will find an outlet to other industries who will eventually find uses for the technique.

Control

An interesting sphere where aeronautical development has gone in parallel with and often led other specialised branches of engineering, is in the development of control devices, usually automatic, and often making use of the gyroscope. The gyroscope was used in torpedoes before 1900 to control the direction of the weapon and on various other ship and gun control systems from about 1905 onwards. Much of the early difficulty of achieving satisfactory powered flight was, however, related to the control of the aircraft and it is not surprising that suggestions were soon made for using the gyroscope as part of the control system. The earliest application (1891) was undoubtedly by Sir Hiram Maxim who fitted two gyroscopes (one to control pitch, the other to control roll) to his early steam powered flying model.

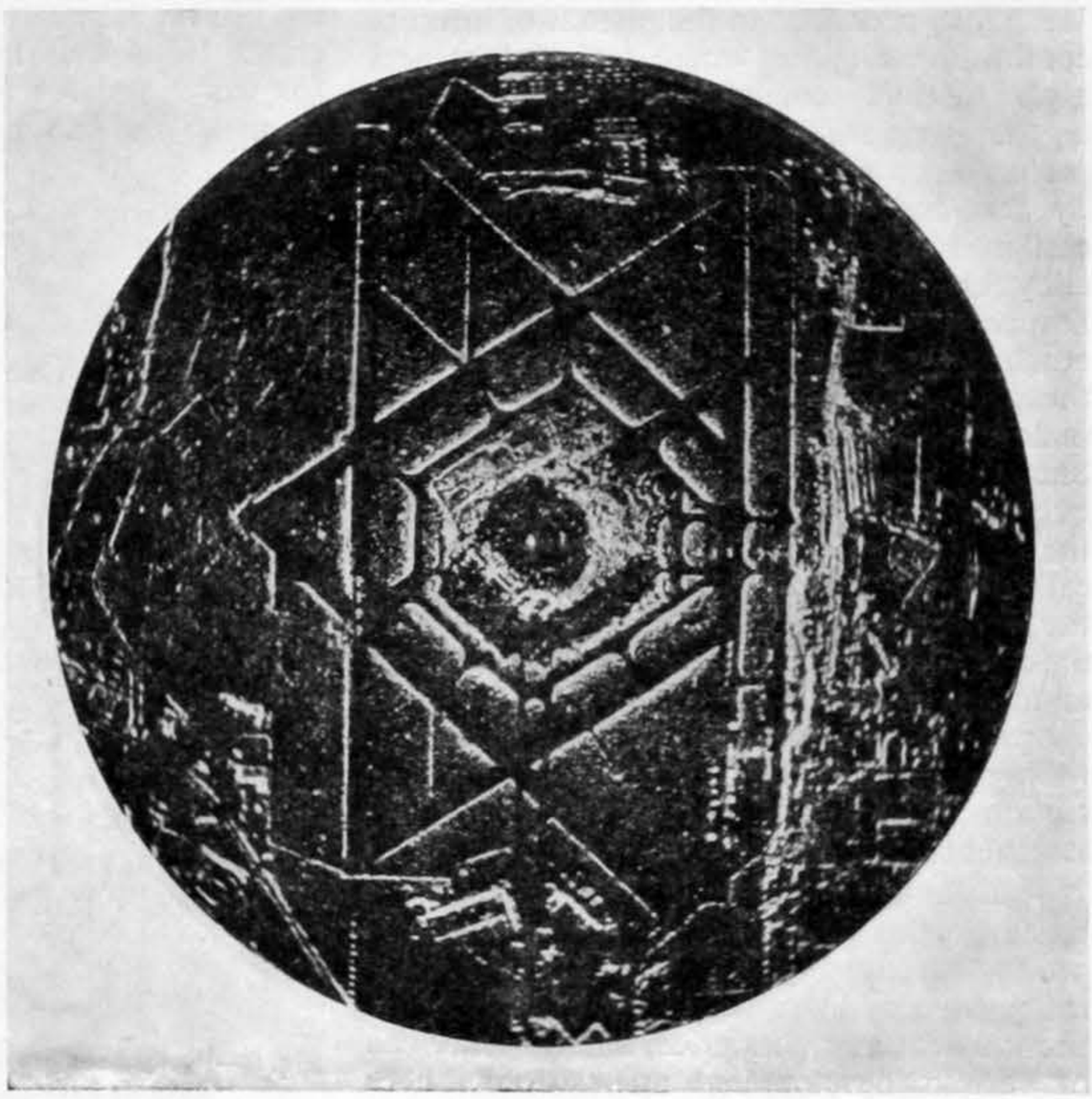


Fig. 11—London Airport seen through a Decca centimetric radar set on the control tower

It has been said that one of the outstanding achievements of the Wright Brothers was in their invention of a system coupling the rudder to their wing warping mechanism used to produce roll, so that they could make a turn without sideslip. They kept this simple solution to themselves for a number of years, and were thereby able to fly successfully while other inventors were searching for the trick, or contemplating fitting synthetic stabilising devices based on the idea proposed by Maxim.

The next application of the gyroscope, however, was in the first successful use of an automatic pilot. E. A. Sperry, who had built his first gyro compass for an aeroplane in 1910, fitted a gyro controlled automatic pilot to an aircraft in 1912 and in 1914 won the French Safety Prize in Paris, being able to demonstrate the aircraft flying safely with no one at the controls.

Gyroscopes have little application on land except on gun platforms on vehicles. They are obviously used to steer ships automatically as they do aircraft. Since, however, a gyroscope is only perfect within limitations of its own gimbal bearing friction and accuracy of balance it has always called for the highest degree of precision in manufacture. Demands of quantity production in time of war have led to the spreading of the knowledge of its manufacture; what is considered to be exceptional precision now may be more widely known in ten years' time. Whereas the earlier units had an ordinary mechanical gimbal system and operated directly the valve of a servo motor, the modern unit may be liquid suspended so that is it not subject to acceleration shocks, and its motion is used only to move an electrical pick-off which exerts a friction infinitesimally smaller than the friction of the servo valve on the early unit. The drift rate of the early unit may be measured in terms of degrees per minute while the modern unit can have a drift rate of some small fraction of a degree per hour.

If the aircraft industry cannot claim the invention of the servo mechanism it can indeed take a large share of the credit for its rapid development over the last few years. The mechanical servo mechanism was invented for ship steering by McFarlane Gray (1867) and Farcot (1873)—Fig. 7. Whitehead used it on torpedoes a few years later and as mentioned above it was used with early auto-pilots. Indeed it might be said that the successful use of a gyroscope implies the use of a servo motor to limit the power demand on the gyroscope. The radio communication and electrical industries can claim the credit for initiating recent activity in servo-mechanism development by evolving modern mathematical servo theory from about 1935 onwards. During the recent war this theory and practice was exploited in many directions for gunfire control and various other military and aeronautical applications. To-day the servo-mechanism is a commonplace feature of factory and machine, and its theory is a new subject studied by all engineering students.

The aircraft industry's particular contribution has been in the development of power controls for direct operation of the

aeroplane control surfaces to amplify the manual efforts of the pilot. Instead of the servo of the automatic pilot taking over to maintain the aircraft on course, servo-mechanisms are now used on many aeroplanes to help the pilot under all conditions.

Fig. 7 illustrates one of the first ship-steering servos by Farcot (1873), which should be compared with a typical modern aircraft hydraulic (oil) power servo, Fig. 8. Farcot used steam, although others used water somewhat later. The latest application of the hydraulic servo is to vehicle steering gear and the illustration, Fig. 9, shows for comparison a typical steering servo for a heavy vehicle.

The more recent needs of aircraft and guided missiles have led to the development of small electro-hydraulic servos where the input signal is derived from an electronic amplifier rather than from the movement of some lever or rod. With the future require-



Fig. 12—Typical modern tractor with hydraulically operated excavator

ments of process control, machine tools, &c., it seems likely that these small electro-hydraulic servos will find many future applications to engineering, for example, in the control of thickness in a rolling mill or the contouring of a copying lathe.

Automatic Flight—Guided Missiles

Early attempts were made at the end of and after the first world war to equip aircraft with fully automatic control devices so that they could be used as drones for target practice, or as flying bombs. Here aircraft followed the development of the torpedo, which was the first guided missile.

The German "V1" flying bomb and "V2" ballistic rocket of the second world war were remarkable examples of engineering development—indeed, it might be said that the "V2" was one of the outstanding engineering developments of this century. An interesting comparison can be drawn between an early Whitehead torpedo of about 1900 and the German "V2" (Fig. 10). The two weapons are not unlike in shape ; both have large storage vessels, the torpedo containing compressed air to drive the propeller motor and the rocket containing liquid fuel (liquid oxygen and ethyl-alcohol), which is subsequently burned in the combustion chamber of the rocket motor, the fuels being pumped by steam-driven turbo-pumps. The steering system of the torpedo makes use of a direction-controlling gyroscope and depth-sensing mechanism to maintain a path at a given depth of water. The signals from these controlling elements go to the valves of small servo motors operated by compressed air, which, in turn, operate the steering rudders. The control system is more complicated in the case of the "V2." Initial control from vertical launch when the speed was low was by means of carbon deflector vanes in the jet efflux from the rocket motor. These vanes were moved by small hydraulic servo motors, controlling signals coming once more from a system of gyroscopes.

The torpedo is expected to maintain a straight path until impact with the ship. The rocket, however, was launched vertically and then made to turn over slightly by its control system so that it began its trajectory in the correct direction. The fuel supply was cut off at an exact velocity as this had an important bearing on the ultimate range. This was effected by means of a novel and remarkable integrating accelerometer—the acceleration sustained being integrated electrically in order to determine velocity, the fuel valves closing when the integral of acceleration reached a predetermined value.

The work of Whitehead at the latter half of the last century has always been considered outstanding. He was one of the founders of precision engineering : the manufacture of torpedoes involved skill of a high order. The development of a ballistic rocket was, however, even more remarkable, involving as it did the entry into many unexplored fields of engineering and chemistry and the development of a whole host of control mechanisms, rocket motors of a size enormously larger than anything ever produced before, pumps and ground equipment on a vast scale. Not the least remarkable factor in this work was the enormous effort put into development before a satisfactory weapon was produced. Over 1000 rounds were fired before operational success was achieved. Even then the percentage of failures was very substantial.

Navigation

Over the years it is the mariner who has been largely responsible for the development of methods of navigation and of accurate timekeepers. Aeronautics has made its own special contributions in the fields of mapping and survey, although the outstanding developments have perhaps been more noteworthy since the invention of radar some twenty years ago. Since then the rate of development has certainly been scarcely credible.

Radar, or radio-location as it was called by its inventor Watson-Watt in 1935, introduced the technique of sending out short-wave radio pulses and measuring the time taken for them to be reflected back from some object encountered. The first systems used wavelengths of a few metres, but as components became available, centimetre, indeed millimetre, wavelengths were introduced. Originally evolved for the detection of enemy aircraft as an essential part of the air defence of Great Britain, it has since become extensively applied in the aeronautical and marine field for determining ranges from a few feet to hundreds of miles, and, indeed, to paint pictures with reflected radio beams instead of light waves. During the war the activities of a few brilliant engineers enabled a whole new series of navigation systems to be evolved, which have now been developed as standard fitments on ships of all types to enable them to navigate safely in all weathers, in dense fog and at night. The technique of the blind bombing which enabled the R.A.F. to see their ground targets through cloud from high altitude has now been extended to the screening or photography of land areas or even buildings through cloud or fog and can produce radar pictures similar to that shown in Fig. 11.

Navigation systems originally developed during the war make use of radio wave patterns emanating from two or more stations to enable an aircraft fitted with a suitable detection unit to get a cross bearing and thus read its position immediately ; this system has since been extended to the marine field, large areas of the oceans now being covered by these networks. Many special radio stations send out rotating V.H.F. beams which can give a ship or aircraft a direct range and bearing.

The needs of aircraft in terms of reduction of weight and size have led to the development of a whole series of miniature radio components and valves. The general tendency has been for radio equipment to get smaller largely as a result of meeting aero-

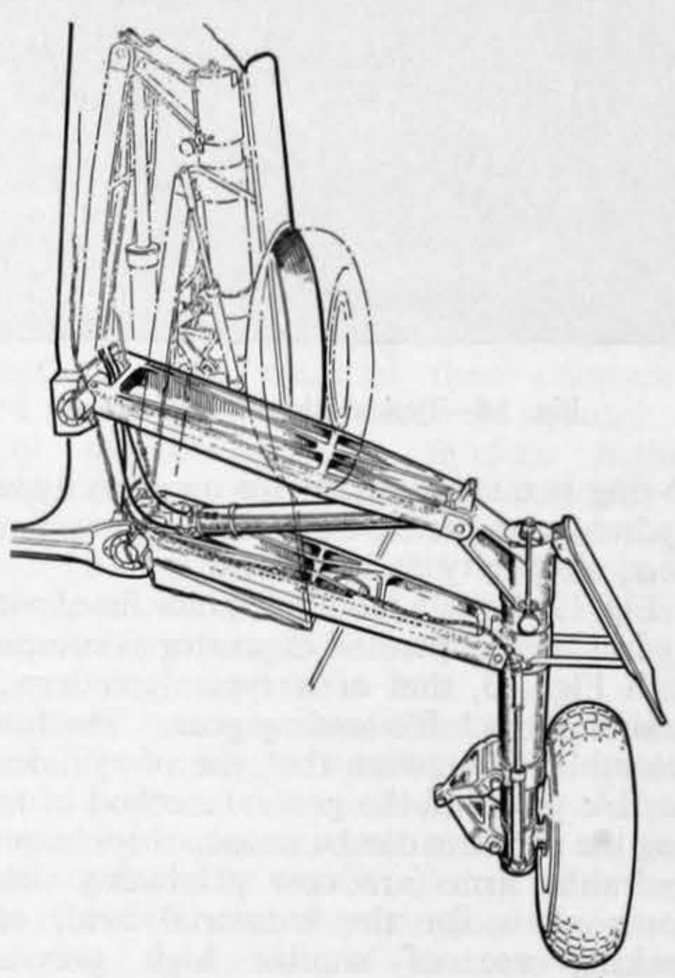


Fig. 13—A typical hydraulically retractable landing gear

nautical demands. Domestic television has been helped by radar development.

Mechanical Equipment

A number of the ancillary devices which have been developed for aircraft have had a considerable influence on parallel developments in general engineering. For example, the introduction of the retractable landing gear about 1932 created a demand for light-weight, high-pressure hydraulic systems for this duty. The conventional hydraulic system used on machine tools or on heavy equipment in docks and factories at that time was obviously quite unsuitable for airborne use, largely on account of the use of low pressures and in some cases water. The first hydraulic systems made use of simple components using methods and packings which had been common in the industrial field and which were scaled down dimensionally to save weight. New high-pressure pumps were designed and here again suitable designs were chosen from the enormous variety of industrial pumps which had been evolved over the period of years. By 1935 the practice of hydraulic operation had become established and a highly specialised hydraulic industry grew up in all the main aircraft producing countries ; a great deal of development work went into new lightweight constructions for hydraulic cylinders, valves, pumps, and produced a large number of ingenious solutions to difficult problems, such as the mechanical locking of jacks and the control of flow to regulate speed, for sequencing operations.

A simple but interesting example where

industry as a whole has benefited from aircraft development is in the evolution of the O-ring. The original packings, as has been mentioned, were substantial and heavy; static seals were largely made by screwing or clamping two components together with a gasket. Simultaneous development in Europe and in America of a simple square or circular section rubber ring, fitted into a groove with radial interference, enabled an extremely effective and remarkably light and cheap sealing method to be introduced. Now the

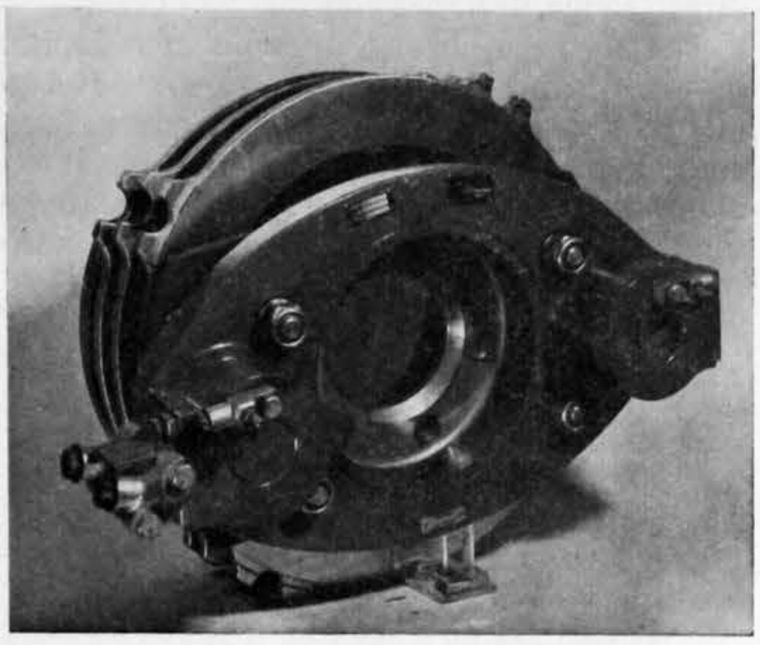


Fig. 14—Typical aircraft disc brake

O-ring is a standard device on every type of hydraulic or pressure system due to its smallness, simplicity and low cost.

Fig. 12 shows a modern tractor fitted with a hydraulically operated excavator as compared with Fig. 13, that of a typical modern hydraulic retractable landing gear. The family resemblance between the type of cylinder or flexible pipe and the general method of tackling the problem can be noted. Most aircraft hydraulic firms are now producing similar components for the industrial field, often making use of similar high pressures. Whereas twenty years ago 500 lb per square inch was considered a high pressure for an operating system, 2000 lb per square inch is not now considered excessive on an industrial machine; 4000 lb per square inch is now a standard aircraft system pressure.

A similar development is taking place in the application of aircraft disc brakes to road vehicles. The classic type of brake on vehicles and other forms of transport has been the internally expanding or externally contracting drum brake. Under arduous duty this suffers from various defects, the most notable of which is the distortion of the drum as it becomes hot. The aeroplane designer's solution to this difficult problem has been to develop the ventilated disc brake. Because of the need to conserve weight the mass of energy-absorbing disc in an aircraft brake is very small, meaning that temperatures are extremely high. Since the brake forces act normal to the two exposed surfaces of the disc, the disc being more or less unstressed mechanically, reliable performance with disc temperatures of 600 deg. Cent. or more have been achieved. There are already signs that similar brakes will be adopted for high-performance motor-cars, and it is quite likely that all vehicles will ultimately be fitted with some kind of disc brake to take full advantage of its improved performance. Figs. 14 and 15 show a typical aircraft disc brake in comparison with its racing car equivalent.

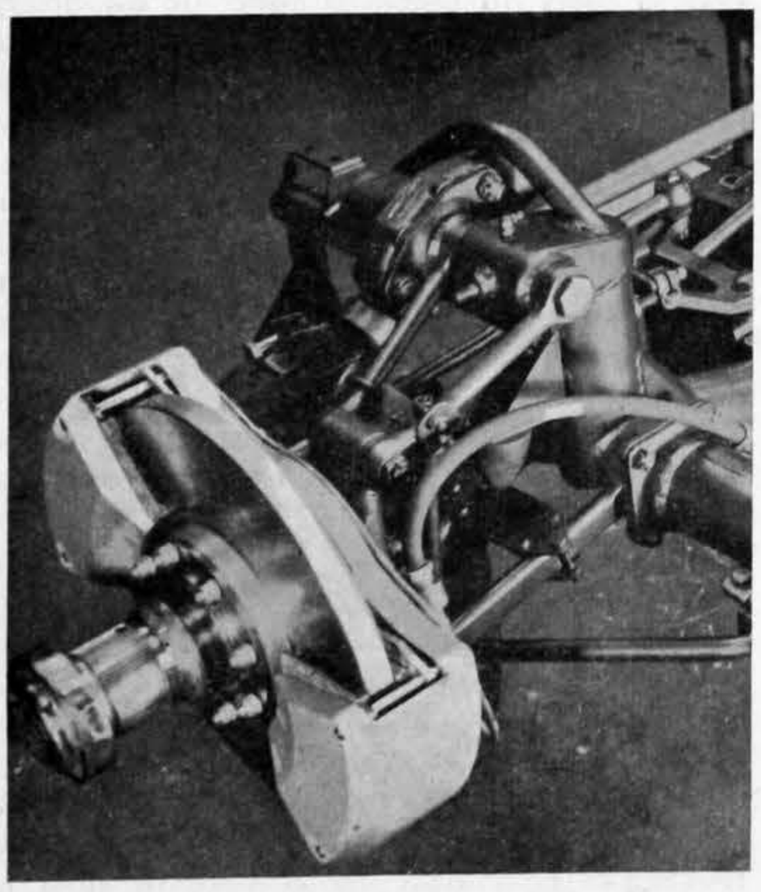


Fig. 15—Racing car disc brake developed from the aircraft type

Conclusion

In the first hundred years of the publication of this journal the effect of aeronautics on engineering as a whole has been profound. The rate of progress, which has been spectacular in the last few decades, cannot be expected to be maintained indefinitely. We may expect in the next decade or so to be flying at high supersonic speeds, to have got over or around the so-called "heat barrier," to have developed long-range rockets for both military and, let it be hoped, peaceful purposes, and to have carried automatic control in flight to very much greater lengths. But the thoughtful engineer may wonder whether supersonic passenger flight is round the corner. In spite of all the progress made in aeronautics, it is still true that some passenger air services are taking almost as long now as they did before the recent war. The incentives for the fare-paying passenger to fly at 300 or 400 m.p.h. in the comfort of altitudes of 20,000ft to 30,000ft are very considerable as compared with alternative forms of travel, but the incentives to travel at 1000 m.p.h. at 60,000ft are relatively much less. Another war similar to the last would undoubtedly develop flight of this type to an appropriate degree of reliability. Without that kind of war or in the shadow of the thermo-nuclear bomb, military development may very well proceed along different lines, concentrating on the defensive missile and the long-range ballistic rocket, leaving transport to look after itself. Many engineers would be content in the circumstances with a less spectacular rate of progress.

Land Transport

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TO review with any degree of completeness the ways in which developments in land transport during the past 100 years have influenced the advance of engineering and to study how engineering advancement has influenced land transport is a task of vast proportions. I can only hope to indicate very broad interactions between these wide fields of human activity, and to draw a few examples from my own special experience, an experience which is heavily weighted on the civil engineering side of road transport.

By 1856, after some thirty years of serious development, the railways had already attained about half their present mileage and were, by then, providing the framework for the transport system of the day. From 1900 onwards the motor vehicle brought road transport back into the picture. Since then, road transport has, as everyone knows, advanced at an ever-increasing rate until to-day, with over 5,000,000 motor vehicles on the road, at least one-seventh of the whole national expenditure is on road transport and travel; this is three or four times the expenditure on rail transport.

Rail and Road

The way of life and the standard of living have always closely depended upon the ease with which people and goods can be moved from place to place—the ease of communication. The railway, coupled as it was to the industrial revolution, transformed conditions in the nineteenth century; the motor vehicle has again transformed them in the twentieth. The location of industry, the siting of individual factories, the mode of operation of industry, the size and weight of units that can be transported, the way in which factories situated at some distance apart can nevertheless work together in creating the parts to be built into a whole unit are all material ways in which land transport has helped and influenced the many branches of engineering industry. Before the advent of the motor vehicle rail transport had created a more rigid pattern, lacking the flexibility of the pattern now emerging. The conception of factories dispersed over a wide area with the roads forming the "conveyor belts" between them is one that has developed with the changing conditions brought about by the motor vehicle as a result of the freedom of movement given both to the component parts and to the final product.

By 1856, not only were the main lines of the railways already in existence, but the design of steam locomotives, rolling stock and permanent way were, fundamentally at least, already settled. By that time the pioneering railway engineers had influenced the growth of mechanical and civil engineering in numerous ways: they had made thousands of bridges and subways, many tunnels, and embankments and cuttings in great numbers; they had evolved a signalling system for safe transportation and they had built stations with high platforms and bridges for the safety of passengers. They had worked out principles of traffic segregation for rail traffic which in many ways were in advance of those used on the roads to-day. Compared with the effect of the achievements of the early railway engineers, it seems that since that time the influence of railway engineering on general advancement, although by no means negligible, has been relatively small, though it is true that railways have been greatly influenced by advances in other fields, such as, for example, in electricity and in the development of the internal combustion engine, especially the diesel engine.

Road Transport and Its Influence

The effect of the development of road transport on engineering advancement has, of course, been much more recent and is virtually confined to the last fifty years. It was, however, the invention of the pneumatic tyre and the safety bicycle which brought life once more to the roads of this country following their eclipse by the railways. It was, in fact, the agitation of the cyclists that brought the County Highway Authorities into being, but it was, of course, the internal combustion engine which was to create the great revolution in road usage that is still in

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its growing pains, and to which no satisfactory well-balanced solution has been found—the disparity between the highways and the numbers, speed and size of the vehicles that they are forced to carry remains one of our most pressing problems. The increasing and insistent demand by the public for motor vehicles, both for private and industrial purposes, has in fact created a vast industry with repercussions in every branch of engineering. Mass production methods, special machine tools, and new methods of producing steel plates owe much to the motor industry, as indeed do many other manufacturing techniques, such as centrifugal casting of metals to produce sound dense castings, hot and cold pressing techniques, painting by electrostatic methods, and rustproofing and chromium plating. Moreover, many of the materials developed for motor vehicles have found a ready use in other spheres. Cast iron is now a reliable stress-carrying material, largely because of the demands from the motor vehicle industry, and even highly stressed parts such as crankshafts are now being made in cast iron. In many cases quite new materials have been developed, such as, for example, safety glass in the form of laminated or toughened glass, and these have stimulated developments outside the vehicle industry. Completely new industries have been created for the production of lubricants and fuels for internal combustion engines ; and these industries have in their turn, by making use of chemical and physical advances in other industries, yielded many valuable products from what were at one time waste products.

The aeroplane in its early days depended for its power on the petrol engine developed for road transport. Its special needs—lightness and strength combined with extreme reliability—have been a continuing challenge to engineers and the results have been fed back into motor vehicle engineering. Similarly, in agriculture and in civil engineering and building, the internal combustion engine has provided the power unit for the revolution in mechanisation that has taken place in recent years. It can also be claimed that the internal combustion engine and the motor vehicle have radically altered military engineering and the whole science of warfare. Synthetic rubber, first produced on a large scale to provide tyres for motor vehicles to overcome war-time shortage, is also associated in a similar way with land transport.

This catalogue of influences from land transport to engineering in other branches, and, in return, from engineering to land transport, is seemingly endless, and the difficulty is to know where to stop the enumeration and to begin with the more detailed examples.

The Road Surface

From its earliest beginnings the motor vehicle has demanded more and more from the road and still continues to do so. McAdam said, quite rightly, that iron-rimmed wheels would grind the surface stones into a coarse powder which would act as a kind of cement, but with the advent of rubber tyres on road vehicles there was no grinding action ; instead the loose grit was sucked up, with the consequence that every motor vehicle was followed by a huge cloud of dust. The original water-bound macadam roads began to disintegrate as more and more motor vehicles came on to them. Seawater was found to be more effective in " laying the dust " than fresh water and the dust problem was so serious at the time that in the early years of this century plans were considered for bringing sea-water by pipeline from Brighton to sprinkle on London streets : in fact, salt is still used in some countries where other methods are too expensive to use. Tar spraying, however, was to solve the dilemma. It was, therefore, the early motor transport with their rubber tyres which brought about radical changes in road engineering. These changes have brought in their wake the mechanisation of road-making, first in the form of steam rollers, then on to tar sprayers, asphalt and tar macadam plants and, more recently, automatic road-surfacing machines, earth-moving and compacting machines, and even quarry plant for producing the vast quantity of road stone now required.

The tyre and the road surface are the surfaces of contact between the moving vehicle and the road and it is the interaction of the two—in both dry weather and wet and when ice is about—which largely determines the stability and safety of the vehicle. As vehicles are produced which are capable of travelling at higher and higher speeds, so must both the tyre manufacturer and the highway engineer seek to create conditions which lead to stability and safety at those speeds. The tread on the tyre must, so to speak, grip the pattern on the road surface. Appreciation of the importance of this grip has led tyre manufacturers to experiment with a wide variety of tread patterns, and has encouraged road research workers to study the way in which vehicles skid, the interaction between tyre and road, how water is expelled from the surface of contact between the tyre and the road, the details of road accidents involving skidding, and ways of using stone and tar, bitumen or cement so as to give the most stable conditions for the motor vehicle. Of recent years it has been found that the higher speeds of post-war vehicles have resulted in the polishing of the stones in the road surface and turned what would appear to be a safe rough surface into a dangerous and slippery one. Research is in hand to ascertain where and when particular types of rocks can be safely used in road surfacing.

The aeroplane and the motor vehicle are not only related by their use of allied power units but the land requirement of the aeroplane, its runway, has much in common with the road. It was, in fact, the highway engineer who was called in when at the beginning of World War II, the grass runway ceased to meet the needs of the aeroplane. The aircraft wheel load was at first comparable with that of the road vehicle, but before long it became much greater—so great in fact that the crude rule of the highway engineer that 6in of concrete was " good enough for anything and if it wasn't—well, make it a bit thicker " soon brought many troubles. These troubles led largely to the methods of design based upon the plate-bearing test and the " California Bearing Ratio," which were used as a measure of the strength of the supporting soil. These methods, refined and modified as a result of research and experience, are now extensively used in the design of road pavements. The huge level-surfaced areas required for airfield operation have, in fact, led to developments in the techniques of construction, in earth-moving equipment and in concrete compaction and finishing, which are having a profound effect on highway building. The scale of this construction will perhaps be appreciated from Sir Ben Lockspeiser's statement to the British Association in 1952, that enough concrete was used in the construction of London Airport to build a motor road from London to Edinburgh. The interaction between tyre and surface has also become of greater importance to the aeroplane of recent years, since jet aircraft cannot use reversed pitch propellers for braking, and have to rely on brakes on the wheels. This has led to research into the tyre-surface phenomena at high speeds.

Concrete

Although concrete has been used as a structural material for centuries—the Romans used it in building—it was not until 1873 that the first concrete road was built in the United Kingdom. This early concrete was, however, a material of low strength and was far from reliable. Long periods were required for the strength to develop. It is only during the last fifty or sixty years that the science of concrete and reinforced concrete has been developed. Knowledge obtained from the use of concrete in structures of various kinds led in fact to the serious use of concrete on a considerable scale for road building only after the first world war. With concrete mixed by hand, with the barest knowledge of how to choose the sand and stone, and with little appreciation of the importance of the amount of water used in making the concrete, there were many costly mistakes both in building and in road construction. The material then commonly used bears little resemblance in strength or other qualities to the modern highly-controlled concrete used, for example, in the factory production of prestressed concrete structural units. The difference is between a concrete of, say, 1000 lb per square inch crushing strength and one with a strength approaching ten times that value. The design of concrete mixes for strength and workability and the application of quality control procedures have been greatly helped forward by experience and research on concrete roads. The results of this work have now extended into many branches of civil engineering ; the building of dams, sea defences, airfields, and bridges are some examples.

The greatest strides in the improvement of quality have been made during the past 25 years. For generations it was the practice to specify the concrete in terms of arbitrary proportions of cement, sand and stone. It is now increasingly common to use proportions based on a careful assessment of the shape and grading of the aggregates available, the kind of cement used, and the workability and strength required of the concrete. This procedure enables the cement and aggregate to be used in the most economical and efficient way. The properties of concrete are highly variable and many of the causes of this variation can be greatly reduced by adequate control of the materials and processes. Experience has shown that controlled concrete can have only a fraction of the variation in strength of uncontrolled concrete. Weigh-batching, and the careful control of grading of the sand and stone, and of the water/cement ratio have now found their way into most fields of civil engineering. Control has been especially developed and used in airfield construction, where the large masses of concrete needed offer particularly favourable opportunities for economy.

Another development affecting the proportions of concrete, and one that was first applied during World War II on any considerable scale to road and airfield building, is the use of air entrainment, that is the addition of special agents to ensure that minute bubbles of air are produced when the concrete is mixed and remain in it when it has hardened. These bubbles are accompanied by a greatly increased resistance to damage by frost, particularly in concrete which is

not mixed with a low water/cement ratio and which is not properly compacted. Many stretches of concrete road built between the wars were of poor quality and suffered from scaling of the surface, especially in countries with a cold climate. The use of air-entraining agents makes it easier to produce frost-resistant concrete ; so great is the improvement that in some countries only concrete containing such air is permitted to be used in roads and certain other structures. In some countries the agent is ground with the cement clinker, as it can assist the grinding process.

The need for the ancillary concrete products used in pavement work, such as kerbs, flagstones and fence posts, has done much to develop the precast concrete industry. The hydraulic press was first used for manufacturing paving flags in 1885, and their manufacture has formed an important part of the activities of that industry ever since. The use of precast posts for street lighting is a more recent development. With the appreciation that the control of the quality of concrete can be more simply and accurately achieved under factory conditions, the precast industry has grown rapidly in the last few years. The difficulties encountered when concrete is made *in situ* can be almost completely eliminated in highly mechanised factory processes, and to-day we see very large factory buildings being erected with all or many of the reinforced concrete units forming the structural frame pre-cast and transported to the site ready for fastening together on the job.

Concreting Plant

There has been continual interchange of developments and experiences in concreting plant between the various aspects of civil engineering. Mixing was the first process to be mechanised. It appears to have been developed during the 1870s, particularly for use in dock and harbour works. At that time mixers were either fixed or portable and were driven by gas or steam engines or even turned round by hand ; capacities were up to 1 cubic yard. Since that time developments have been mainly in matters of detail and size rather than in the basic principle. As far as roads are concerned, the need for large volumes of concrete over an extended site have led to interesting modifications and the introduction of mixers mounted on crawler tracks to speed up the concreting of roads and runways. The use of concrete of low water content to obtain high quality has posed problems in efficient mixing and clean discharge which are receiving special consideration by manufacturers and research workers. To achieve its full density and strength concrete must be fully compacted. During the last forty to fifty years the main improvement has been in the increasing use of vibration to effect compaction. A vibrating device for pavement work has to meet different requirements from those of a vibrator used in mass concrete and reinforced concrete structures. Road slabs are most conveniently compacted by a vibrating beam moving along the surface of the concrete. Such machines were first used on a commercial scale in the early 1930s.

Mechanical batching plants were first developed in Great Britain in the 1920s, when the constituents were measured by volume. But volume measurement has never proved altogether satisfactory, partly because the volume of sand depends on how much water it contains. The use of weigh-batching became increasingly common in road work and was widely used by 1938. It has since come into much more general use in other fields of civil engineering, so that it is now common practice on all large jobs and many small ones to batch the materials by weight, plant for this purpose being available in a wide range of sizes and types. As an example of the present state of development, mention may be made of a weigh-batching plant with push-button controls turning out sufficient material for about 200 cubic yards of concrete per hour. Such plants not only produce large quantities of accurately proportioned materials, but they reduce labour requirements to a minimum. Wherever large quantities of concrete have to be placed—for example, in large main foundations, in dams, or in sea works—these batching plants are to be found.

Soil Mechanics

It is a matter of common experience that most soils in a certain condition are sufficiently strong to support wheeled traffic. Their strength is reduced, however, when they become too wet or too dry, and we know that because of this the earliest roadmakers resorted to the use of layers of stone to support their vehicles, since they knew that the strength of stone is practically unaffected by water. The stability of a soil foundation to a road is in fact largely determined by the amount of water present, both on the surface of the particles and in the pore spaces. For this reason much attention has been given to the study of the movement of water in soil.

This and allied subjects are of basic importance in civil engineering and the comparatively new branch of engineering science —soil mechanics—has largely grown up around a study of the effect of the moisture content on the physical properties and behaviour of soil. The extent and complexity of the subject is great, for soils in the engineering sense range from gravels and sands, on the one hand, to peats and clays on the other. All branches of civil engineering have contributed to the pool of knowledge on the subject, for there are few problems of stability and strength which are not of common interest. The civil engineer's specialist knowledge has in turn developed very largely from the studies of the physical properties of soils made by the agricultural scientist, and although their paths have diverged in their specialist fields the agricultural scientist and the civil engineer still maintain close liaison and interest in each other's work. For example, the problem of bacterial attack on stabilised soil used as a road material was studied by the Rothamsted Experimental Station.

To return to the particular subject of the movement of moisture in soils, it has become clear as the research into road problems has progressed how wide the field of application may be ; two examples that may be cited are foundations of buildings and dissipation of heat in soil. When desiccated clay soils are covered by impermeable building foundations, moisture accumulates under the structure—partly as a result of the condensation of water vapour moving through the soil—and the accompanying swelling is liable to cause severe differential movements and subsequent structural failure. The same problem occurs in reverse, where continuously fired kilns are constructed on shrinkable clay foundations. The drying clay leads to increasing settlement over long periods. The magnitude of the settlement must be estimated and as far as possible taken into account at the design stage.

The thermal conductivity of soil increases with increasing moisture content. This is an important factor in the design and operation of buried electric cables. The heating effect arising from the cable itself tends to dry out the soil ; where however the soil becomes abnormally dry, due, for example, to the presence of fast-growing vegetation or indeed to prolonged drought, the working temperature of the cable may rise to a dangerous level. The increasing demand for electricity since the war has called for a closer examination of the soil properties that largely determine the factor of safety at which buried cables operate. Heat dissipation in soil and its variation with moisture content is also important in the control of temperature below ground, for example, in connection with the air conditioning of underground railway stations.

The movement and distribution of water in soils is even more important in agriculture than in engineering, and many of the results of research in one field are equally applicable to the other. The general principles which determine the movement of water in soil apply to other porous media, such as paper, wood, stone and concrete. For all these materials similar techniques to those developed in soil research can be applied to measure the moisture they retain and the amount of water which is extracted from the air at different humidities. There has been a continuous exchange of ideas among workers in all these fields. One recent application related to the preservation of ancient wall paintings which were being damaged by moisture transmitted through a masonry wall. Another referred to the cracking of thin concrete roofs in Scandinavia which appeared to be due to the expansion on freezing of moisture which had migrated towards the cold external surface. A study of the retention of liquids in a porous medium can sometimes throw valuable light on the pore structure of the material itself, the size of the pores and the pore-size distribution. This method has recently been applied to the sintered materials that are finding increasing use in mechanical engineering practice.

Finally a case may be mentioned where the laws governing the movement of water in soil have been applied to the solution of a shipping problem. Certain fine-grained cargoes which appear to be perfectly stable when loaded tend to become fluid and consequently liable to dangerous shifting during transit. The change of stability arises from redistribution of water caused by the weight of the material itself and by engine vibration. Once the physical processes involved are appreciated in cases like this, laboratory tests can generally be devised to assess the risks involved and indicate the precautions to be taken.

Soil Stabilisation

In recent years treated soil has been increasingly used as a part of the road crust, the strength of the soil being both increased and stabilised against the effects of changing moisture content by the addition of materials such as cement or fluid bituminous materials. This mixture of soil and additive is known as " stabilised soil." In the United States the technology of soil roads dates from the turn of the century, but it was not until the second world war that interest grew in the United Kingdom when the need for high speed construction of road and airfield pavements provided the impetus. The experience then gained has led to an increased civil use of stabilised soil in the post-war period, since it has been found that this kind of construction is often cheaper than traditional methods of road making.

In the relatively wet climate of the United Kingdom, Portland cement has hitherto been found to be the most convenient additive for stabilising cohesive soils, although

certain types of sand and gravel have been successfully treated with bituminous materials. In one process, known as the mix-in-place method, the stabiliser is added to the soil and mixed by rotary tiller : agricultural machines were first used but have since been modified. Another method is to excavate the soil, transport it to a stationary mixer and carry the mixed material to the site of the road (the " stationary plant-mix " method). Both methods have advantages, but the " mix-in-place " method is usually preferred owing to the high output that is possible, rates of construction as high as 5000 square yards per day being attainable. A new British machine has recently been developed which enables mixing and preliminary compaction to be done in one pass.

During the war 4,000,000 square yards of bitumen-sand mixtures were laid on R.A.F. aerodromes in coastal areas. Subsequently, much has been done to encourage the use of the process in which Portland cement serves as the stabiliser (" soil-cement "), particularly in the construction of lightly-trafficked pavements for housing estates and urban roads. More recently lengths of soil-cement road have been laid on heavily-trafficked trunk roads. The process has also been successfully applied to the construction of airfields. Because of the speed of construction and the reduced need for imported material, soil stabilisation is recognised as one of the principal means of constructing temporary roads and airfields for military purposes.

Following upon the successful use of stabilised soil in road pavements, engineers have been prompted to employ the material in a variety of other directions. The use of soil in the construction of walls for buildings is a very ancient practice, which persists in many parts of the world even to-day. Cohesive soils are either formed into bricks, which are then sun-dried, or rammed between movable shuttering (" pisé-de-terre "). Walling of this kind can be surprisingly durable, particularly in areas of limited rainfall, if protected by some form of rendering. However, the stability of the wall is greatly improved by the use of stabilised soil, and this has now been employed successfully on a large scale in the Gold Coast and in India. The development of block-making machines has speeded up production. Uses have also been found for stabilised soil in water supply and hydraulic engineering. In 1948 a cement-stabilised soil foundation was constructed by the Metropolitan Water Board for concrete filter tanks at their installations at Ashford, Kent. In the United States soil-cement has been used on a rather greater scale in this field, for example, for lining irrigation ditches to prevent erosion. A similar instance of this application is the use of sand-bitumen linings on the walls of the Suez Canal, and of soil-cement for the internal facings of the walls of a reservoir. A further interesting application of stabilised soil to prevent erosion under what would be expected to be particularly severe conditions has been its use on the apron of a spillway. In the use of stabilised soil in hydraulic structures the material frequently has to be laid on sloping surfaces. In general this necessitates the use of stationary mixers, together with special techniques for placing and compacting the mixed material. The workability of the material assumes significance in these circumstances, and an innovation tried in the United States of America is to employ soil-cement mixtures with moisture contents so high that they are plastic when laid and resemble plaster.

Studies of Human Behaviour

Some years ago, when Henry Ford, Jr., opened new research laboratories in Detroit for the Ford Motor Company he made the point that a great deal was known about materials and how to use them but comparatively little about human engineering. He was thinking, it is to be supposed, about man in relation to the motor-car. I do not know how far the subsequent studies of his laboratory have been concerned with that aspect but there can be no doubt as to the importance of studying the human being in relation to what he does and is, and particularly in relation to the motor vehicle and road traffic, where questions of public safety and of traffic movement on the highway come to the fore.

There is also no doubt that discoveries made about human behaviour in the sphere of road transport are of interest over a far wider field and, similarly, that allied studies in other fields may have important application in the road problem. For example, the question of accident-proneness, beginning with the examination of accidents in the factory and the relation of accidents to skill, aptitude and personal character, led to methods of test used in the selection of air pilots and to a better understanding of the qualities to look for when selecting motor vehicle drivers.

The study of the way in which people perform certain tasks has led to great economies in industry, and in the same way studies of the behaviour of all classes of road user are providing results of value in deciding what is the best way to make roads safer. These studies have included, for example, the action of pedal cyclists, motor-cyclists and car drivers before turning right from a major road to a minor one and these have been examined in the light of accident statistics. Pedestrians have been observed, to find out when and how they use pedestrian crossings, subways and over-bridges, and how their habits are related to road safety. Attempts have also been made to find out how much time a pedestrian allows himself to cross the road in front of an approaching vehicle. Drivers' habits have been studied also in relation to action at " Halt " signs, " Slow " signs, and their readiness to give precedence to pedestrians at crossings.

Studies of this kind led to the adoption of the Zebra crossing, and showed afterwards that a very marked improvement had taken place, both in the behaviour of road users and in accidents. By keeping records over a period trends are studied and the effects of legislative measures are observed.

These are only some of the studies of human behaviour that are of interest : the arrangement of controls and of instrument panels, the reaction to the road situation, the effect of distractions, and of visibility and eyesight, and of drunkenness are other subjects for examination and on which discoveries in one field may be expected to have a direct bearing on the requirements in another.

Electronics

Modern developments in electronics have had such revolutionary effects on all branches of engineering that it is not surprising to find many common threads in their patterns, and that land transport is being increasingly influenced by techniques developed for other purposes.

We learn, for example, that in at least one city in America the traffic control signals are connected to a central control room and that the time intervals and time cycles allowed for traffic are automatically adjusted electronically according to the volume of traffic using the various city roads, so as to keep traffic moving as speedily as possible. The high-speed computer has also played an important part in traffic studies ; its use has enabled traffic signal problems to be solved and origin and destination surveys for large cities to be analysed rapidly and in such a manner as to indicate the best layout of highways to deal with the traffic.

So far as the construction of roads is concerned the methods of non-destructive testing developed for road purposes have proved of value in most branches of civil engineering : the way the methods have developed provide an interesting example of the interplay between the different branches. In the middle 1930s a piezo-electric strain gauge was developed at the Building Research Station for measuring strains in piles during driving. When war was imminent the research staff was transferred to work involving the measurement of the effect of blast on structures. The strain gauge used for the pile research provided the means for finding out what happened to the structural element, and from that point it was a direct step to the measurement of blast pressures when bombs were exploded. Throughout the war the Road Research Laboratory was responsible for the measurement of pressures developed from explosives, and it was from these observations that the efficiency of various weapons were assessed. They led also to measurements of the effect of underwater explosions in ships and to the design and attack of reinforced concrete structures, both defensive and offensive.

Resuming their peacetime duties, the scientists who had worked on these problems were set the task of developing methods of non-destructive testing for materials and for the finished road. The apparatus they developed has been marketed and has been supplied to many concerns, both at home and overseas. Its uses have ranged from controlling the quality of concrete in a pre-cast concrete factory to the testing of the concrete in prestressed concrete buildings and in massive structures. With appropriate modifications these methods have been used in many industries as a test of quality for materials of all kinds. A modified technique is now being used to study the stress distribution in different parts of the road structure as a vehicle passes over the road. The development of γ-ray and neutron sources with appropriate measuring apparatus for atomic energy purposes has led to an extended use of radiation methods in solving special problems ; for example, density gradients in road crusts are studied using γ-ray methods, and research is also aimed at using neutron methods for measuring the moisture content of soils, sands and other materials.

Conclusion

In the opening paragraph I said that this review would be heavily weighted on the civil engineering side of road transport. In the result it is also weighted by my own research experience, particularly in the examples given. As a review I am conscious that it is incomplete, ragged and in some places perhaps inaccurate, because it is written from a particular point of view. How it will fit into the whole scheme of this review and how much it will overlap or even conflict with the work of other contributors I do not know ; but it leaves me with the feeling that I have only begun to tell a story of interdependence between land transport engineering and other branches of engineering.