ELEMENTARY HANDBOOK OF AIRCRAFT ENGINES

BY THE SAME AUTHOR

AIRCRAFT ENGINES

In Two Volumes

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are now in preparation

This book has been prepared for the benefit of Designers, Aircraft Engineering Students, Research Engineers, Draughtsmen and others concerned with the theoretical, practical and experimental aspects of Aircraft Engineering. The text matter has been selected carefully so as to be directly useful to the individuals concerned; for this reason academic discussions and conjectural subjects have been avoided. The first volume is concerned mainly with theoretical and experimental aspects and the second is devoted principally to the descriptive side.

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ELEMENTARY HANDBOOK OF AIRCRAFT ENGINES

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SECOND IMPRESSION

CHAPMAN & HALL LTD.
LONDON
1945

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CHAPTER I

SOME GENERAL CONSIDERATIONS

THE modern aircraft, as with other means of mechanical transport, depends for its propulsive effort upon the provision of a suitable power unit and source of fuel supply. Indeed, the greater part of the history of aircraft development has been essentially that of the light petrol engine, although it is true that a good deal was learnt in the early days, before the introduction of mechanical power aid, from purely gliding experiments.

In the case of lighter-than-air machines, namely, airships, the power unit is concerned only with the propulsion and manœuvring of the aircraft and not with its aerial support or sustenance, since its buoyancy is ensured by the hydrogen or helium contents of the gas-containers.

With the heavier-than-air machines, *e.g.*, aeroplanes, however, the power unit must provide both for the propulsion and sustenance of the machine; should the source of power fail the machine must inevitably glide or fall to earth. It is therefore of much greater importance with aeroplanes than with other forms of transport that the engines should be designed and maintained to a high standard of reliability. In certain other respects, as is explained later in this chapter, aircraft engines must conform to exacting conditions of design and performance, and for these reasons may be regarded as representing the highest standard of development of the internal combustion engine.

Before continuing these general considerations in regard to modern aircraft engines it may be of interest to give a brief outline of some notable historical examples.

Early Steam Aircraft Engines. The earliest records of engine applications to aircraft are concerned with the steam engine, since the petrol type is of comparatively recent introduction. Thus, in 1840, an Englishman, W. S. Henson, designed and built a light steam engine which was to weigh, with its fuel and water, only 10 lb. and to propel a model aeroplane, but this engine does not appear to have been satisfactory. Henson then collaborated with John

Stringfellow who in 1843–7 constructed a steam engine of the single-cylinder direct-acting type having a diameter and stroke of 1½ in. and 3 in. respectively, and a speed of 300 r.p.m. This engine appears to have worked satisfactorily, but the model aeroplane to which it was fitted was unable to support itself for any distance and glided, gradually, to earth. Later, in 1848, Stringfellow built another engine and applied it to a model aeroplane, to which belongs the distinction of being the first in history to make a sustained flight under power. The cylinder was ¾ in. diameter, and 2 in. stroke. The crankshaft was provided with a bevel gear giving three revolutions of the propellers to one stroke of the engine. It drove a pair of four-bladed propellers of the right- and left-handed types, respectively, each being of 16-in. diameter. The weight of the entire model with water and fuel was under 9 lb. The engine was horizontal and double-acting and the thin copper boiler, with its silver-soldered joints consisted of inverted truncated cones around and above the furnace ; the latter utilized a naphtha lamp.

Apart from the successful use of steam power plant by Giffard in 1852 to propel an elongated balloon, or airship, at 6 m.p.h., the only other notable instances of the application of steam were the large-scale aeroplane of Sir Hiram Maxim and the model aeroplanes of L. Hargrave of Sydney, Australia, and S. P. Langley of the U.S.A.

In 1890 Maxim commenced the construction of a steam plant, and completed this by 1894. It consisted of two compound engines each of which developed about 180 h.p. with steam at 320 lb. per sq. in. pressure. The engines together weighed 640 lb., and the complete plant, with boiler and furnace, weighed rather less than 1,640 lb. (dry), giving a total weight per horse power of about 4½ lb. Although the aeroplane to which these engines were fitted was wrecked during its initial track trials, owing to the mechanical failure of one of the trolley wheel axles, the efficiency of the power unit was ably demonstrated.

From this date the use of steam was abandoned in favour of the petrol type engine, but it should be mentioned that during the past few years there has been a certain amount of experimental work carried out on entirely new steam propulsion systems, the results of which appear promising ; reference to the advantages and demerits of steam for aerial propulsion are made later in this section.

The Internal Combustion Engine. The first authentic instance of the application of this type of engine appears to be the use of a Lenoir gas engine which was fitted to an airship by Paul Haenlein in Germany in 1872. The engine, of some 6 h.p., propelled the airship at about 10 m.p.h., but owing to the fact that it obtained its gas supply from the balloon itself, the buoyancy of the latter decreased progressively, thus reducing the flight period.

In 1879 a Daimler benzine engine was fitted by Baumgarten and Wolfert at Leipzig, to an airship, but unfortunately the balloon was ignited by an explosion of the benzine vapour, killing both inventors.

Experiments were made during the period 1876–82, by Otto, Daimler and others upon light spirit or petrol-type engines with the object of reducing the weight per horse power and improving the design. Although there is no record of the successful application of these engines to aircraft, it was shown possible to reduce their weight from about 100 lb. per h.p. down to less than 10 lb. per h.p.

In passing, it may be mentioned that during the period in question attempts were made to employ *electric motors* driven off storage batteries to propel dirigibles. The more successful of these was a Gramme electric motor of 9 h.p., deriving its energy from chromium-chloride cells. This was fitted by Renard, of Chalais-Meudon, France, to an airship known as " La France," in 1884. Successful flights were made from Meudon to Paris when various evolutions were executed and the airship returned to its starting-point under its own power.

Compressed air has also been used, as long ago as 1879, for propelling model aircraft.

Reverting to the petrol-type engine, in 1898 the Brazilian, Santos Dumont, fitted a 3-h.p. petrol engine to his earliest dirigible and subsequently built other airships having more powerful engines. One of these had a Buchet engine of 7 h.p. ; later, a 16-h.p. engine was employed. Mention should also be made of the Lebaudy airship constructed in France, in 1902, which had a four-cylinder Daimler automobile engine of 40 h.p., weighing about 12 lb. per h.p.

It was not until about 1903, however, that serious attempts were made to reduce the weight per horse power of petrol engines, when C. M. Manly, who was the assistant of S. P. Langley, evolved a five-cylinder radial water-cooled engine developing 50 h.p. for a weight of 187·5 lb., giving the remarkably low value of 3·6 lb. per h.p. This was the *first successful radial engine*, and it had separate water jackets brazed on to the steel cylinders. Moreover, it was the first example to use a master connecting rod with four link rods. The exhaust valves were operated by push-rods and rocker arms from a cam ring which rotated in the opposite direction to the crankshaft: The ignition system employed sparking plugs, coil and accumulator. Langley's aeroplane, to which this engine was fitted, weighed 730 lb. and had a wing surface of 1,040 sq. ft. Known as the "Aerodrome," this machine was launched, without a pilot, from the top of a boat-house on the Potomac River, U.S.A., but, although the engine was working satisfactorily, the machine was wrecked, owing, it is believed, to a defect in the launching gear.

To the Wright brothers belongs the credit for building the first successful aircraft engine and machine to achieve power-driven flight with a pilot. Following a series of experiments with man-carrying gliders, the results of which were considered to be most satisfactory, it was decided to fit a petrol engine of suitable output to the latest design of glider. This was effected by December, 1903, and the first flight of twelve seconds made on December 17th of the same year. The machine took off, remained under control and landed without damage. The succeeding flights were extended, the fourth one being of nearly a minute's duration and covering a distance of nearly half a mile. From thence onwards the flights increased in period and distance, improved engines being fitted for these achievements.

The original Wright engine was a four-cylinder water-cooled one, developed from the automobile type, having a bore of 4 in. and stroke of 4·25 in. The engine weighed about 240 lb. and developed 15 h.p., corresponding to 16 lb. per h.p.; it ran at 1,300 r.p.m.

The cylinders were machined from separate steel castings and attached to an aluminium crankcase provided with four lugs on one side so that it could be mounted horizontally in the machine. It employed a surface carburettor, and the ignition was by means of low-tension make-and-break igniter plugs in the cylinders.

The cylinders had aluminium water jackets, but the cylinder head was air-cooled. A gear-type of water-circulating pump was used. The inlet valves were suction-operated and spring-returned as on most of the early motor-car and cycle engines of this period. The exhaust valves were operated by means of rocker arms from a chain-driven camshaft. Cast iron pistons and piston rings were fitted, the connecting rods being made from steel tubes. The engine had a light flywheel and chain sprockets from which open and crossed chains drove the right- and left-handed propellers respectively; with this arrangement the turning moments of the latter were balanced, so that there was no lateral tilting effect due to the engine torque on the machine.

An electrical generator, chain driven from the rear end of the engine, provided the ignition current.

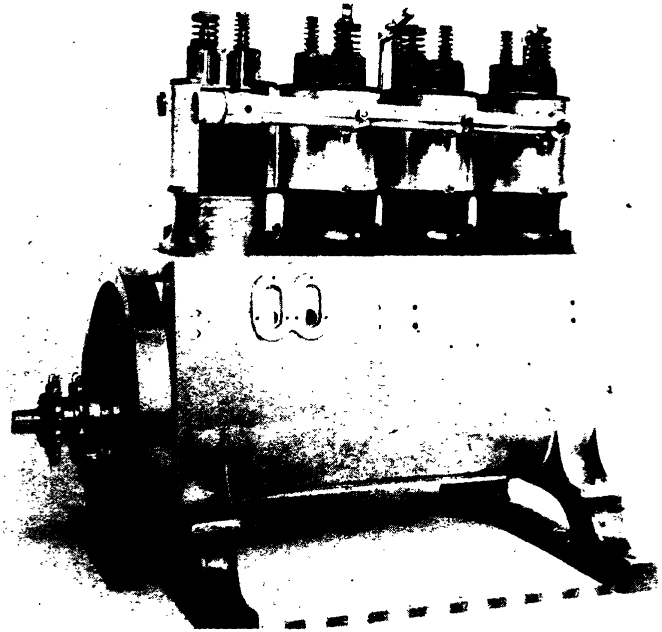

FIG. 1. The Wright Bollée aircraft engine (1909).

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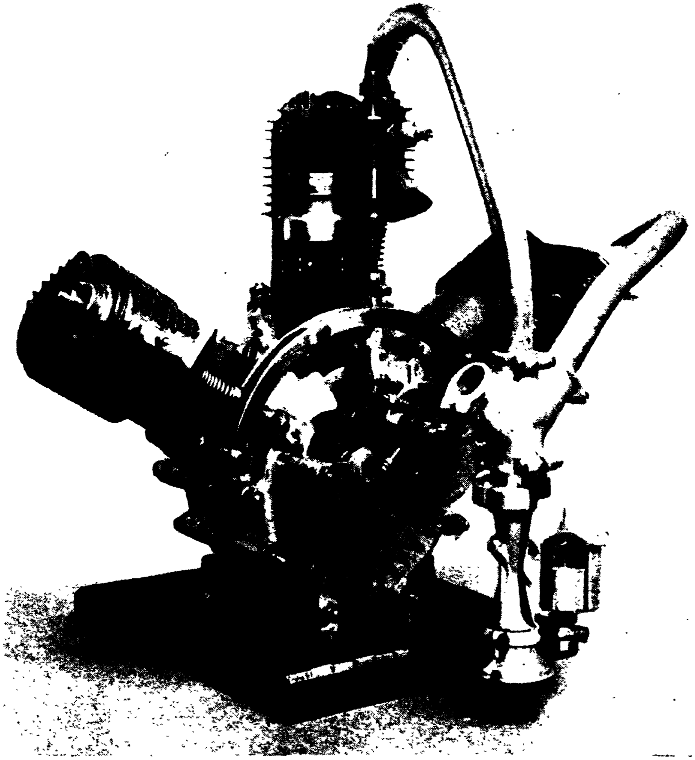

FIG. 2. The 25 h.p. Anzani engine as used by Louis Bleriot on his cross-channel flight, 1909.

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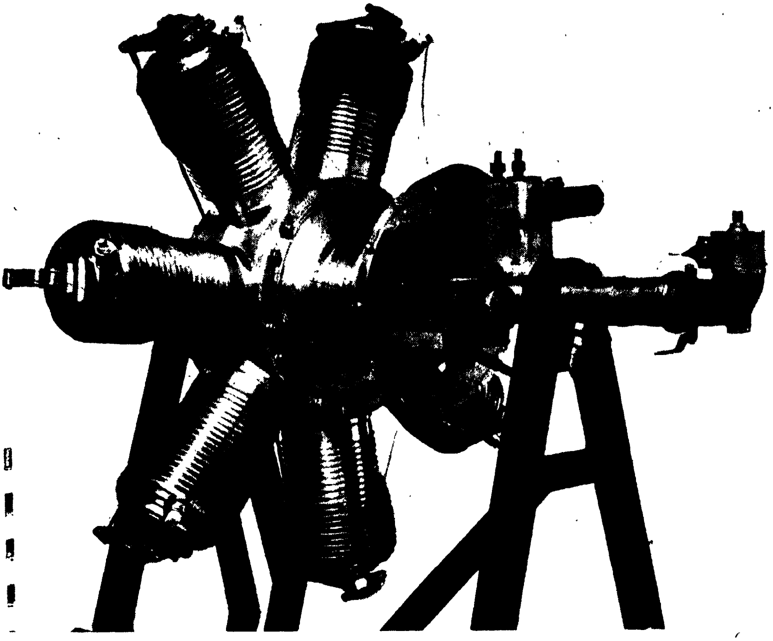

FIG. 3. The 50 h.p. Gnome engine, with fixed crankshaft and rotary cylinder-crankcase unit.

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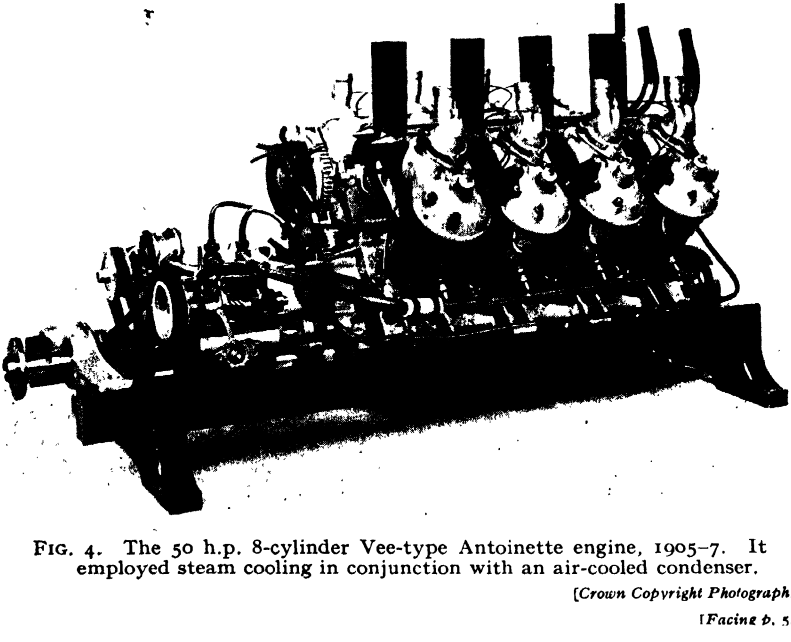

FIG. 4. The 50 h.p. 8-cylinder Vee-type Antoinette engine, 1905–7. It employed steam cooling in conjunction with an air-cooled condenser.

[*Crown Copyright Photograph.*

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Since the original Wright engine a large number of other types of progressively increasing outputs has been produced, culminating to-day in single-engine units of over 2,000 h.p., weighing in some instances less than 1 lb. per h.p., capable of operating satisfactorily at altitudes up to 40,000 ft. and with remarkably low fuel consumptions per h.p. hour.

Among the engine types used on aeroplanes prior to 1912 were the low-powered Anzani air-cooled vee-twin, 3-cylinder arrow and static radial engines, the Simms and Antoinette water-cooled 8-cylinder vee-types, the Green 4-cylinder water-cooled vertical, certain J.A.P. motor-cycle type vee-twin air-cooled engines, the Gnome air-cooled rotary engines with fixed crankshafts and rotating cylinders weighing about 3 to 4 lb. per h.p. The Renault and R.A.F. 8-cylinder air-cooled vee-type engines, the 12-cylinder vee-type and the 6-cylinder vertical water-cooled engines (favoured by German engineers) and the larger single and double-row Gnome, Le Rhone, B.R.1 and B.R.2 rotary engines were the successors to these earlier engines during the period of the war of 1914–8.

Mention should also be made of certain engines of outstanding merit used during the latter part of the war period in question. These included the 160-h.p. Siddeley-Deasy and Beardmore 6-cylinder " in line " vertical water-cooled engines ; the 8-cylinder water-cooled vee-type Wolseley-Viper and Hispano-Suiza engines; the Rolls Royce 250-h.p. Falcon and 360-h.p. Eagle and the 400-h.p American Liberty 12-cylinder water-cooled vee-types.

Subsequent to 1918 the rotary type of engine was abandoned in favour of the air-cooled opposed-cylinder, the vertical "in-line" and static radial types. Similarly, the 12-cylinder water-cooled vee-type engines were developed in this country and abroad. Another successful post-war engine was the 12-cylinder Napier Lion of 450 h.p. with three banks of 4 cylinders each arranged arrow-wise.

More recently, apart from the smaller engines used for light civil aircraft and those for training purposes, the general tendency has been in the direction of developing the high-powered air-cooled radial engine of 14 and 18 cylinders and the liquid-cooled engine with 12 or 24 cylinders, having outputs ranging from about 1,200 h.p. to 2,400 h.p.

Special Requirements of Aircraft Engines. Of the many forms of the petrol-type engine manufactured for various purposes the aircraft one has to satisfy the most exacting requirements ; in these respects it is appreciably ahead of its nearest confrère, namely, the automobile engine. The principal requirements the modern aircraft engine must possess are, briefly, as follows, namely :—

(1) *Maximum power for minimum weight, i.e.*, minimum weight per given horse power. In this connection the development of the aircraft engine has been largely that of a progressive reduction in weight per horse power. Thus, in 1915 the weights of the more efficient British aircraft engines ranged from about 3·0 to 4·75 lb. per h.p., whereas in 1933 these weights had been reduced to 1·25 to 2·25lb. per h.p. ; again, in 1939–40, there was a further reduction to 1·0 to 2·0 lb. per h.p. More recently, values under 1 lb. per h.p. have been attained in certain instances, namely, the largest air-cooled engines.

This achievement in weight reduction is the more remarkable, since the modern engine has several accessories included in its weight that the earlier ones did not possess ; moreover, they are better made and give very much longer periods of service between " top," or light, overhauls and also between thorough, or major, overhauls.

In connection with the term " engine weight " used in the comparison of different types of aircraft engine, this is here taken to mean the *dry weight*, that is, the total weight of the engine with its cooling system—whether air-cooling cowls and ducts in the case of air-cooled engines or radiators and piping for liquid-cooled ones—together with the engine accessories necessary for the proper operation of the engine, such as the carburettor and ignition system, airscrew hub, engine starter, exhaust manifolds, etc.

For accurate comparisons of air- and water-cooled engines it is necessary to include, in the latter case, the weight of the cooling liquid and the circulating pump ; in neither case is the weight of the oil, fuel or oil and fuel tanks included. The total weight thus defined is known as the *weight in running order*, and it is of course greater than the *dry weight* as previously mentioned.

(2) *Minimum Frontal Area.* In the great majority of aircraft the size of the engine has an important influence upon the design of the fuselage, or—in the case of multi-engined machines—upon the dimensions of the power unit casings. The larger the cross-sectional area of an engine for a given horse-power output the greater will be the cross-section of the fuselage or power unit casing, (or " power egg "). A larger cross-sectional area indicates a greater head resistance and therefore a poorer performance for the machine as a whole. It has always been the object of the engine designer to keep the cross-sectional dimensions to a minimum by suitably choosing and arranging the engine cylinders in order to secure the smallest frontal area per horse power.

One method of attaining this end is to place the cylinders in banks, so that the resistance of each bank of cylinders will be little more than that of a single cylinder (Fig. 5). Thus, in the instance of a 12-cylinder vee or opposed engine the frontal area will be little greater than that of a 2-cylinder vee or opposed engine. It has been suggested that the future type of large aircraft will have its engines totally enclosed within the wings or fuselage, so that the head resistance effects of present exposed engine units will be eliminated. In such a case it will evidently still be advantageous to design the engines with minimum frontal areas per horse power.

For military aircraft, *e.g.*, fighters, whilst the greatest cross-sectional area of the fuselage is necessarily appreciably greater than that of the engine, owing to the housing of the pilot, instruments, retractable undercarriage, windscreen or hood, etc., it is a definite advantage to fit an engine of minimum frontal area per horse power, for the fuselage head resistance can be reduced and the pilot's range of forward and downward vision improved.

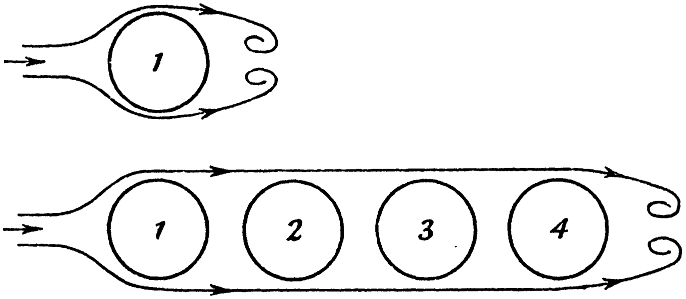

FIG. 5. Illustrating the relatively low head resistance of an " In Line " engine.

It is more convenient in making engine comparisons to refer to the *horse power per sq. ft. of frontal area* when the engine is exerting its full output ; evidently the greater this value the lower will be the head resistance of the engine housing.

In this connection it is of interest to note that a particular 2-cylinder opposed engine as used for light aircraft developed 80 h.p. for a frontal area of 4·0 sq. ft., *i.e.*, it gave 20 h.p. per sq. ft. A 12-cylinder opposed liquid-cooled engine, with cylinders of the same bore and stroke developed 1,000 h.p. for a frontal area of 4·5 sq. ft., giving the greatly improved value of 222 h.p. per sq. ft. ; this is about eleven times the output per sq. ft. of the smaller engine.

Similarly a 9-cylinder air-cooled radial engine gave 1,000 h.p. for an overall diameter of 55·3 in., which works out at 60 h.p. per sq. ft. of frontal area.

Again a 14-cylinder two-bank air-cooled radial engine of a well-known make has an output of 1,375 h.p. and an overall diameter of 52·0 in.; this corresponds to about 93 h.p. per sq. ft. of frontal area. The marked advantage of the 12-cylinder liquid-cooled over the 9-cylinder and 14-cylinder air-cooled radial types will be evident from the figures given.

Fig. 6 shows the front profiles of the Rolls Royce Kestrel and Merlin engines, of about 900 and 1,400 h.p. respectively, whilst the profile of a 9-cylinder air-cooled radial engine of about 1,000 h.p., to the same scale is shown by the dotted outline; the differences in frontal areas are most marked. It is, however, important to remember that for a strictly accurate comparison of the two types the exposed area of the liquid-cooled engine's radiator—and its aerodynamic resistance—should be taken into account. The differences between the two are then reduced, although with modern liquid cooling systems the liquid-cooled engine is still superior to the well-cowled air-cooled radial type.

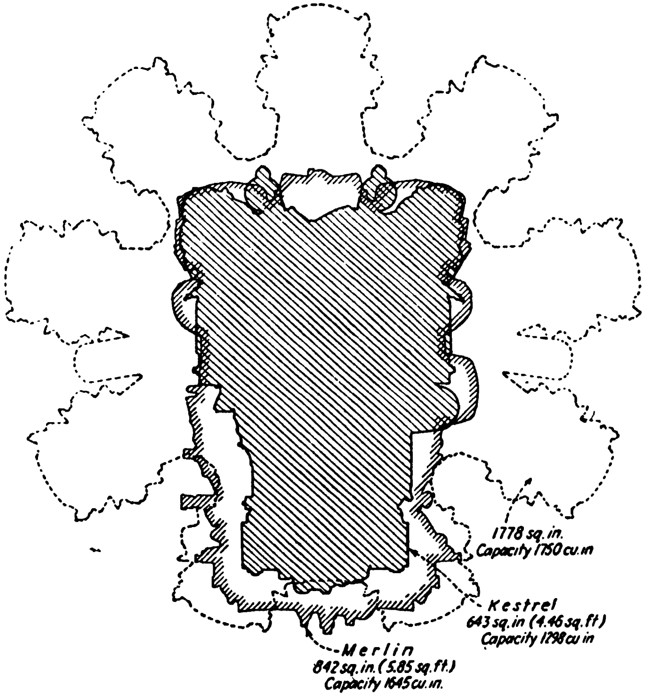

FIG. 6. Frontal areas of liquid-cooled and air-cooled engines of approximately equal power outputs.

(3) *Minimum Fuel Consumption.* In order to cover the greatest flight distances or to carry the maximum useful load it is necessary for an engine to operate under normal flying conditions with the minimum fuel consumption per horse power developed. This condition necessitates very careful attention on the parts of the engine and carburettor (or fuel-injection pump) designers, for the problem of effecting this economy under all conditions of flight, *e.g.*, starting, climbing, high altitudes involving widely varying air temperature and pressure conditions and at different flight speeds, is far more complex than in the case of automobile engines.

In order to obtain minimum fuel consumption the following conditions should be fulfilled, namely :—

(1) The mixture of fuel and air normally used should be about 10 per cent. weaker than that giving complete combustion of the fuel.

(2) Fuels of high octane value * should be employed.

(3) The highest compression ratios that can be used without detonation in the cylinders, for the fuel in question, should be adopted.

(4) The combustion chamber should be of suitable design to avoid detonation or excessive heat losses.

(5) The mechanical components of the engine should work with the minimum loss of power due to friction or vibration.

(6) The most suitable valve timing must be adopted for the particular engine, *i.e.*, the inlet and exhaust valves must open and close at the correct moments and remain open for the maximum practicable periods.

The importance of employing the highest compression ratio within practical limits for the fuel used is shown by the results of tests made upon a single-cylinder engine unit, which with a compression ratio of 4·0 to 1 gave a fuel consumption of 0·55 lb. of petrol per brake horse power (b.h.p.) per hour of running. As the compression ratio was increased, progressively, to the limit of 7·0 to 1, so the fuel consumption was reduced until at the highest compression ratio mentioned it was only 0·420 lb. per b.h.p. hour. The fuel consumptions of modern aircraft engines lie between the values of 0·37 and 0·55 lb. per b.h.p. hour.

(4) *Reliability.* It is of much greater importance for an aircraft engine to be free from breakdown under flying conditions than in the case of land engines, since in the former instance engine stoppage necessitates descent to earth or, if over the sea, to the latter element.

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* *Vide* p. 44.

A considerable amount of experimental work and numerous endurance tests have been carried out during the past 20 to 30 years with the object of improving the performance and obviating the possibilities of engine breakdown. The various causes of earlier engine troubles included ignition and carburation failures, broken exhaust valves, fractured crankshafts, valve spring breakages, piston and piston ring failures, bearing and piston seizures due to lubrication trouble, fractured fuel and oil pipes and breakdown of certain accessories or engine fittings. By a process of careful investigation the causes have been ascertained and the troubles have been eliminated by the re-design of faulty parts and the use of higher quality materials. To quote but one of many possible examples, namely, that of the exhaust valve which is called upon to operate at temperatures of 700° to 800° C. in the presence of hot corrosive gases, the earlier designs of valves made from carbon and certain alloy steels would not stand up to these conditions for long periods under the high temperature and impact conditions that existed. As the cylinder pressures and engine speeds increased the problem became even more difficult, but was eventually solved by the employment of hollow stem and head exhaust valves partly filled with a cooling salt, such as sodium, the valve material being a special alloy steel capable of withstanding both the high temperature and corrosion conditions almost indefinitely. The impact surfaces, namely the valve seating face and valve stem end were coated with an extremely hard material in order to withstand impact conditions without exhibiting signs of wear.

Sparking plugs were another frequent source of trouble, but to-day, owing to improvements in the design and materials used, they have become almost as reliable as any other engine component.

Design improvements such as improved cylinder finning (in the case of air-cooled engines), better disposition of the valves, improved bearing surface finishes and bearing alloys, the use of alloy steels of greater impact and fatigue-resisting properties for crankshafts, camshafts and gears, much improved lubrication systems, etc., have also been contributory factors to greater reliability.

As a further safeguard to engine reliability new designs must pass a 100 hours' duration test at 90 per cent. of their full power output and must conform to certain minimum fuel and oil consumption requirements.

(5) *Maintenance.* At regular intervals during the working life of an aircraft engine it is necessary to attend to certain items for cleaning and adjustment; at longer intervals the engine will need a

top overhaul, whilst at still longer ones it will require a thorough overhaul. After each long flight the engine is given a superficial inspection for any possible external signs of faults. The sparking plugs are removed, cleaned and, if necessary, their electrodes or " points " adjusted to the correct gap. The oil and petrol filters are also removed and cleaned ; external control mechanism bearings lubricated ; contact breaker gaps checked and other minor points of attention checked, etc.*

It is therefore important, from the viewpoint of carrying out these maintenance operations as quickly as possible, that engines should be designed for maximum accessibility, when installed in aircraft ; moreover, as far as possible the use of special tools, such as spanners and unlocking devices, should be avoided in favour of the ordinary tools to be found in the mechanic's tool kit.

The standardisation and interchangeability of engine components is another important item, since it then becomes a relatively simple matter to replace a defective or damaged part by a spare part with the assurance that it will fit properly and give the service of a similar part in a new engine.

(6) *Miscellaneous Desirable Features.* Whilst it is not possible to deal with each and every desirable feature in the present instance, some of the less important items may be enumerated. These include the following :—

(1) Ease of mounting in the aircraft, by the provision of satisfactory brackets or lugs in accessible positions, for rigid or flexible mounting of the engine, as the case may be.

(2) Freedom from torsional vibration effects. This requirement necessitates special attention to engine balance and crankshaft design.

(3) Convenient and quiet exhaust dispersal means. Exhaust manifolds should be of suitable dimensions, adequately cooled by the relative airstream or airscrew slipstream and of minimum head resistance.

(4) Correct inlet manifold design to give good distribution of the mixture to the various cylinders and without restricting the supply of mixture.

(5) Ready and easy methods of starting the engine by automatic means.

(6) Inclusion in or on the engine unit of all engine-driven accessories instead of using external drives. Thus, the airscrew reduction gears would be an integral part of the engine, whilst such items as

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* See also p. 210.

the electric generator, air compressor, fuel and oil pumps, hydraulic pumps, etc., would be housed on or in the engine unit and driven by suitable gearing and shafts from the crankshaft.

Alternative Types of Engines. Whilst the petrol-type of engine has practically monopolised the aircraft field it should not be overlooked that there are some possible alternative kinds of engines which may eventually compete with or supersede the present designs. These include (1) The high-speed compression-ignition engine which is usually referred to as the high-speed Diesel engine. (2) The steam engine. (3) The internal combustion turbine. (4) Swash-plate or rotary engines. There are also the possible jet- and rocket-propulsion systems, which may be included in combustion propulsion systems. Some of these alternatives are dealt with more fully in Chapter II.

(1) *The Compression Ignition Engine.* At present this is the closest rival to the petrol engine. Its chief merits include appreciably lower fuel consumption per h.p. hour—in some instances as much as 25 to 30 per cent. less; use of less expensive fuels such as Diesel oils in place of high octane petrols; higher standard of reliability due to absence of carburettor and electric ignition system; freedom from fire risks due to use of fuels of much higher flash points; reduced cooling areas are needed; easier cold starting; quicker pick-up in power from the cold; more uniform distribution of fuel to the cylinders and less maintenance attention.

Against these considerable advantages must be offset the fact of these engines, in their present lightest forms, being appreciably heavier than petrol engines of the same outputs.

For long-range aircraft these engines enable a marked saving in fuel cost to be effected, although for shorter flights, up to 8 to 10 hours, the petrol engine installation is usually the lighter.

(2) *The Steam Engine.* It is somewhat surprising that, although most of the early developments in aircraft engines were centred around steam engines, the petrol engine should subsequently have ousted it. The principal reasons for this are that the latter type of engine can be made much more compact, since instead of combustion of the fuel taking place around or within a water-type boiler, it actually occurs within the cylinder head of the petrol engine; moreover, the fuel is utilised much more efficiently in the latter instance. Thus the petrol engine replaces the steam boiler, furnace and steam engine and extracts a greater amount of useful power at the airscrew shaft than is possible in normal steam plant.

There have, however, been many recent improvements to steam installations which have resulted in a marked improvement in their efficiency and reduction in both weight and space. By the use of steam at very high pressures and temperatures (or superheats) it has been found possible to extract an appreciably greater proportion of the fuel's heat in the form of useful power, so that results comparable with that of the petrol engine are possible. There have also been considerable advances in steam production methods and plant resulting in light compact automatic boiler units and much smaller steam engines than hitherto. The boiler units, being separate from the steam engine can be housed in any convenient part of the aircraft so that the dimensions of the fuselage are not increased. The use of steam turbines in aircraft would give smoother drives to the airscrews, good streamlining and absence of engine noise. Another inherent advantage of the steam engine is that, unlike the petrol engine, its power does not fall off, as the altitude increases, to anything like the same extent as in the latter engine. It is necessary to use a greater degree of compression for the air used to burn the crude liquid oil used for the fuel in order to counteract the decrease of air density at higher altitudes. If the same steam pressure can be maintained to the engine there will actually be an increase in the output, since the steam will be exhausted at a lower pressure to the atmosphere. There is no difficulty in making a rapid start with the later steam plants, since it takes only about one minute to attain the required steam pressure. Already flights have been made in the United States with the Besler engine of 250 h.p., using two cylinders and employing a light-weight boiler ; the complete steam power unit weighs about 660 lb., *i.e.*, 2·64 lb. per h.p. In Germany flights have taken place with the Huettner rotary boiler steam unit, and it is claimed that no difficulties have occurred in connection with the condensation of the steam into water and its utilisation again.

It has been advocated, as a result of these trials, that a central steam generating plant might be installed in a large aircraft, supplying high-pressure steam to a number of steam turbines distributed along the wing and driving individual airscrews. The fundamental difficulty to be overcome in such an installation would be that of the steam condenser which would have to deal with about four times as much heat as in the case of a petrol engine of equal power ; this difficulty is not, however, insoluble.

(3) *The Internal Combustion Gas Turbine.* Since about 1790 inventors have sought, with varying degrees of success, to produce a turbine that could be operated by high-pressure gases instead of

steam. During the past 30 years several promising designs of gas turbine have been invented, and some of these have attained the commercial stage. An earlier example is the Holzwarth turbine made by Messrs. Körting, of Hanover, in 1906–8. Several later designs of this turbine were produced by Messrs. Brown, Boveri and Messrs. Thyssen between 1909 and 1930 for stationary purposes.

The gas turbine, although as yet in the experimental stage, offers distinct advantages in the matter of its compact and convenient form, continuous and vibrationless operation and comparative simplicity over the reciprocating petrol-type engine. It has been shown possible to attain high efficiencies comparable with those of the petrol engine, if suitable materials can be found to withstand the very high temperatures of operation.

The Rateau turbine, driven by the exhaust gases of high-powered petrol engines, has frequently been used for the purpose of driving centrifugal air compressors employed for supercharging aircraft engines; further, an efficient design of gas turbine is actually used for operating a compressor that is employed to supply high velocity air to the boiler of the Velox steam generator.

(4) *Swash Plate or Rotary Engines.* These engines, whilst employing cylinders, pistons and rods after the manner of the ordinary petrol engine, arrange the cylinders around the driving shaft, with their axes parallel to that of the driving shaft. Instead of the conventional connecting rod and crankshaft for converting the reciprocating motion of the piston to rotary motion an inclined disc or " swash plate " is used. Automobile and one or two aircraft engines (of which the 150 h.p. Herrmann is a more recent example) have been built on this principle. Such engines are very compact in form and give high outputs per square foot of frontal area. They have not, hitherto, proved so efficient as the petrol type, and there is, as yet, insufficient experimental evidence to show that they are capable of running for long periods without exhibiting signs of wear in the swash plate mechanism.

(5) *Jet Propulsion Systems.* In the search for light but powerful means of propulsion for high-speed aircraft a certain amount of attention has been given chiefly in Germany and Italy to the possibility of using the rocket principle, whereby the products of combustion of a mixture of fuel and air, suitably compressed, are ignited so as to generate pressure by the combustion of the fuel. The high-pressure exhaust gases are then allowed to escape at a high velocity at the rear of the aircraft, their reaction furnishing the forward thrust required for the propulsion of the machine.

Part of the combustion pressure is employed to operate a gas turbine driving the compressor for the air supplied to the combustion chamber, the fuel being injected as fine sprays into the latter.

A certain amount of progress has been made with the Heinkel and Caproni-Campini aircraft propulsion systems based on this principle in recent years. Several difficulties require to be solved, however, before the system can attain practical success. The chief difficulty is that of the, at present, low efficiencies attained. Other ones are concerned with the effective control of the power output to suit the various conditions of aircraft operation. If higher overall efficiencies are to be attained then the high temperatures employed will probably require the use of special metals having much greater heat-resisting properties than those at present available.

CHAPTER II

THE FOUR-CYCLE ENGINE

THE engines that have been considered or actually used for aircraft purposes may be divided into two main groups, namely, (1) *The External Combustion* and (2) *The Internal Combustion* types.

The External Combustion Engine. The external combustion group includes the steam engine, which derives its energy from steam under relatively high pressure, the steam being generated by the hot gases or products of combustion of coal or liquid fuel and air burnt in an external vessel containing water. There are thus two principal units, namely, (1) the boiler and (2) the steam engine.

Certain types of combustion turbines might also be included in this category, namely, those in which a mixture of air and gas or fuel vapour is burnt in one vessel and the products of combustion supplied to a separate engine unit.

As the steam engine has been entirely replaced by the internal combustion type, in present aircraft it is not proposed to devote any further space to the former, although it must not be overlooked that the steam engine is again receiving much attention, experimentally, as mentioned in the previous chapter.

The Internal Combustion Engine. This group includes many well-known prime movers, notably, the gas, oil and petrol engine and certain internal combustion gas turbines. In these engines the combustible fuel is mixed with air in suitable proportions and supplied to the engine, where it is compressed and exploded, or burnt within the engine itself and directly in contact with certain internal parts of the engine.

In order to appreciate the principles of the internal combustion engine it is necessary to understand something about the process of the combustion of fuels with air, in closed vessels ; the following introductory notes on the subject are therefore given.

Combustion is the name given to the chemical combination of elements such as carbon or hydrogen—or compounds of such elements—with oxygen. During this process much heat is developed, and if the combustibles are ignited in a closed vessel the pressure during combustion increases appreciably above the value before ignition.

The fuels used in petrol, gas and oil engines almost invariably consist of chemical compounds of carbon, hydrogen and, sometimes, a certain proportion of oxygen.

It is not proposed in this section to deal with the purely chemical side of the process of combustion.

It is sufficient, here, to state that when a fuel containing hydrogen and carbon is burnt with oxygen, the hot products that result are water (in the form of steam), nitrogen and carbon-dioxide. It is assumed that the proportions of oxygen and fuel are correct for complete burning of the fuel.

If there is an excess of either of these constituents, then there will be somewhat different products of combustion. Thus, if the fuel is in excess of that necessary for complete combustion the products, after ignition, will contain some carbon monoxide in addition to steam, nitrogen and carbon-dioxide. If, on the other hand, there is an excess of oxygen, then there will be a certain amount of unburnt oxygen in addition to the other constituents. These facts are important from the point of view of correct carburation—or mixture adjustment—in petrol engines. The fuels used in petrol engines are *hydrocarbon liquid ones,* that is to say, are combinations of carbon and hydrogen. The *alcohol group* of fuels contain oxygen in addition to carbon and hydrogen. The fuels, known as *anti-knock* or *high octane* ones contain also small additions of special chemicals, known as *fuel dopes,* the object of which is to prevent premature detonation in the engine.

A typical simple petrol contains 6 parts of carbon and 14 parts of hydrogen by volume or, since carbon weighs twelve times as much as hydrogen, 72 parts, by weight, of carbon to 14 parts, by weight, of hydrogen, *i.e.*, 83·6 and 16·4 per cent., respectively.

To burn a given volume, say 1 cu. ft. of petrol vapour will require 9½ cu. ft. of oxygen. If, however, air is used instead of oxygen, then a greater volume of air, namely, 45·5 cu. ft., will be needed, since air consists of 20·9 per cent. oxygen and 79·1 per cent. nitrogen, by volume. Considered by weight, however, it can be shown that 1 part of petrol of the simple composition previously mentioned will require 3·5 parts of oxygen or 15·2 parts of air for its complete combustion.

It may here be mentioned that it is very much more convenient to use air instead of oxygen in petrol engines. Moreover if oxygen alone were used the combustion (or explosion) would be a violent one, whereas when air is used the greater nitrogen content—which is about four times that of the oxygen, by volume—has the effect of rendering the explosion less violent and thus preventing excessive pressures within the engine. The outline of the combustion process that has been given will now enable the reader to understand the methods of operation of petrol engines. A fuller account of the subject of fuels, combustion and carburation is given in Chapter III.

The Four-cycle Engine. This is the most widely used method of converting the combustion energy, or to be more precise, part of this energy, of the fuel-air mixture into mechanical energy; it is employed in the large majority of internal combustion engines used for aircraft and automobiles and is sometimes known as the Otto or constant volume cycle.

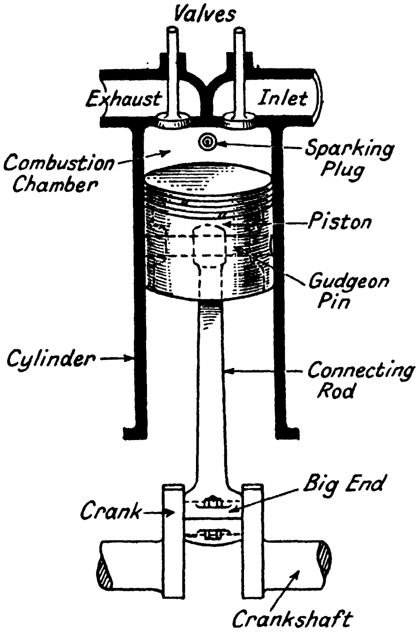


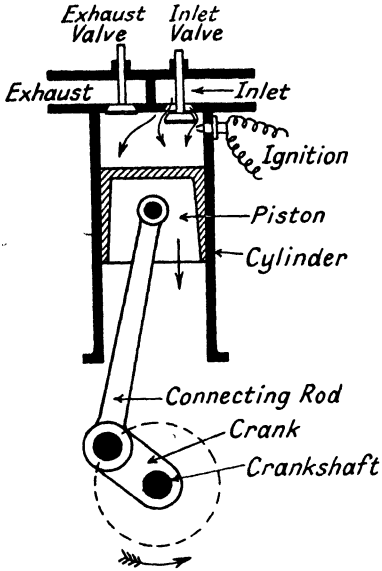
FIG 7. Elements of the petrol engine.

Nearly all reciprocating engines, whether steam or internal combustion, employ the crank and connecting rod principle of converting the reciprocating movement of the piston into one of rotation of the crankshaft; the swash-plate engine is an exception to this rule.

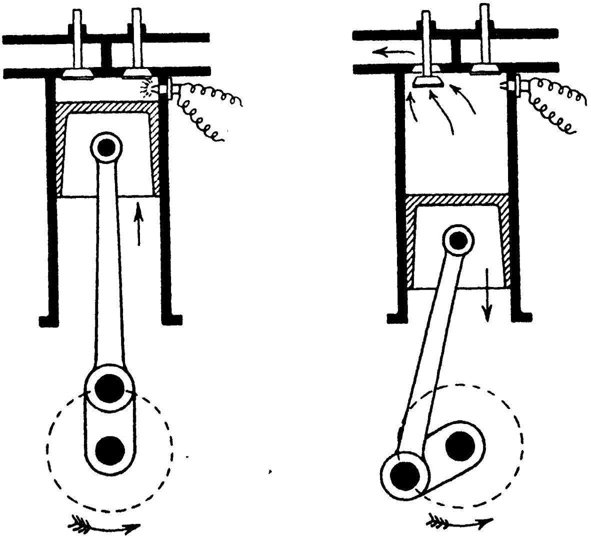
The primary elements of the petrol engine are illustrated, diagrammatically, in Fig. 7. They consist, essentially, of a cylindrical barrel, known as the *cylinder*, in which is fitted the *piston*. The latter is made a gas-tight sliding fit in the well-lubricated cylinder and is hollow and provided inside with a cylindrical pin upon which the upper, or *small end*, bearing of the connecting rod can rock. The latter rod transmits and converts the up and down motions of the piston into one of continuous rotation at the *crankshaft*, by means of the big-end bearing and crank pin shown. It will be evident that the stroke of the piston must be equal to twice the crank-pin radius.

The *inlet valve* shown above ensures the admission of the mixture of fuel vapour and air (supplied by a separate device, known as the *carburettor*) at the correct point in the cycle of operations and also the cutting off of this mixture later, at the correct moments. We are not, however, concerned at this stage with the mechanism that operates this valve.

The *exhaust valve* provides for the escape, at the proper time in



(1) SUCTION (2) COMPRESSION



(3) IGNITION (4) EXHAUST

FIG. 8. The four-cycle engine principle.

the cycle, of the burnt products of combustion or " burnt gases " ; this valve, also, is operated mechanically so as to perform its opening and closing processes at the correct times.

The combustion, or explosion, of the mixture admitted through the inlet valve occurs in the cylinder space between the top of the piston and the cylinder head above. Both valves must, of course, be closed during this process and also the subsequent expansion of the burnt gases. The mixture is ignited at the correct instant by means of a high voltage electric spark which occurs across the electrodes of the sparking plug; the latter is screwed into the head or wall of the combustion chamber.

The cycle of operations is shown, schematically, in Fig. 8.

Referring to Diagram 1, this shows the piston descending and the crankshaft rotating in an anti-clockwise direction. In its descent the piston tends to create a suction effect, and as the inlet valve is opened, mechanically, just as the piston begins to travel downwards and remains open during all of the downward stroke the piston draws in a charge of air and fuel from the carburettor. The inlet valve closes at the bottom of the stroke or, as will be explained more fully later, soon after the start of the next upward stroke. During the remainder of this latter stroke (Diagram 2) the two valves are kept closed so that, since the charge cannot escape it becomes compressed. Just before the piston reaches the top of its stroke (known as *top dead centre*, or T.D.C.) and the charge is at about its full compression (Diagram 3) an electric spark is made to pass between the electrodes, or sparking points of the plug, shown just below the inlet valve, and the charge explodes. The explosion which is in fact a rapid process of combustion, results in a considerable rise in the cylinder pressure and also in the temperature of the burnt gases. This pressure acts upon the piston and drives it downwards, the gases expanding during the downward stroke so that the pressure (and also the temperature of the gases) falls progressively. When the piston is nearing the lower end of its stroke (known as the *bottom dead centre*, or B.D.C.) the exhaust valve—which, together with the inlet valve, has remained closed during both the compression and the expansion stroke—is opened, mechanically (Diagram 4), and the hot gases, still at an appreciable pressure above atmospheric, commence to escape into the exhaust pipe or manifold. During practically the whole of the next upward stroke of the piston the exhaust valve remains open and the inlet valve is kept closed, so that the exhaust gases are swept out through the exhaust valve by the ascending piston. When the latter reaches its top dead centre the cycle of operations is completed and the next and similar cycle commences with the opening of the inlet valve as shown in Diagram 1.

The Four-cycle Process in Detail. Having described the four cycle (or *four stroke*) principle it is now possible to consider it in more detail and to give some information and facts about it.

It will be observed that this cycle of operations occurs during two complete revolutions of the engine, or four successive piston strokes, of which only one stroke is a power stroke ; the other three are idle strokes and absorb some of the power supplied during the expansion stroke. If the engine under consideration were a single-cylinder one it would tend to run rather jerkily at its lower speeds so that it would be necessary to fit a flywheel in order to give more uniform running.

It has been mentioned that the charge which fills the cylinder at the end of the suction (or *induction*) stroke is *compressed*, before it is ignited. The reason for this is that unless this were done very little power could be developed by the ignition of a charge of air and petrol at atmospheric pressure. It is necessary, therefore, to compress the mixture before it is ignited, and in this connection it can be stated that the higher the amount of compression, as expressed in pounds per square inch pressure, the higher will be the explosion pressure and temperature and, within limits, the greater will be the amount of useful energy that is obtained from the combustion of the fuel. It is thus possible to save a good deal of weight and space, by using relatively small cylinders and high compression pressures as compared with, for example, those of a low compression gas or oil engine.

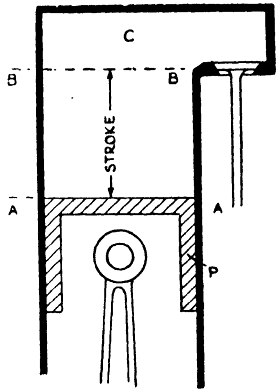


FIG. 9. Illustrating compression ratio calculation.

The compression pressure is governed by the relative volumes of the cylinder space just before compression commences and at the upper end of the compression stroke. This in turn depends upon the relation between the *stroke volume*, *i.e.*, the piston area × its stroke, and the *clearance volume* or volume of the combustion chamber when the piston is on its top dead centre.

Referring to Fig. 9 the stroke volume is the cylindrical space between the upper dotted line position (or T.D.C.) marked BB and the lower position (or B.D.C.) marked AA. It can be estimated from the following relation :—

$$\text{Stroke volume} = \frac{\pi D^2 l}{4} \text{ cubic inches.}$$

Where $\pi = 3{\cdot}1416$; D = cylinder diameter in inches and l = stroke in inches.

This expression can more conveniently be expressed as follows:—

$$\text{Stroke volume} = 0{\cdot}7854D^2l \text{ cubic inches.}$$

It should be noted that if D and l are expressed in centimetres then the result will be in cubic centimetres (or c.c.'s.).

When the piston is on its T.D.C. (Fig. 9) if the volume of the combustion chamber C or the *clearance volume* is denoted by V cu. in. then the following relation holds:—

$$\text{Compression ratio} = \frac{\text{Stroke Vol.} + \text{Clearance Vol.}}{\text{Clearance Vol.}}$$

$$= \frac{0{\cdot}7854D^2l + V}{V}.$$

Example. An aircraft engine cylinder has a bore of 4 in. and stroke of 5 in. If the clearance volume is 11·4 cu. in., find the compression ratio.

$$\text{Compression ratio} = \frac{0{\cdot}7854 \times 4^2 \times 5 + 11{\cdot}4}{11{\cdot}4}$$

$$= \frac{62{\cdot}832 + 11{\cdot}4}{11{\cdot}4} = 6{\cdot}5.$$

The compression ratios of modern aircraft petrol engines range from about 6·0 to 1 to 7·5 to 1 and the compression pressures from about 145 to 200 lb. per sq. in. It is possible to employ higher ratios than the ones mentioned if special fuels, namely, those having strong anti-knock properties are used.

Owing to the rapidity of the combustion process and to other reasons the petrol engine impulses can occur with exceeding rapidity so that considerably *higher engine speeds* are possible than with the slower impulse steam engines. As the power output of any engine is proportional to the average impulse, or mean load on the piston, multiplied by the frequency of occurrence of such impulses, it follows that by using a high engine speed for a given power output the actual impulses can be kept down to a minimum and therefore the dimensions of the cylinders can also be made relatively small.

It is for this reason that modern aircraft engines run at relatively high maximum speeds, namely, from 2,400 to 4,000 r.p.m. and can thus be made lighter on account of the smaller cylinder dimensions that can be used for a given power output.

Much higher engine speeds are, however, possible, and in the case of certain experimental petrol type engines operating with special fuels and at compression ratios up to about 11 to 1, using relatively small cylinders, maximum speeds of 8,000 to 12,000 r.p.m. have been attained. The general adoption of such speeds, however, would necessitate very careful attention to engine design, balance, lubrication and cooling; further, if used for aircraft purposes *reduction gears* of relatively high ratio would be necessary since modern *airscrews operate* at *their best efficiency* at speeds of 1,000 to 2,000 r.p.m.

In regard to the *valves*, these are only required to open and close once per cycle, *i.e.*, once every two engine revolutions, so that the operating mechanism is arranged to be driven at one-half engine speed. Similarly, since one ignition spark only is needed per two engine revolutions, *the ignition apparatus* for a single cylinder engine is also driven at one-half engine speed.

It may be mentioned that as the valves, for practical reasons, must be made of much smaller diameter than the piston, the velocity of the inlet charge and of the exhaust gases is considerably greater than the average piston velocity. Usually the diameter of the valves is about one-third to two-fifths of the piston diameter, so that the gas velocities are of the order of 3 to 2½ times the mean piston speeds.

In practice the velocity of the mixture past the inlet valve is from 150 to 240 feet per sec., *i.e.*, about 102 to 164 miles per hour.

Cylinder Pressures and Temperatures. During the cycle of operations that has been described the cylinder pressures undergo a series of variations or fluctuations each cycle, ranging from a slightly negative pressure during the suction stroke to considerable values immediately after ignition, namely, from about 500 to 700 lb. per sq. in. in modern engines.

The manner in which these pressures vary can best be studied by means of a graph or diagram showing, on a piston-stroke base, the values of the cylinder pressures as represented by the heights of perpendicular lines or ordinates for each position of the piston. As there are four overlapping piston strokes there will accordingly be four pressure curves which, however, are actually joined at their ends and so are continuous. Such a diagram of pressures during a complete cycle is known as an

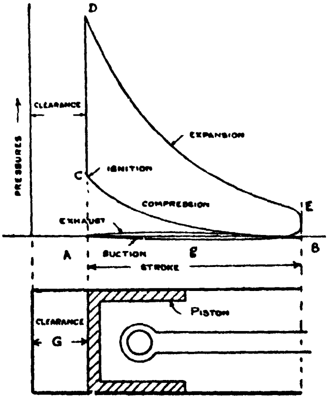


Fig. 10. Pressures in four-cycle engine operation.

indicator diagram, and from its area can be estimated the power developed within the cylinder.

Referring to Fig. 10 this shows, schematically, a horizontal cylinder fitted with a piston, and above is a corresponding diagram of cylinder pressures for each position of the piston during its stroke —or, more exactly, during its four successive strokes. The base of the pressure diagram AB corresponds to the piston stroke. During the suction stroke, from A to B, the pressure line is that denoted by AgB, and this indicates by its lower position than the atmospheric pressure straight line AB that the cylinder pressure is slightly below atmospheric ; in practice this is usually only a matter of 1 to 2 lb. per sq. in. below atmospheric pressure (14·7 lb. per sq. in.). During the succeeding compression stroke from B to A, the pressure rises continuously, along the line BC, reaching its maximum value at C.

For a compression ratio of 6·0 to 1 the value of the compression pressure at C will be about 145 lb. per sq. in. At C the compressed mixture is ignited and the pressure rises with much rapidity along the line CB to its maximum value at D.

The *maximum combustion* (*or explosion*) pressure, corresponding to the height of the ordinate D is usually from 3½ to 4 times the compression pressure, so that for a compression ratio of 6·0 to 1 it will be from about 500 to 580 lb. per sq. in.

From D the burnt gases expand as the piston moves from A towards B. The curve DE indicates that the pressure falls as the expansion proceeds ; for approximate purposes it may be assumed that the volume of the gases at each point of the expansion stroke is inversely proportional to the pressure ; thus if the volume is doubled the pressure will be halved, and so on. Just before the piston reaches the end B of its stroke the exhaust valve opens and the pressure within the cylinder—which is usually at about 40 to 50 lb. per sq. in—falls rapidly nearly to atmospheric value. During the following exhaust stroke from B to A the pressure is still slightly higher by 1 to 4 lb. per sq. in. than atmospheric pressure.

The temperature of the fresh charge is about the same as that of the outside air, although it becomes heated in its passage into the cylinder. During the compression stroke the temperature increases until at the end of this stroke it reaches a value of approximately 445° C. for a compression ratio of 6 to 1 and 475° C. for one of 7 to 1.

When ignition occurs the temperature increases very rapidly with the pressure and attains a maximum value of 1,500° C. to 2,000° C. according to the engine design, compression ratio, mixture strength, ignition setting and other controlling factors.

During the expansion stroke the temperature falls with the increasing volume of the burnt gases and heat extraction by the relatively cool walls of the cylinder until, when the exhaust valve opens, the temperature is usually between 600° C. and 750° C.

The crown or top of the piston is always very hot, relatively, to the other engine parts, its value for aluminium alloy pistons ranging from about 250° C. to 270° C. at the centre and diminishing towards the edges.

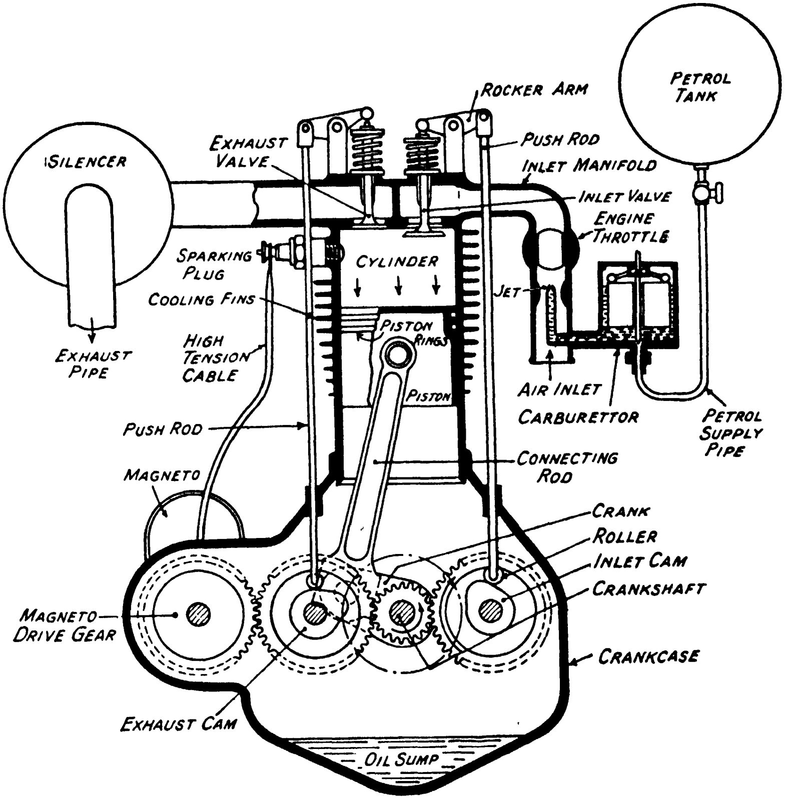


FIG. 11. The complete single cylinder four-cycle petrol engine.

The Complete Engine Unit. Following the preceding outline of the operation of, and properties associated with, the four-cycle engine it is appropriate at this stage to describe the complete single-cylinder engine and its parts, taking as an example an overhead valve air-cooled engine with the various components annotated, as shown in Fig. 11. It should be pointed out that the engine is shown diagrammatically for the purposes of explanation, and does not represent any particular modern design. Further, it is not proposed here to describe the engine components in detail, but to devote a later chapter to this subject.

Referring to Fig. 11, the hollow piston with its gas-tight spring rings and the rocking connecting rod are shown; the lower, or big-end bearing of the connecting rod is arranged to work on the crank pin, as mentioned previously. The crankshaft, to which this crank is securely fixed, is provided with a small gear wheel that meshes with two other gear wheels having twice the number of teeth, so that each rotates at one-half of the crankshaft speed.

Each of these larger gears has a *cam* secured to it for operating the valves. The cam may here conveniently be regarded as a narrow cylinder having a projection at one part of its periphery. The rotation of this cam about its central axis causes the projection to rotate also and in so doing to engage with a roller on the end of the vertical push rod so as to lift it once every revolution of the gear wheel. The push rod operates one end of a hinged lever known as the *rocker arm*, lifting up this end so as to depress the other end, which in turn depresses or opens the valve. When the cam rotates free of the roller, so that the latter rests on the cylindrical part of the cam, the valve is then kept closed by the action of the strong spring shown; this spring also returns the valve on to its seating when the cam has passed its position of greatest life and its lifting action diminishes.

In practice it is usual for reasons of weight and space saving to arrange for both valve cams to be made on the same shaft, which is then known as a *camshaft*. Only one gear train and set of camshaft bearings is then necessary and both push rods can be arranged to operate side by side in a single or double tubular casing. It should be noted that the two cams are set at different angles on their shafts so as to open the valves at the correct times.

The *magneto* or high tension-spark producing apparatus may be regarded as a kind of dynamo with a high voltage coil arrangement for producing the spark at the right moment. The shaft of this magneto, in the case of a single cylinder four-cycle engine is driven at one-half engine speed, so that it can conveniently be driven by means of a gear wheel of equal number of teeth from one of the cam wheels; in practice it would usually be driven from one end of the single camshaft of a bank of cylinders.

The mixture of air and petrol is provided by the carburettor shown in Fig. 11. This is a device consisting, in principle, of a fine orifice jet through which petrol is drawn in the form of a spray by the suction effect of the air flowing through a restricted part of the air inlet tube around the jet. The exhaust gases flow out into an exhaust collector or manifold bolted to the cylinder; from thence they flow through a silencing device and from the latter into the atmosphere.

The Two-cycle Engine. The petrol engine can also operate upon another cycle during which the processes of induction, compression, ignition, expansion and exhaust are completed in two successive piston strokes or one revolution.

This cycle, invented by Dugald Clerk in 1880, in its simplest form utilises the suction and compression effects *beneath the piston* to draw the petrol-air charge into the crank chamber (made airtight for this purpose) and to compress it to a small degree before it is transferred to the main cylinder.

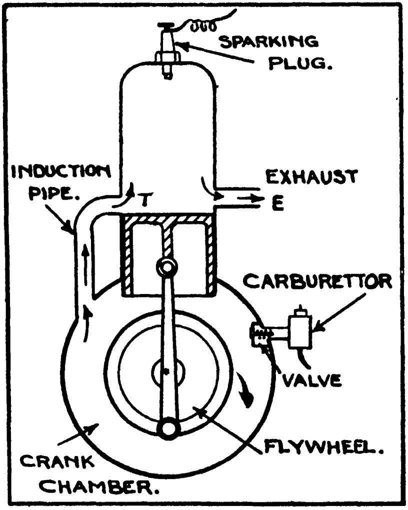


FIG. 12. The two-port two-cycle engine.

The principle of the simple *two-port engine*, as it is termed, is illustrated in Fig. 12, in which the piston is shown at the bottom of its stroke, the crankshaft rotating in a clockwise direction. The previous downward stroke was the expansion one, and just before the piston reached its bottom dead centre its upper surface had uncovered a port or opening E leading to the exhaust pipe so that the burnt gases escaped through this port. Slightly lower, and on the other side of the cylinder, is another port T leading by means of the induction (or transfer) pipe shown to the crank chamber in which a compressed charge of mixture has just been released, by the uncovering of this port by the upper edge of the piston. The mixture thus flows into the cylinder under this compression effect, and in doing so tends to force the remaining burnt gases out through the exhaust port on the other side.

As the piston ascends it first shuts off the transfer and next the exhaust port, and then proceeds to compress the charge that has passed into the cylinder through the transfer port, until when the piston is nearly on its top dead centre the spark occurs and ignites the compressed charge. During the following downward stroke the burnt gases expand in a similar manner to that of the four-cycle engine and as the piston nears the bottom of its stroke it uncovers the exhaust port, thus completing the cycle of operations in two consecutive piston strokes.

In regard to the induction, or drawing into the crank chamber, of the fresh charge this occurs when the piston moves upwards on its compression stroke, the lower side of the piston creating a suction effect in the crank chamber and drawing mixture into the latter from the carburettor mounted on the side, through a lightly loaded non-return valve; the latter opens into the crank chamber but closes when the piston descends.

The Two-cycle Engine in Practice. The simple two-port engine described is the least efficient of the many alternative two-cycle engines, although it is a convenient example to consider for explanation purposes.

The method of utilising the crank chamber for compressing the charge before admission into the engine cylinder is not entirely satisfactory or efficient, although convenient for light and inexpensive engines for purposes such as small motor-cycles, lawn mowers and small dynamo charging plant.

It is wasteful in fuel, since during the period the transfer and exhaust ports are open together part of the charge from the crank chamber sweeps out into the exhaust port and is lost. The results of some accurate tests that have been made on this type of engine have shown that as much as 25 per cent. of the charge can be lost in this manner, although with improved designs using deflector pistons and better port timings this loss can be reduced to 10 to 15 per cent. for three-port engines.

The reader may have observed that there are twice as many expansion or working strokes for the two-cycle as for the four-cycle engine, so that he may have concluded that for the same cylinder bore and stroke the two-cycle engine would give twice the power. If this were the case aircraft engines could be made at one-half their present weights per horse-power; unfortunately it is not the case, for there are several other reasons why the two-cycle engine has not yet been developed to a satisfactory stage for aircraft purposes.

In the first place it is not possible by simple methods to fill the cylinder with the same quantity of charge as for a four-cycle one of similar dimensions and therefore a smaller amount of power is developed. If, on the other hand, the cylinder is properly filled by using a charge compressor, there a certain proportion of the additional power obtained is used up in driving the compressor; the results are, however, definitely better than for the simple two and three port engines.

The loss of a small part of the fresh charge through the exhaust port is difficult to avoid unless the design is complicated by fitting special valves for this purpose of cutting off the exhaust port when the charge port is opened.

Another difficulty is that of cooling the cylinder and piston effectively, since considerably more heat is developed in the same time as for the four-cycle engine and the surplus heat must be got rid of through the cylinder walls and exhaust port; otherwise the engine would overheat and thus lose power.

In order to dissipate this additional heat it is usual in air-cooled engines to provide deeper cylinder cooling fins; in water-cooled engines bigger water jackets or increased rate of water circulation must be employed.

Yet another disadvantage is the relatively small part of the cycle during which the exhaust gases can escape from the cylinder.

In the case of a four-cycle engine running at a given speed the exhaust period corresponds to a crank angle of 220° to 240°, whereas for a two-cycle engine operating at the same speed the exhaust period corresponds to a crank angle of only 120° to 130°, *i.e.*, only about one-half that of the four-cycle engine. The ordinary two-cycle engine cylinder remains with practically all of its working and clearance volumes full of exhaust gases when the piston has shut off the exhaust port, whereas only the clearance volume of the four-cycle engine contains exhaust gases when the exhaust valve closes. It will thus be apparent that in the two-cycle engine unless these waste gases can be got rid of they will tend to dilute the incoming charge to a serious extent; further, they tend to keep the cylinder hotter.

Modern two-cycle engines employ some form of air compressor to get rid of the exhaust gases, this procedure being known as *air scavenging*. Afterwards a rich mixture of petrol and air is admitted or, alternatively, the pure air charge is compressed by the piston and the fuel is injected early in the compression stroke by means of a fuel-injection device; in this arrangement no fuel is lost through the exhaust port.

Although very much more efficient than the simpler types, the air-scavenged engine—which also give better cylinder charging—obtains its increased power output partly at the expense of the

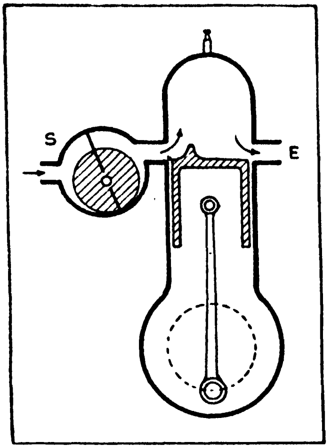


Fig. 13. Principle of the air scavenged and supercharged two-cycle engine.

power required to drive the compressor, so that the net gain in power is not so great.

The principle of the air-scavenged or mixture-scavenged two-cycle engine is illustrated in Fig. 13, which shows a rotary compressor S, delivering its air or charge under pressure through a port past a deflector-type of piston, so as to sweep the residual gases out through the exhaust port E. If the charge is left in the cylinder, when the exhaust port closes, at a greater pressure than that of the outside atmosphere, the engine is said to be *supercharged.* It is a relatively simple matter to supercharge an engine of the type shown, diagrammatically, in Fig. 13, by arranging for a suitable size of compressor ; the engine will then give a greater power output.

It is not possible within the confines of this volume to describe the various alternative designs of two-cycle engines that have been made,* more especially as there are at present no two-cycle petrol type aircraft engines.

The most promising designs appear to be those in which separate mechanically-operated exhaust valves are used in the cylinder head, and engines working upon the sleeve-valve principle, with the charging ports at the top and the exhaust ports at the bottom ends of the cylinders.

Mention should also be made of the opposed piston type of engine having two pistons within the same cylinder. These pistons move inwards and outwards together as shown in Fig. 14. It will be noticed that each piston has a connecting-rod that works a separate crankshaft, the cranks of these being arranged to give the symmetrical piston movements previously

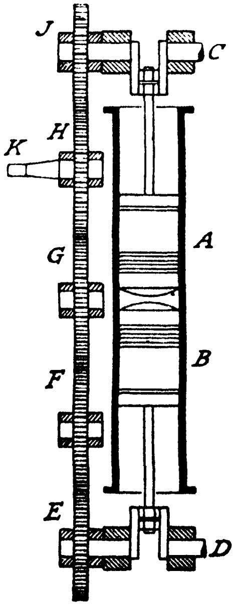


Fig. 14. The Junkers opposed piston engine principle.

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* An account of many of these is given in the section on Two-Cycle Engines in *Automobile Engines*, A. W. Judge (Chapman & Hall Ltd.).

mentioned. The crankshafts C and D are connected together by means of a train of gears, E, F, G, H and J, so that they operate at the same speed. One of these gears, H, drives the airscrew shaft K.

When the two pistons A and B are nearest together the space between forms the combustion chamber in which the compressed charge is ignited, driving the two pistons away from one another. When the upper piston has almost reached its uppermost position it uncovers exhaust ports through which the exhaust gases escape. A little later the lower piston uncovers a series of air inlet ports through which compressed air enters and drives the remnants of the exhaust gases before it upwards and through the exhaust ports; this gives an efficient scavenging action and leaves the double cylinder filled with air at a pressure rather greater than atmospheric.

The principle described is identical with that used on the Junker's two-cycle compression-ignition aircraft engine which in its pre-war design had a weight of about 1·4 lb. per h.p.

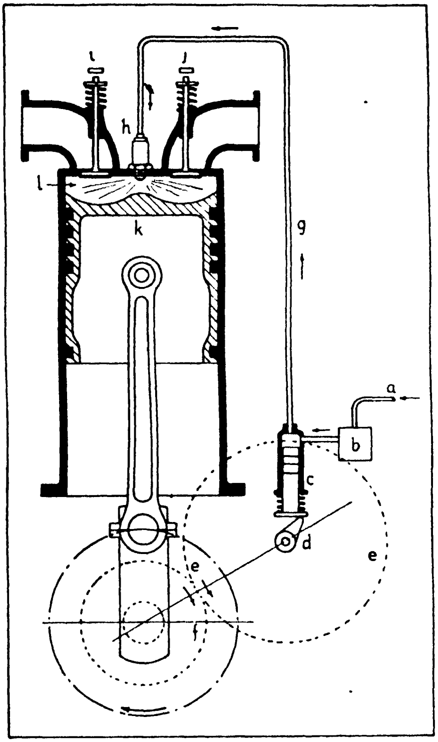

Fig. 15. Illustrating the principle of the compression-ignition engine.

The best results that have previously been obtained from two-cycle petrol engines have shown that for a given size of engine it is possible to obtain a maximum of 40 to 55 per cent. more power at the same engine speed than from a four-cycle engine of similar cylinder dimensions, after due allowance has been made for the power absorbed in driving the air compressor used for scavenging.

The Compression-Ignition Engine. The basic principle of this type of engine, which offers special advantages for aircraft purposes, is that of compressing a charge of pure air to a much higher compression pressure than that used in the petrol-type engine and injecting the fuel into this air charge, where it ignites owing to the heat developed by the compression; no separate electric ignition apparatus is necessary and a fuel pump and injection nozzle take the place of the ordinary carburettor.

The C.I. engine can operate upon either the four- or the two-cycle principle.

Referring to Fig. 15, which shows, schematically, the chief items of a typical C.I. engine of the class known as *direct injection*, or *open combustion chamber*, it employs the same piston, cylinder and valve arrangement as the four-cycle petrol engine, the only important difference being that the inlet valve admits pure air instead of a carburetted mixture of fuel and air. The inlet and exhaust valves are shown at *i* and *j*, respectively, and are of the overhead type. The combustion chamber, *l*, is formed between the flat cylinder head and the curved crown or head of the piston *k*.

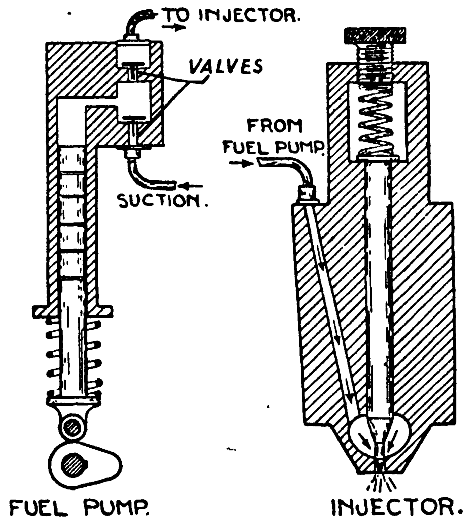

FIG. 16. Principle of the fuel injection system.

The crankshaft has a gear wheel *f* which meshes with another, *e*, having twice the number of teeth so that it runs at one-half crankshaft speed. On this gear shaft there is a cam, *d*, which, during its rotation, lifts the plunger of a fuel pump *c*, a spring keeping the plunger in contact with the cam during the return stroke. The pump draws it supply of fuel—which is a special hydrocarbon liquid heavier than petrol—from the supply line *a* through a filter unit *b* and on the delivery stroke discharges a measured amount of this fuel through a fine-bore steel pipe *g* to an injection valve *h*, consisting of a plug containing a spring-loaded conical pointed valve resting normally on a seating covering an orifice or several orifices leading into the combustion chamber. When the injection pump discharges its fuel the pressure of the latter is sufficient to overcome the spring pressure on the injector valve and cause it to lift, thus uncovering the orifice or orifices and allowing the fuel to issue into the combustion chamber in a fine conical spray or several sprays.

The principle of the fuel injection pump and injection nozzle is more clearly illustrated in Fig. 16. It should be noted that the pump has two non-return valves, namely, one on the suction and the other on the delivery side; the former opens on the down-stroke of the plunger and shuts on the up-stroke, whilst the latter opens on the up-stroke and closes on the down-stroke. The direction of movement of the fuel is indicated by the small arrows. The cycle of operations is as follows: Assuming the piston is on its T.D.C. at the top of its exhaust stroke, its next descent gives the suction stroke during which the inlet valve *i* (Fig. 15) opens, the exhaust valve *j* remaining closed. Air, which first passes through an air filter to get rid of any dust, enters the cylinder and, when the piston reaches its B.D.C., the cylinder is practically filled with clean air. On the next upward stroke the piston compresses the air, but to a much higher pressure than that used in the petrol engine. It is necessary here to digress for a moment to explain that the compression ratios used in C.I. engines range from about 12 to 1 to 18 to 1, and the compression pressures resulting, from about 450 to 650 lb. per sq. in. During compression the air becomes heated until at or near the end of its compression stroke it becomes so hot that its temperature reaches 450° to 600° C.; these temperatures are well above the ignition temperature of the fuel, which usually lie between 250° and 300° C. Referring to Fig. 17, this shows a diagram of the cylinder pressures that occur at different crank angles during the compression and firing strokes. The temperatures of the compressed air and the ignition temperatures required to ignite the fuel are shown on the left. It will be observed that from about 60° before top

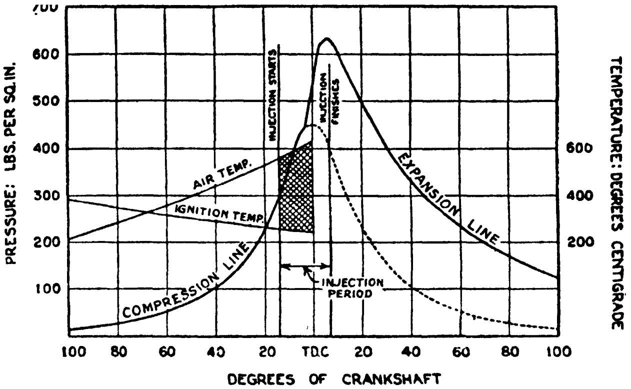

FIG. 17. Pressure and temperature diagrams for compression-ignition engine.

dead centre onwards, the air temperature increases progressively above that required for igniting the fuel. Fuel injection begins at about 15° before top centre. The maximum compression pressure is about 450 lb. per sq. in. and the resulting maximum combustion pressure 635 lb. per sq. in.

Returning to the consideration of the compression stroke, when the piston is nearly on its T.D.C. the fuel injection pump is timed so as to commence its delivery of fuel through the injection nozzle in the form of a finely divided or atomised spray into the combustion chamber, where it at once ignites and burns with the greatly heated air charge. The fuel pump continues to deliver fuel during a period equivalent to an angular movement of the crankshaft of some 10° to 25° or more. Soon after injection commences the pressure due to the combustion of the fuel increases to a certain value, above the maximum compression pressure, depending upon the engine design, moment of injection and certain other factors. Usually, in commercial high-speed C.I. engines, this maximum combustion pressure is limited to a value of between 600 and 750 lb. per sq. in. in order to avoid the excessive engine weights that would result were higher pressures used.

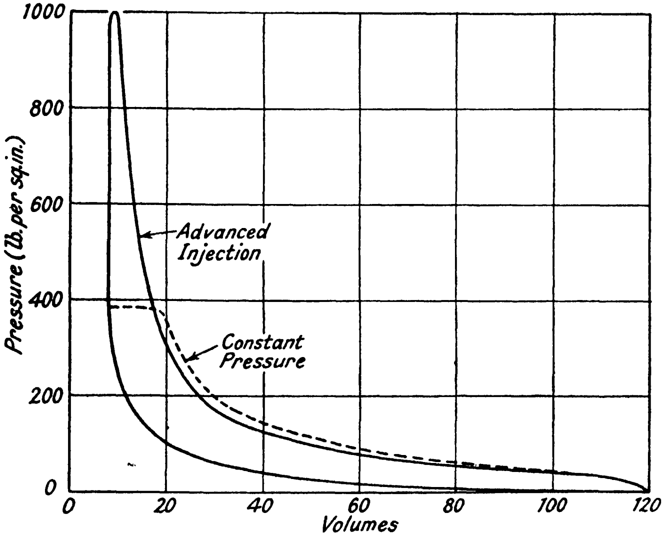

FIG. 18. Alternative cycles for the compression-ignition engine.

Referring to Fig. 15, the piston *k* is shown on its T.D.C., compression stroke with the fuel injection occurring. It will be noted that the fuel is being sprayed in all directions in order to penetrate the whole of the air charge ; for this type of engine a multiple orifice spraying nozzle is employed. Following the fuel injection the piston is forced downwards by the high pressure products of combustion, the expansion stroke being similar to that of the petrol engine. At a crank angle of about 40° to 45° before B.D.C the exhaust valve begins to open, thus releasing the exhaust gases. The following upward stroke of the piston sweeps most of the remaining gases out of the cylinder, thus completing the four-cycle operation.

Notes on C.I. Engine Operation. If the fuel were injected when the piston was actually on its T.D.C., and the injection was continued for a certain period after T.D.C., the cycle of operations would be similar to one known as the *constant pressure* cycle, in which the combustion pressure is maintained at a constant value during the fuel injection period as shown by the dotted line pressure diagram in Fig. 18. In practice, however, it has been found advantageous from the points of view of fuel economy and improved combustion process to commence fuel injection some 25° to 10° of crank angle before T.D.C. The pressure then rises to a higher maximum value, as indicated by the full-line diagram in Fig. 18. The cycle of operation then approximates to the previously mentioned one used in four-cycle petrol engines and known as the Otto or *constant volume* cycle. It is more efficient in practice, as shown by the increased arc of the indicator diagram.

Although the high-speed C.I. engine utilises higher compression pressures and develops higher combustion pressures than the petrol engine it does not yield the same power output from a given size of cylinder and at a given speed. The higher compression pressure used in the C.I. engine absorbs more of the power developed, so that the indicator diagram is usually of more slender form and therefore of smaller area and average height, *i.e.*, mean pressure; as the area is a measure of the power developed it follows that the latter will be less than that of a petrol engine of similar dimensions using a lower compression ratio.

The horse-power output of an internal combustion engine is proportional to the average value of the pressure developed during the complete cycle, *i.e.*, to the *mean effective pressure* (M.E.P.). In the case of modern aircraft engines M.E.P.* values of 130 to 160 lb. per sq. in., are obtained, whereas the best values that have hitherto been obtained from high-speed C.I. engines range from about 100 to 125 lb. per sq. in. ; in each case, unsupercharged engines are referred to, much higher pressure values are possible with supercharging.

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* **Brake M.E.P. values.**

The C.I. engine, on account of its high compression ratio, is *considerably more efficient* than the petrol engine. It can be shown mathematically, that the *heat efficiency of an internal combustion engine increases as the compression ratio is increased.* Thus, in the case of two engines having compression ratios of 7 to 1 and 15 to 1, respectively, the heat efficiencies are in the ratio of 54 to 66, *i.e.*, the latter engine is therefore 22 per cent. more efficient than the former. The C.I. engine with its compression ratios, ranging from 12 to 1 to 18 to 1, is accordingly more efficient than petrol engines with compression ratios of 6 to 1 to 8 to 1. The practical result of this higher heat (or *thermal*) efficiency is that the *fuel consumption* of the C.I. engine for a given power output and time is appreciably less than that of the petrol engine, so that a greater flying range is possible on a given quantity of fuel for engines of equal weight.

The C.I. aircraft engine is, however, heavier than the petrol engine, so that it is necessary to take the total weight of the engine and fuel into account when making comparisons of maximum flight ranges. It can, however, be shown by using data obtained from existing C.I. engines of light design, that if the same aircraft was fitted, respectively, with a petrol engine and a C.I. engine of modern design and of equal power, the former, with its fuel, would be lighter for flights up to about 8 to 10 hours' duration ; beyond this period the C.I. engine installation would be the lighter, and the longer the flight period beyond this figure the greater would be the saving in weight of the latter engine and fuel unit.

The 9-cylinder air-cooled Bristol "Phœnix" radial engine, built some years ago, developed a maximum of 470 B.H.P. at 2,000 r.p.m. and showed a fuel consumption of 0·39 lb. per B.H.P.-hour as compared with that of 0·49 for the best corresponding Bristol petrol radial engine of the same period. The total weight of the engine, fuel and oil for a flight of 6 hours was 5·95 lb. per B.H.P., whilst that of the petrol engine was 6·10 lb., thus showing that at this flight duration the petrol was slightly heavier. For a 10-hour flight the respective weights were 7·73 lb. and 8·32 lb., values which indicate the increasing lightness of the C.I. engine and its fuel for longer flights than 6 hours; for shorter flights the petrol engine combination was the lighter.

In regard to actual figures, the usual fuel consumptions of high-speed C.I. engines under the best operating conditions are from 0·32 to 0·35 lb. per B.H.P. per hour ; these values are from 25 to 35 per cent. lower than for engines using 80 to 85 octane petrol.

With the increasing use of petrols of 100 octane value and above the aircraft petrol engine gives appreciably lower fuel consumptions under cruising conditions than for lower octane fuels, although the advantage is still with the C.I. engine; moreover, the high octane fuels are much more expensive than the Diesel oils used in C.I. engines and give smaller weights per gallon, owing to their lower specific gravities; the latter fact indicates that larger fuel tanks would be needed to carry the same weight of fuel.

In regard to *engine speeds*, the C.I. engine will operate satisfactorily at speeds up to at least 4,500 r.p.m., and in this respect it does not appear to be at any disadvantage as compared with the petrol engine.

Advantages of C.I. Engines. The main advantages of C.I. engines for aircraft purposes are conveniently summarised as follows:—

(1) Lower fuel consumption per horse-power hour.

(2) Lighter engine and fuel weights for flights of over 8 to 10 hours' duration.

(3) Cheaper fuel of small volume for a given weight and therefore smaller tank weight and space.

(4) Immunity from fire risk due to use of fuel of much higher flash point than aviation spirit, absence of carburettor and electric ignition apparatus.

(5) Fewer components for an engine with given number of cylinders.

(6) More easy to maintain on service owing to absence of carburettors, magnetos, sparking plugs, etc.

(7) More uniform mixture distribution due to direct injection of fuel into individual cylinders instead of single carburettor per bank of cylinders.

(8) Owing to higher thermal efficiency, smaller heat losses to cooling fins or radiator, thus saving weight and space of the cooling elements; also less difficulty in keeping cylinders, pistons and exhaust valves cool.

(9) Easier starting in cold weather and much quicker pick-up in power after starting than petrol engine.

(10) Absence of complicated aircraft type carburettor with its automatic mixture controls for speed and altitude effects, variable temperature and icing effects.

The main disadvantage of the C.I. engine at present is its appreciably greater weight than the equivalent output petrol engine, but in the high power output multiple-cylinder opposed-piston engines this gap will no doubt be reduced and, whilst the petrol engine operating on high octane fuels will undoubtedly always be preferred for military aircraft of the high speed type, the C.I. engines may come into their own for long range commercial purposes.

Power Output of Engines. The power developed by a petrol or C.I. engine can be estimated from a knowledge of the cylinder dimensions, the average or mean pressure developed during a complete cycle and the engine revolutions per minute. The horse-power unit employed for expressing the outputs of engines represents the rate of doing 33,000 foot-pounds of work every minute. The horse power calculated from the actual cylinder mean pressures, as measured by means of an instrument known as an *indicator*, is known as the *indicated horse power* (I.H.P.) and is obtained from the following formula :—

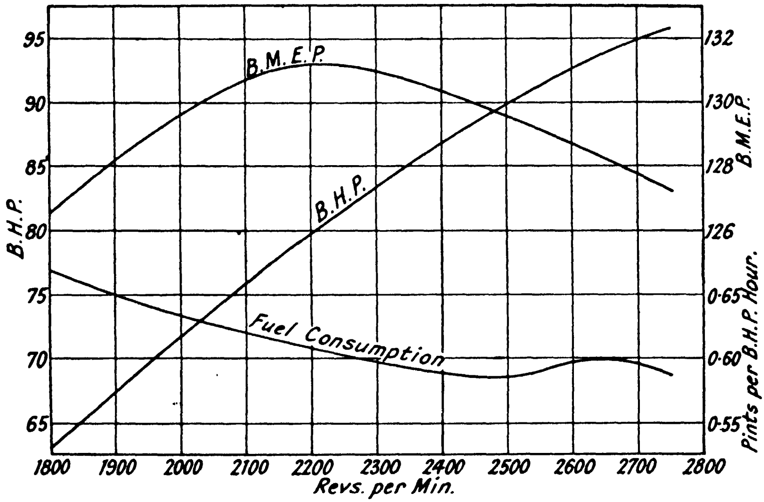

FIG. 19. Performance curves of a petrol engine.

$$\text{I.H.P.} = \frac{plAN}{33{,}000 \times 2}$$

where p = indicated mean effective pressure in lb. per sq. in.
l = length of stroke of piston, or twice crank radius, in feet.
A = area of piston, in sq. in. ($= 0{\cdot}7851 \times \text{diameter}^2$).
N = revolutions per minute, ($N/_2$ = explosions per minute).

For a two-cycle engine there will be twice as many firing strokes, so that $N/_2$ in the above formula then becomes N.

Usually it is more convenient to measure the horse power of a engine at the crankshaft end, by means of a brake or dynamometer, as explained in Chapter X. This is termed the *brake horse power*, and by working backwards, using a similar formula to the above, the corresponding value of the mean pressure p can be estimated. This value is termed the *brake mean effective pressure* (B.M.E.P.) to distinguish it from the indicated mean pressure or I.M.E.P.

The I.H.P. is always greater than the B.H.P. on account of the power absorbed within the engine in overcoming the friction of the moving parts, windage in the crank chamber and that used up in moving the charge into the cylinder (pumping losses), etc.

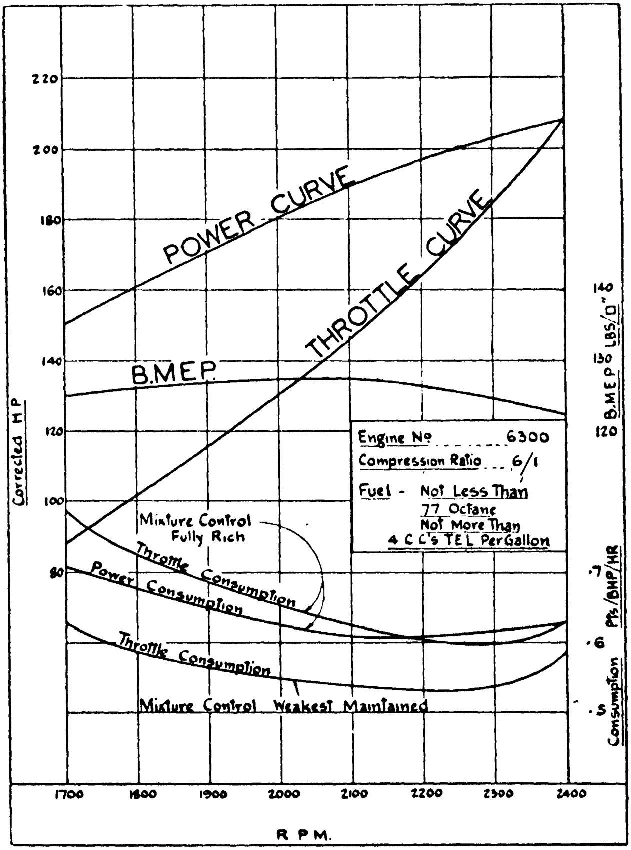

FIG. 20. Performance curves of Gipsy Series II, 6-cylinder aircraft engine.

Some useful formulæ relating to horse power calculations are given in Appendix I. at the end of this volume.

The manner in which the B.H.P. and B.M.E.P. of a well-designed petrol engine vary with the engine speed are illustrated by the graphs given in Fig. 19. It will be observed that the greatest pressure occurs at 2,200 r.p.m., above which speed the pressure falls progressively, although the B.H.P. increases continuously, since it is proportional to both the mean pressure and the engine speed. The results shown relate to one cylinder of a multi-cylinder aircraft engine. The fuel consumption curve included in this diagram indicates that there is less fuel used at 2,500 r.p.m. than at any other speed and that at low engine speeds appreciably more fuel is used per horse-power hour.

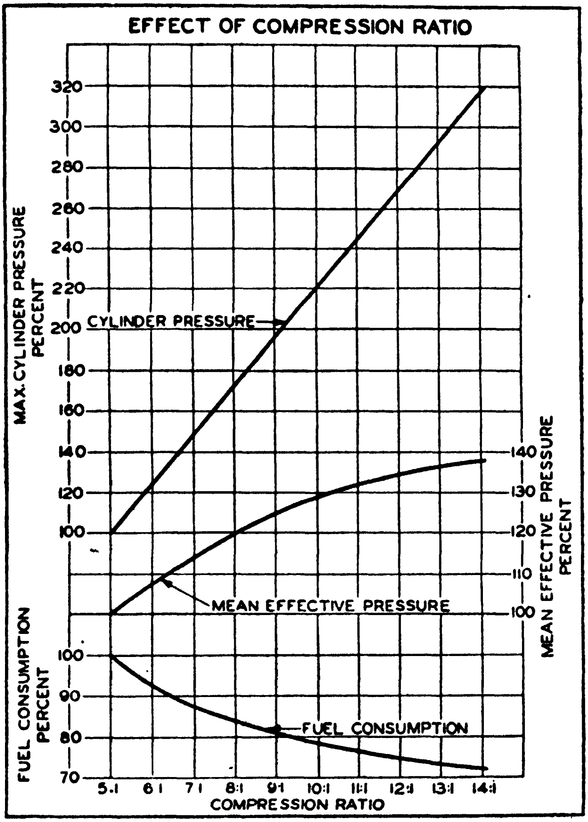

Fig. 21. Illustrating the beneficial efforts of increasing the compression ratio.

A typical performance curve, for a small aircraft engine, namely, the Gipsy Series II 6-cylinder engine, is given in Fig. 20. The maximum power at each engine speed that can be obtained by suitable adjustment of mixture strength and ignition advance is shown by the *Power Curve*, whilst that obtained by leaving the other controls fixed and opening the throttle progressively is shown by the *Throttle Curve*. The fuel consumption curves for various adjustments of the throttle and mixture strength are also shown in the lower part of Fig. 20.

Effect of Compression Ratio on Engine Performance. The general effect of the compression ratio upon the performance has been mentioned earlier in this chapter. It is now proposed to illustrate the beneficial influence of high compression ratios upon the power output and fuel consumption.

The graphs shown in Fig. 21 refer to results obtained from aircraft engines tested with compression ratios over a range of 5 to 1 to 14 to 1, using in each case suitable fuels, *i.e.*, fuels that would not detonate.

The results given indicate that the B.M.E.P. increases progressively from 100 to 139 per cent. over this range of compressions. The B.H.P. of the engine, at any given engine speed, will also increase continuously as the compression ratio is raised.

A somewhat detrimental effect of the increased compression is the higher values of the maximum cylinder pressures, which for a compression ratio of 14 to 1 is 320 per cent. higher than for one of 5 to 1 ; such high pressures necessitate stronger engine components and therefore greater weight per horse power.

The fuel consumption falls off continuously with increasing compression ratio, the value at 14 to 1 being only about 72 per cent. of that at 5 to 1.

In general, the most useful range of compression ratios for present and future types of aircraft engines, using higher octane fuels, appears to be that between 7 to 1 and 10 to 1.

CHAPTER III

THE CARBURATION SYSTEM

THE carburation system comprises the fuel tank or tanks, fuel piping, filters, fuel pumps and the carburettor or its equivalent, *e.g.*, the fuel injection system.

The purpose of the three former items is to supply clean fuel to the fuel pump, which, in turn, delivers fuel under a slight pressure to the carburettor ; the latter is a mechanical device for supplying the desired proportions of air and fuel to the inlet port side of the engine during the suction strokes, under all operating conditions.

It will be convenient, here, to consider the subject under three principal headings, namely, (1) Fuels ; (2) Carburettors and Fuel Injection Systems ; and (3) the Fuel Supply System.

(1) **Fuels.** The fuels used in aircraft engines are volatile hydrocarbon ones obtained from crude petroleum by distillation or "cracking" processes, followed by the distillation of the lower boiling point constituents.

The name "fuel" is now generally given to petrols of varying compositions and to mixtures of petrols with other constituents such as alcohol, benzole and certain anti-knock substances.

Most petrol engine fuels consist of mixtures of *Aromatic fuels*, *e.g.*, benzene, toluene and xylene ; *Naphthenes*, *e.g.*, cyclohexane ; *Paraffins*, *e.g.*, heptane, octane, iso-octane ; and *Unsaturateds ;* the latter have a similar constitution or chemical formula to that of the naphthenes.

The three chief properties that distinguish different petrol engine fuels include (a) *The Calorific Value ;* (b) *The Anti-Knock Properties ;* and (c) *The Boiling Range.* Other important properties are the *specific gravity* (light fuels being required for aircraft purposes) and *dew point ;* the latter has a bearing upon the tendency of the fuel to dilute the lubricating oil.

The *Calorific Value* of a fuel is usually defined as the number of British Thermal Units (B.T.U.'s) evolved during the combustion of 1 lb. of the fuel ; this value depends essentially upon the composition of the fuel, *i.e.*, upon the proportions of carbon, hydrogen and oxygen.

The calorific values of hydrogen and carbon are 62,030 * and

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* Includes the latent heat of the steam formed and is therefore known as the *Higher Heating Value ;* otherwise, if it does not include the latent heat it is termed the *Lower Heating Value.*

14,540 B.T.U.'s respectively, and for most aviation fuels (petrols) from 18,500 to 19,500 B.T.U.'s per lb.

Fuels with high hydrogen contents give the higher calorific values.

In general, aircraft fuels have high calorific values, but the *amount of power developed* by the combustion of any fuel in a petrol engine depends primarily upon the amount of oxygen (or air) that can be supplied to the cylinder in unit time ; it is therefore independent of the nature of the hydrocarbon fuel.

In this connection it has been shown that *the amount of energy liberated for each pound of air* consumed by an engine is 1,300 B.T.U.'s, or about 45 ft.-lb. per cu. in. of mixture, for rich mixtures.

(B) *The Anti-Knock Properties.* In order to obtain the greatest power output from a given capacity engine it is necessary to employ as high a compression pressure as possible, other factors remaining the same. If, however, when using a given grade of fuel the compression pressure (or ratio) could be raised gradually, it would be found that the power output would increase to a certain value of the compression pressure, above which the engine would begin to develop a knocking noise and, at the same time, would lose power and run somewhat erratically. If another grade of fuel were used it would be observed that this knocking tendency would be associated with another value of the compression pressure and that, in general, each different fuel used would have its own particular compression pressure at which knocking commenced, when tested in the same engine and under similar engine running conditions. For each fuel, therefore, there is a limiting value of the compression ratio, above which knocking and power loss occur. This compression ratio has been termed the *Highest Useful Compression Ratio* (H.U.C.R.). The following are some typical values for petrol engine fuels obtained a variable compression engine by H. Ricardo :—

Fuel	H.U.C.R.	Maximum Compression Pressure	Minimum Fuel Consumption
		lb. per sq. in.	lb. per I.H.P. per hour
Aromatic-free petrol .	4·85	105·5	0·422
Aviation petrol (undoped)	6·0	148·5	0·393
Heavy aromatic petrol .	6·5	163·5	0·447
Paraffin (kerosene) . .	4·2	86·0	0·581
Benzene (pure) . .	6·9	179·0	0·392
Ethy alcohol (98 per cent.)	7·5*	204·0	0·565

* Highest compression ratio tested ; higher values could probably be used.

Octane Rating of Fuels. More recently the anti-knock properties of fuels have been more accurately defined by comparing their behaviour in a standard test engine, known as the C.F.R. one, under uniform operating conditions, with that of a standard fuel mixture having two constituents, namely, *heptane*, which is a very poor anti-knock fuel whose rating is taken as zero, and *iso-octane*, a fuel of higher knock rating than ordinary petrol engine fuels; its rating is taken as 100. The fuel to be rated is employed to operate the standard engine and its knocking tendencies are measured with a special device. Next, the mixture of heptane and iso-octane that gives the same knock effects is determined by trial, in the same engine. Thus, if it is found that a mixture of 75 parts of iso-octane and 25 parts of heptane give identical results then the fuel under consideration is said to have an *octane rating or value* of 75.

Most commercial motor and motor car engine fuels, other than Ethyl petrol have octane rating of 65 to 75; Ethyl petrols from 75 to 85 and aircraft engine fuels from about 80 to over 100. The D.T.D. 230 Specification fuel hitherto used on aircraft engines has an octane rating of 87.

As the octane rating is increased, so can *a higher compression* ratio be used in any given engine; more power is thus developed, whilst the *fuel consumption per B.H.P. per hour is reduced.*

It follows from these considerations that *the H.U.C.R. increases with the octane rating*. Thus for heptane that has an octane rating of 0 the H.U.C.R. in a test engine of variable compression (Ricardo's E.35 engine) was 3·75 to 1; an inferior petrol of octane rating, 50 had an H.U.C.R. of 4·3 to 1, whilst an aviation petrol containing ethyl fluid, with an octane rating of 85, had an H.U.C.R. of 6·5 to 1.

Anti-knock Fuels. In general, petrols containing higher proportions of aromatics and unsaturated constituents have higher octane ratings than those with excess of paraffins and naphthenes. *Benzene*, *i.e.*, the commercial benzole obtained by distillation from coal, has a higher octane rating than ordinary petrols; for this reason it has sometimes been mixed with petrol to improve the anti-knock properties. *Alcohol* has a much higher octane rating than benzene or any of the petrols, and it can therefore be employed with much higher compression ratios. It has, however, a greater latent heat of evaporation so that more heat must be supplied to the carburettor system in order to vaporise alcohol; it is a more expensive fuel than petrol or benzole. Modern anti-knock fuels are selected petrols having the required physical properties, such as low specific gravity, boiling range, vapour pressure, etc., to which small quantities of chemical compounds, known as fuel " dopes," are added. Various substances, including tin and lead ethyls, amines, xylidine and tellurium diethyl have been used as dopes, but the best results, in practice, have been obtained from tetra-ethyl lead, mixed with ethyl dibromide and a colouring dye (for distinguishing purposes only). It requires less than half of one per cent. of this fluid to raise the H.U.C.R. by nearly 50 per cent. ; one part of ethyl fluid in 900 parts of petrol give an increase in the H.U.C.R. of 15 per cent.

Fuels containing tetra-ethyl lead, are known as " leaded," ones. Such fuels have a tendency to scale and burn the exhaust valves ; attack (or corrode) the piston, cylinder head and exhaust manifolds and erode the sparking plugs. These effects are counteracted in aircraft engines by the use of special materials and design methods.

Detonation in Petrol Engines. Reference has already been made to the effects associated with the use of compression ratios that are too high for the grade of fuel employed ; the conditions in question are known as *detonation* ones.

The chief characteristics of detonation are a regular series of knocking sounds somewhat similar to those of a hammer being tapped on the cylinder walls ; loss of power ; increase in the maximum cylinder pressures and increase in the maximum cylinder temperatures with risk of burning the piston heads and loosening the valve insert rings. If serious detonation is allowed to continue the engine will lose power rapidly and eventually stop. The cause of this engine failure is usually that of *pre-ignition*, whereby the excessive cylinder temperatures cause projecting points, *e.g.*, the sparking plug electrodes, or edges of metal to become " red hot," so that the incoming charge is ignited before it is fully compressed, *i.e.*, before the occurrence of the electrical ignition spark. Thus, *detonation always precedes pre-ignition.*

Detonation is believed to be due to excessive rates of inflammation of the charge ; when this rate of travel of the flame from the sparking plug points exceeds a certain critical value, detonation then occurs. This critical rate of flame travel depends upon various factors, including the compression ratio, combustion chamber design, nature of fuel, mixture strength and degree of agitation, or turbulence, of the mixture in the combustion chamber.

It is now considered that the earlier stages of combustion in the cylinder are normal, but that towards the end, namely, over about the last 25 per cent. of the flame travel, sudden inflammation of the last portion of the charge occurs, giving a rapid rate of pressure rise that creates a kind of impact effect upon the walls of the combustion chamber.

(2) **Carburation Principles.** Air and petrol vapour mixtures are combustible in petrol engines over a fairly wide range, namely, from a weak mixture consisting of about 20 parts, by weight, of air to 1 part of petrol, to a rich mixture having about 8 parts of air to 1 part of petrol.

The mixture giving practically complete combustion is one composed of about 15 parts of air to 1 part of petrol; this value varies a little with the composition of the petrol.

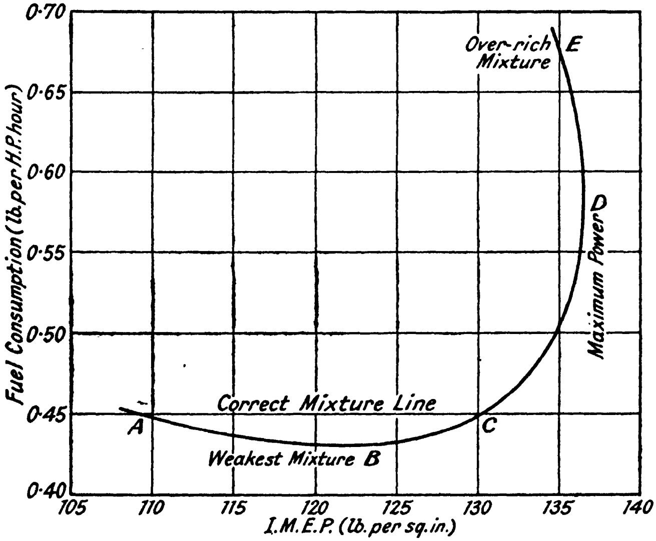

FIG. 22. Mixture strength and power output.

Weaker mixtures than the correct one give *less power* and a *slower rate of combustion,* but also lower fuel consumptions per h.p. than richer mixtures. In this connection the *most economical mixture* to employ is one about 15 per cent. weaker in petrol than the correct one.

Richer mixtures than the correct one *give more power* and *an increased rate of combustion* up to proportions of about 12 of air to 1 of petrol; mixtures richer than this show a progressive falling off in power and combustion rate. Very rich mixtures, *i.e.*, of 8 to 10 of air to 1 of petrol, produce a pungent exhaust containing an appreciable amount of the poisonous carbon monoxide gas and also fine carbon dust. When an engine is operated on a very weak or very rich mixture it not only gives less power than for normal mixtures but, owing to the lower rate of burning of the fuel, tends to become overheated.

In the case of very weak mixtures, the rate of burning may become so low that the mixture continues to burn after the exhaust valve is opened and throughout the exhaust stroke, so that when the following suction stroke commences the flame from the still burning mixture will ignite the incoming fresh mixture and cause an explosion in the inlet manifold and carburettor ; this effect is known as *popping back* and is always associated with weak mixtures (or fuel shortage).

The power output, it has been stated, depends upon the mixture strength, richer mixtures giving more power than weaker ones. The general effect of the mixture strength upon the power output over the usual working range of mixtures is illustrated by the results of tests on a medium-compression engine, reproduced in Fig. 22. The power output is represented by the values of the mean effective pressure, the engine speed being constant during the tests. The results show that the most economical mixture, namely, the weakest one shown at B, gives a fuel consumption of about 0·43 lb. per indicated h.p., per hour, and an indicated m.e.p. of about 123 lb. per sq. in.

The correct mixture, at C, gives 0·45 lb. per i.h.p. per hour and indicated m.e.p. of 130 lb. per sq. in.

The greatest power mixture is a richer one, as shown at D, with a fuel consumption of 0·58 lb. per i.h.p. per hour and an indicated m.e.p. of 136·5 lb. per sq. in. If the mixture is made any richer, as shown at E, the power falls and the fuel consumption increases.

For aircraft purposes since it is necessary to provide the greatest power output for taking off, the carburettor is arranged to give this richer mixture, whilst for normal climb and level flying conditions the approximately correct mixture would be employed.

For long range flights and cruising conditions, fuel economy is of the greatest importance, so that the aircraft carburettor is provided with a control to weaken the mixture from the correct value by about 10 to 15 ger cent.

The Exhaust Gases. It is possible to ascertain what proportions of fuel and air are being used in an engine by analysing the exhaust gases, or by a more simple apparatus or instrument to find out whether the mixture is richer or weaker than the correct one.

With the *correct mixture* the exhaust gases are almost entirely carbon-dioxide, nitrogen and water vapour.

Richer mixtures contain, in addition, carbon monoxide. Thus a mixture strength of 14 air to 1 petrol gives 1·5 per cent. of carbon monoxide, whilst one of 9 air to 1 petrol gives 14 per cent. There is no oxygen present in the exhaust from rich mixtures.

Weaker mixtures give exhaust gases containing carbon-dioxide, nitrogen, water vapour and oxygen, but no carbon monoxide; a mixture of 22 parts air to 1 part petrol gives about 9 per cent. of oxygen in the exhaust gases, falling to practically nothing for the correct mixture (15 of air to 1 of petrol).

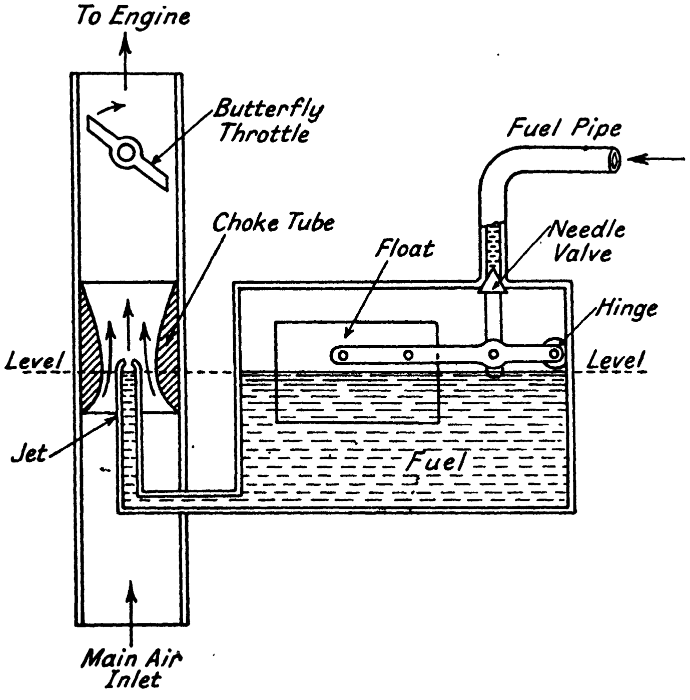

FIG. 23. The simple carburettor.

The Simple Carburettor. The simplest form of carburettor is one consisting of a fuel jet situated in a tube through which air is drawn by engine suction. If the velocity of the air past the jet is sufficient to cause a drop in pressure the fuel will be drawn out of the jet and carried along with the air to the engine. In order to obtain a sufficiently high velocity for this purpose a restricted area is provided around the jet by a device known as a *choke tube* or *venturi* (Fig. 23); the increased velocity thus obtained has the additional advantage of assisting in atomizing the fuel and thus promoting vaporisation.

The fuel is supplied from a reservoir, known as the *float chamber*, in which it is kept at a constant level by a float or diaphragm device, such that when the fuel level falls a cone valve is opened so as to admit more fuel to restore the level and in doing so to shut itself; the level of fuel in the jet is therefore maintained constant.

The mixture of air and fuel is drawn into the inlet pipe past a *throttle valve*, the object of which is to enable the quantity of the mixture supplied to the engine to be regulated; or, in other words, to enable the power output to be controlled.

The simple carburettor shown in Fig. 23, whilst giving the correct proportions of air and fuel for one throttle opening or speed, will not maintain the mixture strength constant over the whole range of speeds. Thus if the mixture is set correctly at a certain speed *it will become too rich as the speed increases* and *too weak for a reduction of speed.* The reason for this is that liquids and gases do not follow the same laws of flow, a given increase in the air (gas) speed producing a proportionately greater flow of fuel (liquid). Thus in a certain example when the air velocity was doubled the quantity of petrol from the jet was increased two-and-one-half times, making the mixture richer by about 25 per cent.

In modern automobile carburettors various devices are embodied to correct, automatically, for this enriching of the mixture; alternatively, a hand-control for the air or fuel could be provided, as on early cars and motor-cycles. The automatic mixture regulators include the hydraulic or submerged jet or well; suction-operated variable jet devices; mechanical compensators whereby the opening of the throttle operates an air supply valve or variable jet so as to increase the proportion of air or reduce the fuel quantity.

It is not possible in the present limited space to describe these mixture compensating devices,* but it can be stated that all automobile and aircraft carburettors embody one or other of them in their design.

In addition to providing the correct mixture under all speed or throttle opening conditions the carburettor must give good atomising of the fuel; enable the engine to run slowly, or to " idle " without hunting or misfiring; allow the engine to be started readily from cold; enable maximum engine acceleration to be attained when the throttle is opened quickly; give relatively low fuel consumption and permit maximum power to be obtained at full throttle opening.

The carburettor must not be too complicated in design, since

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* For fuller information the reader is referred to " Carburettors and Fuel Systems," A. W. Judge (Chapman and Hall Ltd.).

numerous working parts are liable to wear effects and consequent interference with its performance. It must not be too bulky and should be readily accessible for inspection or cleaning purposes.

The above requirements are equally applicable to automobile and aircraft engines.

Aircraft Carburettors. Whilst the automobile carburettor is designed to operate, without adjustment, under practically fixed ground level conditions and over a relatively small range of temperature variation, the aircraft carburettor is called upon to give the desired mixture strength over a wide range of altitudes and temperature conditions.

The effect of increase in altitude is to *reduce the density of the air* and *to lower its temperature.* In this connection it may be mentioned that if the density of the air at ground level be represented by 100 per cent., then the following are the standard densities and temperatures at the altitudes stated.

TABLE I

Standard Densities and Temperatures

Height in Feet	Relative Density	Temperature °C.
0	100	15·0
5,000	86·2	5·1
10,000	73·8	— 4·8
15,000	62·9	— 14·7
20,000	53·3	— 24·6
25,000	44·8	— 34·55
30,000	37·4	— 44·55

It will be observed that at a little over 20,000 ft. the air density is halved and the temperature is about — 25° C.

The effect of altitude increase upon mixture strength is such that, at any given engine speed (or throttle opening), the mixture tends to become richer in fuel. This result is due primarily to the reduced air density, whilst that of the fuel remains either constant or increases owing to the drop in temperature.

Theoretically, if the fuel density is assumed to be constant, the ratio of air-to-fuel varies as the square root of the air density, so that the mixture must become richer in fuel.

It is necessary, therefore, to provide an altitude control for the mixture strength in addition to the previously mentioned speed control. This may operate either by increasing the air supply or reducing the quantity of fuel delivered by the jet (or jets) as the altitude increases. In most aircraft carburettors the latter expedient is adopted.

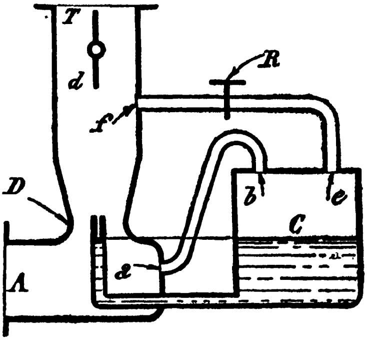


FIG. 24. Altitude mixture control.

An early method that was used for compensating the mixture at different altitudes is shown in Fig. 24. In this method the float chamber C is made airtight and provided with a tube *ef* communicating with the carburettor body at *f*. A control tap R is fitted in the pipe *ef* whilst a second pipe *ab* communicates with the air inlet side. For low altitude flying and take-off purposes R is closed so that the pressure in the float chamber C is atmospheric.

At higher altitudes R is opened by the pilot so that the reduced pressure existing at *f* is communicated to C ; this has the effect of lowering the fuel level in C and also in the jet, so that the quantity of fuel that flows from the latter is reduced, *i.e.*, the mixture is weakened to compensate for the natural enrichment due to the altitude.

Another method of regulating the fuel supply, illustrated diagrammatically in Fig. 25, employs the air bleed principle. The fuel passage from the float chamber to the main jet has two metering orifices, or plugs, A and B, and a valve seating covering a larger orifice at C. At low altitudes the valve at C is raised well clear of the seating so that the metering orifice A is cut out of action. At higher altitudes the needle valve is brought down gradually on to its seating so that the second metering orifice is brought, progressively, into operation, thus restricting the supply of fuel to the jet.

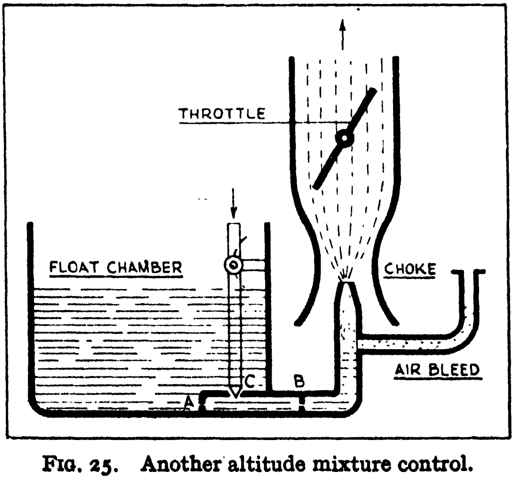


FIG. 25. Another altitude mixture control.

When the altitude control is in full operation the needle valve shuts off the orifice at C so that the fuel can only reach the jet by way of the metering orifices A and B.

Yet another method of varying the fuel supply for altitude mixture control consists in the provision of a tapered needle, which is submerged for part of its length in the fuel jet ; the annular area between the needle and jet hole therefore determines the quantity of fuel that can emerge from the jet. The altitude control, in this case, consists in lowering the tapered needle into the jet so as to reduce the effective jet area as the altitude increases. The tapered needle is connected to an aneroid bellows (or exhausted thin corrugated metal box) and its movement is thus controlled automatically by the outside air pressure variations. As the bellows expands under the reduced pressures corresponding to the higher altitude the needle is moved down into the jet.

The automatic correction of mixture for altitude effect has now replaced the hand-control methods, in modern aircraft carburettors ; in this connection the aneroid bellows method is usually adopted.

Pressure Balance in Carburettors. In the example shown in Fig. 23 the fuel in the float chamber is subject to atmospheric pressure, an air hole being left in the lid of the float chamber. Thus the pressure causing the fuel to flow from the jet will be proportional to the difference between atmospheric pressure and the pressure in the choke tube ; the latter depends upon the forward speed of the aircraft and other local conditions. The mixture strength would therefore vary continuously were it not for the fact that the top of the float chamber is now sealed and the space above the fuel is placed in communication by means of a duct with that of the air intake as shown in Fig. 24, thus giving a *pressure balance* under various flying conditions ; the mixture strength therefore remains constant. It is also usual in aircraft carburettors to take the air required for the fuel jet diffuser from the pressure balance communication duct mentioned previously.

Aircraft Engine Mixture Requirements. From the preceding considerations it has been shown possible to control the mixture strength for both speed (or throttle) and altitude conditions. The question now arises as to what particular proportion of air to fuel the carburettor should initially be adjusted ?

In practice the *aircraft carburettor must be designed to give* not one particular mixture strength but a *certain range of mixtures.*

Thus, when an engine is required to deliver its full power the mixture, as previously shown, must be some 15 to 20 per cent.

richer in petrol than the proportions giving practically complete combustion. Again, for economical cruising conditions, during which the engine may be running at 0·50 to 0·80 of its maximum output, it is necessary to provide mixtures up to about 15 per cent. weak (in fuel).

The carburettor must therefore be arranged to provide an economical mixture over a range of about 0·50 to 0·80 of its maximum output and an increasingly rich mixture up to 15 to 20 per cent. rich at full throttle.

In this connection it should be mentioned that the reason for running multi-cylinder engines on rather richer mixtures, *i.e.*, from 15 to 20 per cent. rich, than the mixture giving maximum power, viz., about 15 per cent. rich, in single-cylinder engines, is on account of the better mixture distribution, increased cooling from the evaporation of the additional fuel and reduced cylinder temperatures resulting from such slightly over-rich mixtures, *i.e.*, richer than 15 per cent.

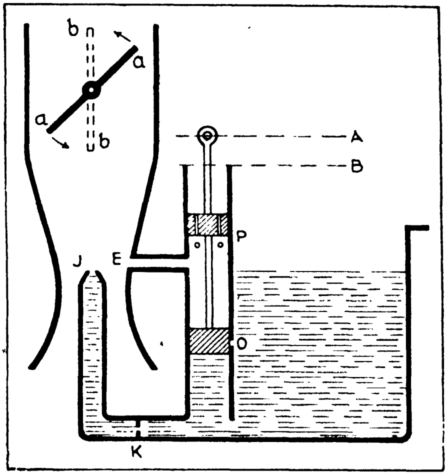


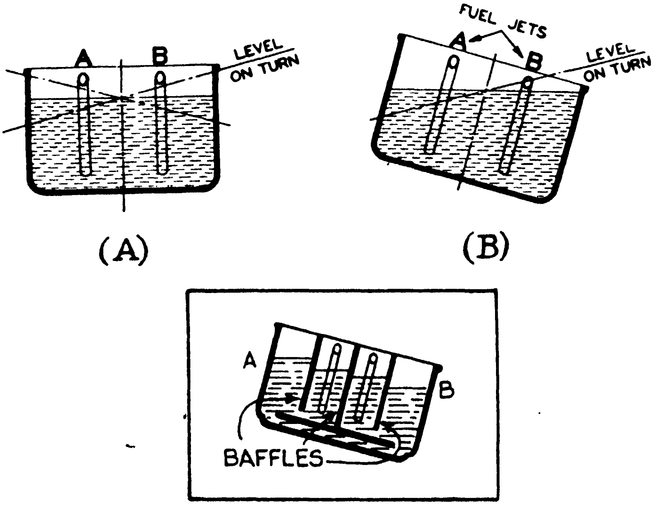
FIG. 26. Full power mixture device.

Full Power Carburettor Setting. One method that is often adopted for enrichment of the mixture from about 80 per cent. to full power outputs is to connect the throttle lever with a device in the carburettor so that during the last stages of throttle opening the device in question will allow more fuel to be admitted to the main jet or a separate jet.

There are several alternative methods of arranging for the increase of fuel when the throttle is fully open, two of which will be described.

Referring to Fig. 25, if the valve C were normally kept closed the fuel would be supplied by the metering orifices A and B. If, however, the valve C were opened by the throttle mechanism, then orifice A would be cut out of action and all the fuel would then be governed by B, which would be of larger orifice diameter than A. Actually, the device illustrated in Fig. 25 is for altitude control and operates the reverse way, but it will serve as an illustration of an alternative (or additional) method of mixture enrichment at full throttle.

One other example of mixture enrichment device that merits attention is that shown diagrammatically in Fig. 26. Apart from the main jet J with its metering orifice K, there is a small vertical cylinder on the side of the float chamber having a hole through its side, at O, communicating with the float chamber and a small passage leading to the choke tube at E. Air holes P are provided in the upper end of the cylinder. When the engine is operating under cruising conditions the throttle is in the position *aa* and the top of the piston rod at level A. It will be observed that there are two pistons, the lower one covering the petrol orifice O—and thus shutting off the petrol—and the upper one uncovering the air orifices P. Under these circumstances a small quantity of air passes through these holes and into the choke tube at E. When the throttle is opened fully to position shown dotted at *bb*, the throttle mechanism moves the piston rod top to level B and the upper piston then closes the air holes at P, whilst the lower one opens the petrol orifice at O. Petrol therefore enters the cylinder above the lower piston level and emerges into the choke tube at E, mixed with a certain amount



(A) (B)

(C)

FIG. 27. Carburettor float chamber. *A*—Ordinary two-jet arrangement. *B*—Effect of tilt is to increase petrol supply to B and reduce it to A. *C*—Illustrating use of baffles to prevent surging of fuel.

of air which enters through holes in the upper piston; the result is to provide a richer mixture at full throttle opening.

Slow Running Devices. As in automobile carburettors aircraft types require some means of permitting a small quantity of rich mixture to be supplied for slow-running purposes. It is usual to provide a separate small jet—known as a *pilot jet*—with its own air supply tube for this purpose. The quantity of slow-running mixture is varied by means of a screw-adjustment stop which alters the "nearly closed" position of the throttle.

Acceleration Device. In order to prevent the weakening of the mixture which would otherwise occur when the throttle is opened quickly, a fuel pump device is provided and connected to the throttle lever in such a way that sudden movement of the latter forces the pump down in its barrel and thus causes a jet of fuel to be sprayed into the normal air and fuel supply to the engine. One method of effecting this by means of a small pressure-type pump having ball-type suction and delivery valves.

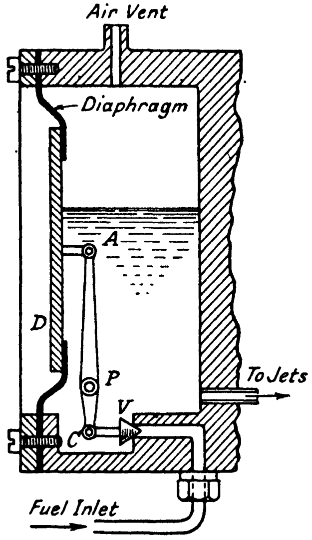


FIG. 28. Diaphragm type of float chamber.

Fuel Supply to the Jets. The automobile pattern float chamber, shown in Fig. 23 is not satisfactory for aircraft carburettors, which frequently have to operate when tilted to various angles or even inverted, as during a loop. In some systems the float chamber is dispensed with and the fuel is supplied direct to the jets. In other instances a multiple partition type of float chamber, as shown in Fig. 27, is provided; in this case the baffles prevent any appreciable surging of the fuel across the jets. Another method is to employ a diaphragm instead of the usual float mechanism; an example of such a fuel regulation device is given in

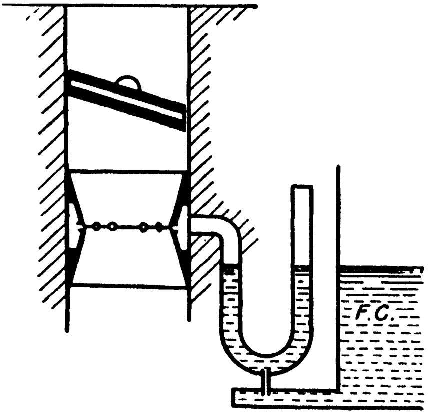


FIG. 29. Throttle closed.

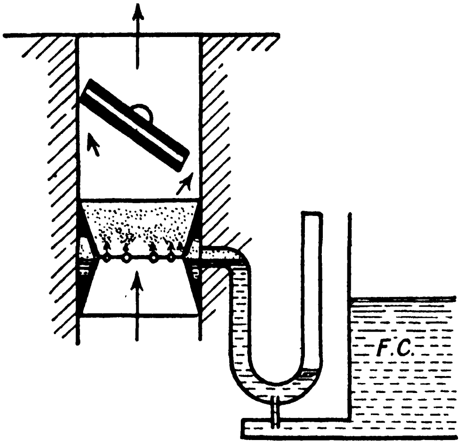


FIG. 30. Throttle partly open.

Fig. 28. One side of the fuel chamber is provided with a flexible diaphragm clamped around its edges and having a metal plate D for its central portion. The simple lever system for operating the fuel admission valve V consists of a lever APC, with a fixed bearing at P. When the level of fuel in the diaphragm chamber tends to fall the diaphragm D moves to the right, since the pressure within becomes less, and it operates the lever APC causing the valve V to open so as to admit more fuel. When sufficient of the latter has entered the level rises within the chamber and causes an increased pressure on the diaphragm, causing it to move to the left and thus close the valve V. In another design of aircraft carburettor a spherical float is employed in a spherical shape of float chamber to give constant fuel feed under all conditions.

A Typical Aircraft Carburettor. The Claudel Hobson carburettor uses the principle of a well of fuel from which that required by the engine is drawn, together with a system, known as the " air-bleed " one in which atomisation of the fuel is assisted by the provision of a small air leak or "bleed" on one side of the fuel jet device.

Fig. 29 shows the arrangement in question, from which it will be seen that the float chamber FC supplies fuel to a U-tube device, one side of which is open to the air whilst the other communicates with the annular space around a choke tube provided with a series of small holes through which the atomised fuel and air pass to join the main air

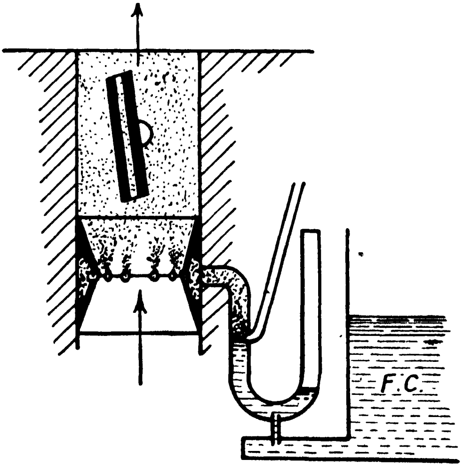


FIG. 31. Throttle fully opened.

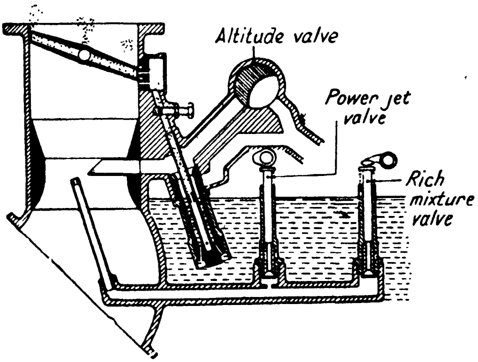


FIG. 32. Slow running conditions.

stream flowing through the choke tube. In Fig. 29 the throttle, which is hollow, is shown in the closed position, the fuel level being the same in each limb of the U-tube.

In Fig. 30 the throttle is slightly open and air is passing through the choke; the result of this is to create a lower pressure in the choke than atmospheric pressure, *i.e.*, the pressure on the right-hand limb of the U-tube device.

The fuel is therefore drawn out into the choke by way of the diffuser device shown ; this consists of a series of small holes through which fuel or fuel-air passes into the choke. Fig. 31 depicts a pipe supplying air below the ordinary fuel level in the U-tube, on the ordinary air bleed principle ; the air-fuel emerging through the holes in the choke tube thus becomes well atomised and distributed.

The slow-running position of the throttle is shown in Fig. 32. It will be observed that the diffuser is then cut out, the fuel with its proper amount of air being drawn by engine suction through the holes to the right of the hollow butterfly throttle ; it then enters the carburettor up-take from the centre and two ends of the throttle.

In Fig. 33 the throttle is shown slightly open ; the slow-running device is still in operation and the diffuser is commencing to act. It will be noted that the first row of depression holes is uncovered, the air proceeding by way of these holes to mix with the petrol and thereby atomise it.

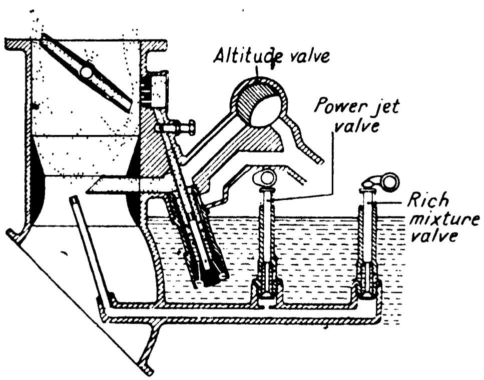


FIG. 33. Throttle slightly open.

In Fig. 34 the throttle is fully open, *i.e.*, in the full-power position. The slow-running jet and throttle transverse passage are then out of action and the diffuser is in full operation ; all of the depression holes are uncovered and supplying air to mix with the fuel. In addition, the power-jet valve has opened and is supplying additional fuel to that of the main jet, so as to provide the richer mixture necessary for full power.

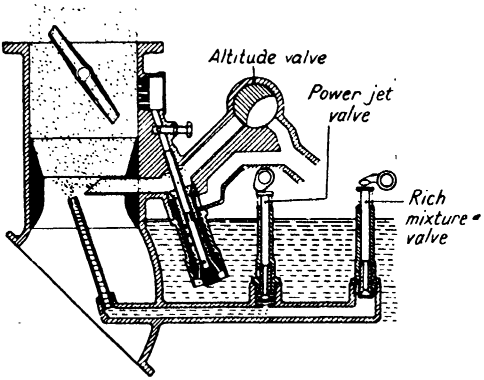


FIG. 34. Throttle fully opened.

In Fig. 35 the carburettor is shown in the condition for take-off from the ground and is assumed to be operating with a Hobson induction pressure "boost" control but with the over-ride of this control in action. The rich-mixture valve, working in conjunction with the boost control over-ride, is open and is shown supplementing the normal fuel supply of the carburettor. This supplementary fuel supply is arranged to provide from 10 to 15 per cent. more fuel.

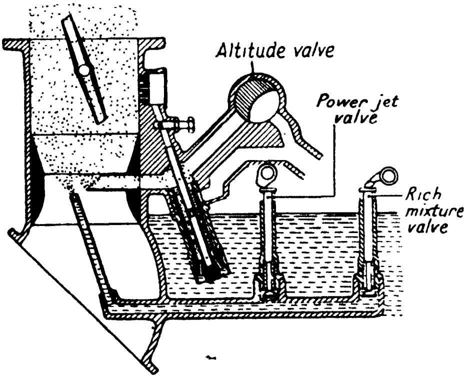


FIG. 35. Rich mixture for take-off from the ground (rich mixture valve opened).

In Fig. 36 the carburettor is shown in full power operation, but the cock for the mixture control and its connecting passage are shown open. It will be seen that the admission of air through the mixture control cock into the emulsion passage will weaken the suction on the jets in proportion to the air admitted through the cock. This constitutes

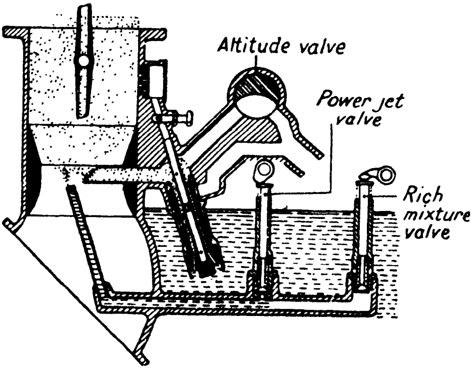


FIG. 36. Full throttle mixture operation.

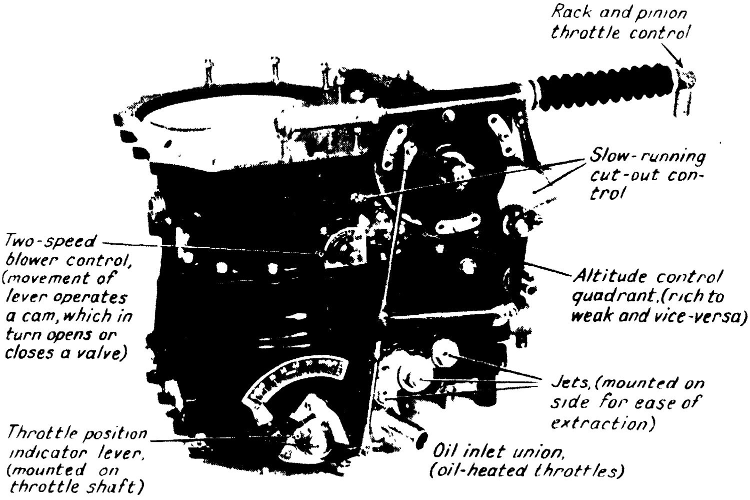


FIG. 37. The Hobson aircraft carburettor, showing controls, etc.

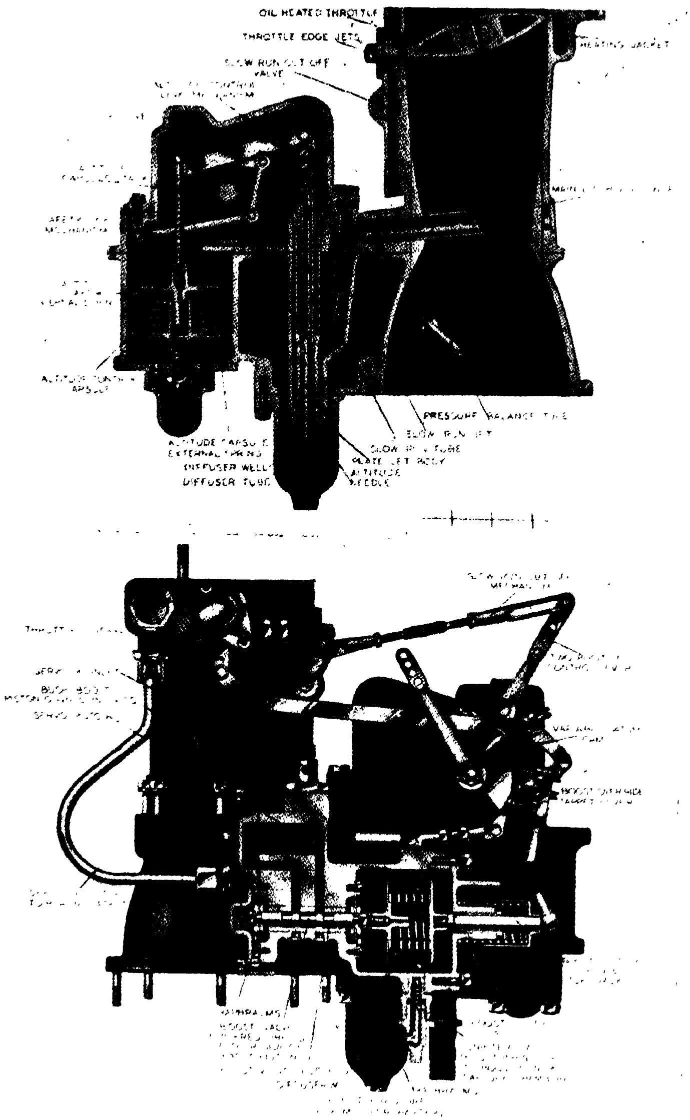


FIG. 38. The S.U. aircraft carburettor, showing principal components.

the altitude control for weakening the mixture as the altitude increases.

Notes on Aircraft Carburettors. The carburettor throttle control in the case of supercharged engines designed to give their full power at a given or " rated " altitude must be arranged so that the throttle cannot be opened fully, except for take-off purposes, at any lower altitudes. Both manual or automatic means can be provided for this purpose ; this subject is dealt with again in Chapter IV.

The aircraft carburettor main air supply should be arranged so that under cold flying conditions and for starting purposes *the air may be heated* in order to assist in vaporising the fuel and to prevent freezing up. One arrangement (Fig. 39) is to provide for a cold air inlet to the carburettor, facing the forward direction, with an alternative warm air inlet, brought into operation by means of a flap valve controlled by the pilot. The heated air is obtained by admitting cold air through the louvres shown by the dotted lines above, in Fig. 39. This air passes over the hot parts of the engine before reaching the warm air inlet shown.

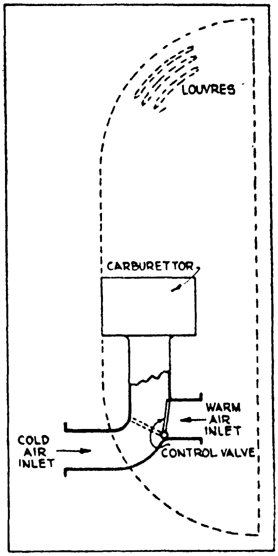


Fig. 39. Cold and warm air supply method.

Flame traps, consisting of wire gauze screens or a series of close concentric circles formed from corrugated metal strip, edgewise, over the main air intake are usually fitted to modern carburettors ; the object of these flame traps is to prevent back-fire flame through the carburettor igniting any combustible fuel vapour outside the air intake.

Under severe cold weather conditions the evaporation of the fuel from the jets may lower the temperature of the incoming air to such an extent that *snow or ice is formed on the throttle* and in *the induction manifold ;* the throttle may even become fixed by the ice so that means must be provided to overcome the trouble. In some instances, as in the S.U. carburettor, the throttle is made hollow and warm engine lubricating oil circulates through it. In other cases an automatic device supplies alcohol to the carburettor for the purpose of liquefying any ice formed, by lowering its freezing-point. A separate alcohol supply is introduced automatically, as soon as any ice tends to form in the inlet pipe, so as to prevent further solidification.

Fuel Injection. Modern aircraft carburettors are necessarily complicated, and, to some extent, bulky, as they have to provide for a wide range of operating conditions ; a further drawback is the icing-up tendency mentioned in the preceding section.

In order to simplify the method of fuel and air mixing and introduction to the engine a good deal of attention has been given to the alternative method of supply fuel direct to the cylinder during the suction stroke, when the cylinder is being filled with air. The fuel is injected under pressure through an injection nozzle, from which it emerges in the form of a fine spray.

The fuel injection system is identical in principle to that of the compression-ignition engine, but much lower injection pressures are employed. The engine uses the same compression ratio as for a carburettor-fed one, and the mixture of fuel and air is ignited by a spark from the sparking plug.

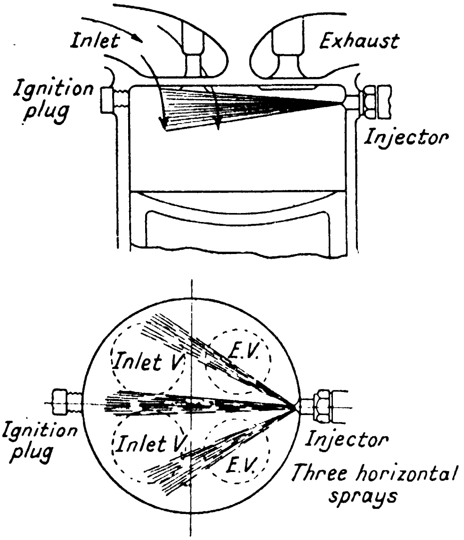


FIG. 40. Fuel injection system.

The advantages claimed for the fuel-injection system—which is a standard feature of German aircraft and one or two American engines—are as follows :—

(1) Better distribution of mixture to the cylinders ; each cylinder receives an equal amount of fuel. (2) Icing-up troubles are completely avoided. (3) No danger of back-fire. (4) Engine can work equally well in any position, as during aerobatics. (5) Rather higher volumetric efficiencies, *i.e.*, a greater quantity of charge can be introduced owing to the absence of carburettor ports and passages.

The disadvantages of the system are, briefly, as follows :—

(1) More complicated owing to provision of a separate fuel pump and injector for each cylinder. (2) Necessity of a separate power drive to the fuel pumps. (3) More bulky than a single carburettor

unit. (4) More vulnerable, as each cylinder must be provided with a separate fuel pipe from the fuel pump. (5) Less reliable for the same reason. (6) Greater maintenance attention necessary.

The modern carburettor has been developed to a high standard of reliability, automatic control and general performance in this country, and is considered to be fully satisfactory for present designs of aircraft engine.

In connection with the fuel injection system one method of application is illustrated in Fig. 40, which shows the cylinder head of an aircraft engine in side sectional and plan views; it has two inlet and two exhaust valves. The injection nozzle is provided with three holes giving three fuel sprays as shown in the plan view; this arrangement gives good penetration of the fuel into the air charge. The injection occurs during the suction stroke and the fuel spray tends to have a cooling action on the exhaust valve; this is an advantage over the carburettor mixture supply method.

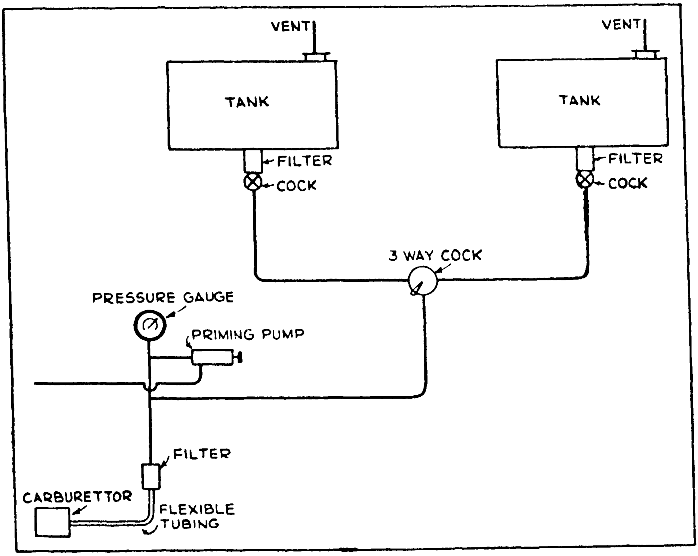


FIG. 41. Gravity fuel supply system.

In some instances the fuel is injected into the inlet valve ports and is there taken into the cylinder with the fresh air charge.

In supercharged engines the fuel may be sprayed in the form of a hollow cone into the air inlet orifice at the centre of the impeller of the centrifugal compressor; it then mixes with the inflowing air and the latter is then compressed and delivered to the cylinders.

Alternatively, only the air need be compressed and the fuel injected direct into the cylinder heads; the disadvantage of this method is that as the air becomes heated by compression it cannot be cooled by the evaporation of the fuel before it reaches the cylinder, so that a lower charge efficiency results.

(3) **The Fuel Supply System.** The fuel tanks of aircraft may be of the gravity or pressure feed patterns. The simpler arrangement, for light aircraft, is the gravity fuel tank one in which two separate fuel tanks of the same or unequal capacities are mounted above the carburettor—preferably in the wings—and fuel feed pipes lead from these tanks to a three-position master control cock (Fig. 41), which enables either tank to supply the carburettor independently of the other. The master cock is controlled by the pilot. Filters are provided at the outlets of each of the gravity tanks to ensure that no solid matter reaches the jets. A special hand-operated fuel pump, known as a *priming pump*, is fitted to provide a jet of fuel to the induction pipe for starting purposes.

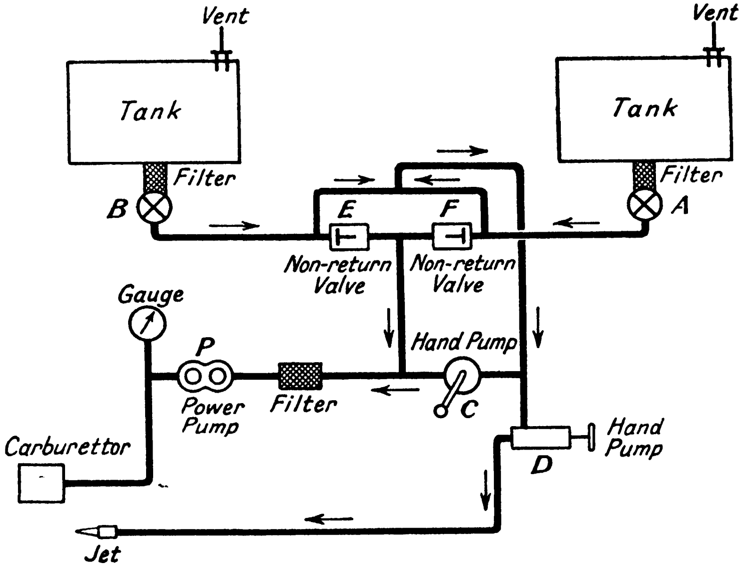


FIG. 42. Gravity and pump fuel supply system.

The lay-out of another fuel system is shown in Fig. 42. The fuel tanks are mounted in the wings and each tank has a fuel filter and cock, A and B, under the pilot's control, so that either tank may be used to supply fuel to the carburettor. An engine driven fuel pump P draws its supply from either tank through a fuel filter and non-return valve, E or F, in the direction shown by the arrows. The fuel is then pumped direct to the float chamber of the carburettor, a fuel pressure gauge being provided. Usually there is also a fuel pressure regulating valve to control the fuel pressure in the carburettor supply pipe; this is arranged to give from 1½ to 2½ lb. per sq. in. pressure.

A hand pump C is provided for the purpose of drawing fuel from either tank and pumping it direct to the fuel pump P (for priming purposes) and to the carburettor. Another hand pump D enables fuel to be injected into the induction manifold for starting purposes.

In practice, whilst the general principles of fuel supply outlined are followed, the detailed arrangements vary in individual instances.

The fuel feed pump P may be of the engine-driven automobile diaphragm pattern or of the gear-wheel type, similar to that of oil pressure supply pumps. The Amal duplex pump is an example of the former and the Rolls-Royce pump of the latter type. In certain designs of aircraft, fuel pumps were of the centrifugal kind, operated by means of a windmill placed in the slipstream of the airscrew.

CHAPTER IV

SUPERCHARGING AIRCRAFT ENGINES

General Considerations. It is necessary in the case of aircraft engines to obtain high outputs from relatively small sizes of engines so as to reduce the weight and bulk to a minimum.

In order to provide for a greater output from an engine of given cylinder dimensions, (1) The compression ratio can be increased, provided a suitable grade of fuel is available. (2) The two-cycle principle can be employed; or (3) The weight of the mixture of fuel and air per cylinder can be increased.

The high compression ratio engine gives a higher M.E.P. than the lower compression one, but is open to the objection of higher maximum cylinder pressures which necessitate stronger and therefore heavier engine components. The two-cycle aircraft engine has not yet challenged the four-cycle one, owing chiefly to practical design and constructional difficulties.

Four-cycle engines of the ordinary type, in which the charge is drawn into the cylinders by piston suction action, appear to have reached about the limit of performance in regard to mean effective pressures and engine speeds for the available grades of high octane fuels. In order, therefore, to obtain a greater output it is necessary to dispense with the usual piston-suction method of drawing in the charge of fuel and air and to employ, instead, a method of forcing the charge into the cylinders by means of a compressor; this is known as *the supercharging method*, and it is now universally employed for medium and large sizes of aircraft engines.

Principle of Supercharging. It has been pointed out that the normally aspirated engine can only draw a certain quantity of charge into its cylinders by engine suction alone. In this connection it should here be explained that the *volumetric or charge efficiency* of an engine is the ratio of the weight of the charge actually drawn into the cylinder, to the charge weight that would completely fill the cylinder at the outside air pressure and temperature; the cylinder volume, in each case, is the working volume plus the clearance volume.

Owing, chiefly, to obstructions met with by the air in flowing through the carburettor, inlet manifold and inlet ports, and to the premature heating of the charge by the hot surfaces of the cylinder, valves and pistons, the volumetric efficiencies obtained are seldom more than 80 per cent., *i.e.*, only 80 per cent. of the possible maximum charge is drawn in.

It has been demonstrated, experimentally and theoretically, that *the power output from a given capacity of cylinder is proportional to the weight of charge* in the cylinder, within certain limits. Thus, if the charge weight is increased by 50 per cent., then the power output is approximately 50 per cent. greater.

It has been shown, however, that as the weight of charge forced into the cylinder is increased, the maximum pressure of combustion also increases so that the engine stress-bearing parts must be made stronger.

Thus, in a typical example of a normally aspirated engine, the maximum cylinder pressure, with a compression ratio of 5 to 1, was 490 lb. per sq. in. and the indicated M.E.P. 140 lb. per sq. in. When the charge weight was increased by 50 and 100 per cent., the maximum pressures were about 735 and 980 lb. per sq. in. respectively; the corresponding indicated M.E.P. values were about 205 and 270 lb. per sq. in., respectively.

When an engine is supercharged *the maximum cylinder temperatures are also increased*, but to a much smaller extent; thus for a 100 per cent. increase in charge weight the *maximum* cylinder temperature, in the above example, was increased by only 140° C.

It should here be pointed out that since it requires a certain amount of power to drive the supercharger (or air compressor), it is necessary to deduct this power—which is supplied by the engine—from the total power developed as a result of supercharging, in order to obtain the net or effective power. In the case of a gear-driven centrifugal supercharger, the horse-power absorbed at ground level is from 6 to 8 per cent. of the maximum power developed at the rated altitude, *e.g.*, 12,000 to 15,000 ft.

The High Compression Engine. It may be of interest to compare

Comparison Between High Compression and Supercharged Engines

Type	Compression Ratio	Indicated M.E.P. lb. per sq. in.	Maximum Cylinder Pressure lb. per sq. in.
Unsupercharged engine .	5 : 1	126	455
Engine supercharged to 50 per cent. . .	5 : 1	157	595
High compression engine	11 : 1	154	1,000

the performance of a normally aspirated high compression engine with that of an engine or normal compression ratio supercharged to give about the same power output. The results shown in Table on p, 65 were given by A. H. R. Fedden, of the Bristol Aeroplane Company, for the unsupercharged, high compression and supercharged engines.

From these results it will be observed that the power outputs, which are proportional to the indicated M.E.P. values, are very nearly the same for the supercharged and high compression engines, but whereas the maximum cylinder pressure is 595 lb. per sq. in. in the former instance, it is 1,000 lb. per sq. in. in the latter, so that the engine would have to be made much heavier in order to withstand these high pressures.

Power Variation with Altitude. It has been shown that the power output of a non-supercharged engine depends upon the quantity of mixture drawn into the cylinder. A little consideration will indicate that the quantity of mixture depends upon the difference between the outside air pressure and the suction effect caused by the piston during its inlet stroke, which for present purposes may be regarded as constant.

As the outside air pressure diminishes, so will the quantity or weight of mixture diminish. Again, if the temperature of the outside air decreases the air density will increase and, for the same outside pressure, a greater quantity of charge will be drawn into the cylinder.

It follows, therefore, that the quantity of charge induced will depend upon the atmospheric pressure and temperature, *i.e.*, upon the atmospheric density. The power output, for most practical purposes, may be considered to be proportional to the air density, although for more exact purposes the following relation may be used :—

$$\text{H.P.} = k \times (\text{density})^{1\cdot 05} \text{ where } k \text{ is a constant.}$$

It may be mentioned that more recently the exact relationship has been shown to include both the atmospheric pressure and density terms.

For present purposes the power may be assumed to fall off progressively, as the density decreases, and as the latter diminishes with increasing altitude so the power falls off in a similar manner.

Thus at 10,000, 20,000, 30,000 and 40,000 feet, the H.P. of an unsupercharged engine will be about 74, 53, 37·5 and 25·5 per cent. of the H.P. at ground level; in each case the maximum full-throttle power output is considered.

Supercharging Terms. The degree of supercharging is denoted by the relation of the pressure of the charge in the cylinder at the end of the induction stroke to atmospheric pressure. Thus, if the pressure at the end of the induction stroke is 22·05 lb. per sq. in. and atmospheric pressure 14·7 per sq. in. the excess pressure is $22{\cdot}05 - 14{\cdot}7 = 7{\cdot}35$ lb. per sq. in. and the supercharge is then said to be $7{\cdot}35/14{\cdot}7 = 0{\cdot}5$ or 50 per cent.

Supercharging is employed in British aircraft engines *to compensate for the falling off in engine power* with increase in altitude, due to the decreasing density of the air. Except for taking-off purposes the engine throttle is kept partially closed after the aircraft leaves the ground, and it is opened progressively by automatic means as the aircraft climbs until at a certain altitude, namely, the *rated altitude*, the throttle is fully open and the engine is then developing its *rated power.* If the altitude is increased above the rated value, the power falls off; if the altitude is decreased, the throttle is gradually moved towards the closed position in order to limit the power output, *i.e.*, to maintain it at a practically constant value.

When *the machine is climbing* some increase of the normal lower altitude becomes necessary, namely, by increasing the supercharging pressure.

For aircraft purposes it is usual to specify the amount of supercharging in terms of the *boost pressure, i.e.*, the air pressure in the inlet manifold above the sea-level atmospheric pressure (14·7 lb. per sq. in.). Thus, a boost pressure of 5 lb. per sq. in. at ground level would indicate that the pressure in the inlet pipe was 5 lb. per sq. in. above atmospheric, *i.e.*, 14·7 lb. per sq. in., so that the total, or absolute pressure in the inlet manifold would be 19·7 lb. per sq. in. In regard to aircraft cruising conditions *the maximum cruising boost pressure* is specified as being that which gives not less than 90 per cent. of the sea level maximum power output. It is usual, also, to specify the maximum permissible engine revolutions per minute; these are allowed for periods of about five minutes.

As distinct from its use in maintaining the engine power practically constant up to the rated altitude, the supercharger has also been used—notably in the U.S.A.—to obtain an appreciable increase in the ground level power output over that of normally aspirated engines of similar dimensions. This method of application is known as *Ground Boosting.* Its success depends largely upon the use of high-octane fuels.

With the employment of positive pressure, *i.e.*, above atmospheric, for take-off purposes, the former method of using the super-

charger to maintain power up to the rated altitude appears to have definite advantages.

As previously stated the power of an engine falls off progressively as the altitude increases. Thus an unsupercharged engine developing, say, 700 B.H.P. at ground level, will develop about 420 B.H.P. at 15,000 ft. and about 370 B.H.P. at 20,000 ft. Similarly, a ground-boosted engine, developing its maximum power at ground level will show a corresponding falling off in power at altitudes. The ground-boosted engine is usually heavier than the rated height one and the higher the degree of supercharge the greater is the power-to-weight ratio.

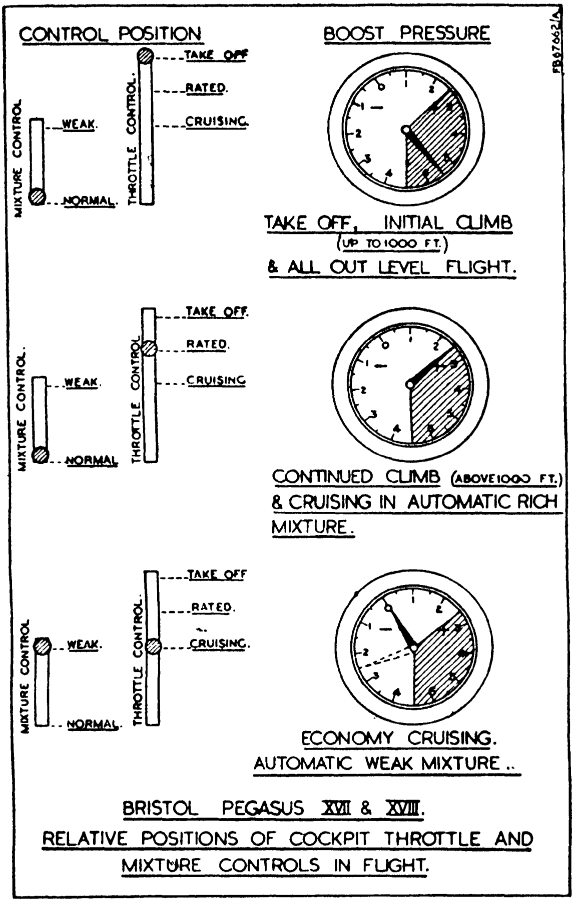


FIG. 43. Boost pressure readings and throttle control positions.

Boost Pressure Gauge. This gauge is mounted on the pilot's instrument board and is connected up to the inlet manifold between the supercharger and the inlet valve. It is graduated in pounds per square inch and shows the difference between the absolute pressure in the inlet manifold and ground or sea-level atmospheric value. When the engine is at rest the gauge reads zero, but when developing an appreciable proportion of its maximum output it shows positive readings. Thus, at full power, it would show its *maximum boost pressure* value. If, for instance, this was 7 lb. per sq. in., this would indicate an absolute pressure of $14{\cdot}7 + 7 = 21{\cdot}7$ lb. per sq. in. at sea-level; as the aircraft climbs this boost pressure reading, namely, 7 lb. per sq. in., would remain constant up to the rated altitude, above which it would begin to decrease. When the engine is idling on the ground the pressure within the inlet manifold will be less than atmospheric pressure, due to the throttle being almost shut and only a small fraction of the full charge being taken into the cylinders. The boost pressure gauge then gives a *negative reading*; the latter is also shown when the engine is throttled down in flight in order to fly at a slower speed. Thus, if the boost pressure gauge were to show a negative reading of 1 lb. per sq. in. at sea-level, this would mean that the absolute pressure within the inlet manifold was $14{\cdot}7 - 1 = 13{\cdot}7$ lb. per sq. in.

It should here be mentioned that American aircraft employ boost pressure gauges graduated to read the *absolute inlet manifold pressures* in terms of inches of mercury. In this connection it is useful to remember that the standard atmosphere at 15° C = 14·7 lb. per sq. in. = 29·920 in. of mercury and that 1 lb. per sq. in. = 2·040 in. mercury at 15° C.

When the engine is at rest the American boost pressure gauge reads 29·920 in. For a positive boost pressure of 7 lb. per sq. in. it would read

$$29{\cdot}920 + 7 \times 2{\cdot}040 = 29{\cdot}92 + 14{\cdot}28 = 44{\cdot}20 \text{ in. mercury.}$$

Boost Pressure and Throttle Control. As mentioned previously, the maintenance of full power at any given rated altitude necessitates restricting the engine output at lower altitudes, for if the throttle were opened to its full extent under the latter conditions excessive cylinder pressures and temperatures would result that might cause damage to the engine. It will be seen that if manual control of the throttle is employed there will always be a risk of opening the throttle too wide at lower altitudes. In order to prevent this supercharged engines were previously fitted with definite stops or " gates," so that in conjunction with the altimeter readings these stops could be opened in succession as the machine attained the corresponding altitudes. Whilst satisfactory for many civil machines, this method has obvious drawbacks for military ones which have to be used for manœuvring and other purposes involving frequent change of altitude.

In order to do away with the manual control and thereby relieve the pilot of frequent attention to " boost " pressure maintenance the automatic control of inlet manifold or " boost " pressure was instituted.

This automatic control utilises the expansion or contraction of barometric capsules, under the influence of inlet manifold pressure, to operate a kind of piston valve which can admit oil (usually from the engine pressure lubrication system) to one side or other of a servo piston in a cylinder. The outer end of the piston rod is connected, by a suitable linkage, to the throttle-operating mechanism in such a way that it tends to close the throttle independently of the pilot's hand control when the engine is working at altitudes below the rated one. Thus, if the throttle hand control is moved to the wide open position when the machine is on the ground with engine running, the automatic control almost at once closes the throttle to the safe maximum power output position for ground conditions. As the machine climbs towards its rated height, *i.e.*, the maximum altitude at which ground inlet pressure can be maintained by the supercharger, the automatic control opens the throttle gradually until at the rated height it is fully open. Above this altitude it is impossible to maintain ground inlet pressures, and the power then falls off progressively with further increase in altitude.

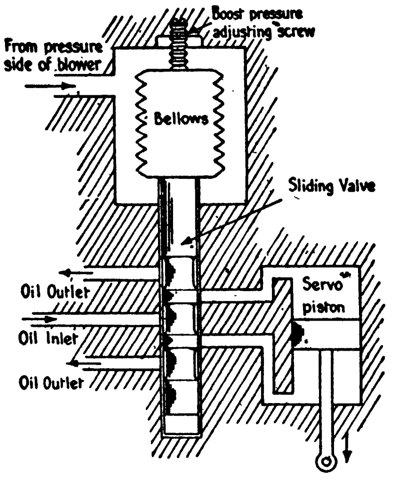


FIG. 44. Principle of induction boost pressure control.

The Hobson method of applying boost control is shown in Fig. 44 ; it employs the principle of maintaining a constant inlet manifold pressure up to the rated altitude by progressive throttle opening or closing. The control consists of an airtight chamber having a connecting passage with the delivery side of the supercharger or " blower." Inside this chamber is arranged a set of barometric capsules which expand or contract with changes of external pressure and thus alter in overall length. One end of the capsule unit is fixed and the other connected to a piston valve (Fig. 44) ; the latter admits oil under pressure to the upper or lower side of the servo cylinder.

The arrangement shown is such that under ground level conditions the oil is admitted to the upper side of piston when the induction pressure is increased—as by opening the throttle fully on the ground. The servo piston is thus forced downwards and the connecting rod attached tends to shorten the connecting links between the pilot's throttle lever and the carburettor throttle, thus moving the latter in an anti-clockwise direction, *i.e.*, towards the closed position.

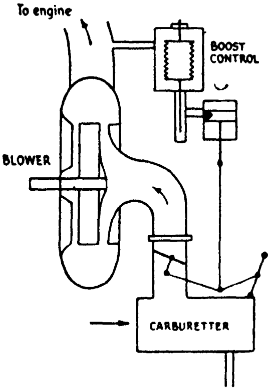


Fig. 45. Operation of boost control and carburettor connections.

The arrangement described for automatic boost control results in *a certain amount of idle movement of the pilot's throttle lever* at altitudes below the rated one. Thus, at ground level, the throttle may be open by only one-half of its full travel, due to the operation of the boost control device, but the pilot's throttle lever can be pushed over to its " full-open " position, although the last half of its movement has no effect on the engine's output. In order to eliminate this *lost motion* a device known as a *variable datum boost control* is employed.

The method in question consists in varying the boost pressure by means of a cam (in place of the usual adjusting screw) operated by the pilot's throttle lever. It will be seen that full boost pressure at ground to rated height can only be obtained with the pilot's lever fully open and that each partial movement of the lever will alter the boost pressure in proportion to the angle of movement of the pilot's lever. In this way the latter lever can be used in an identical manner to that of an unsupercharged engine.

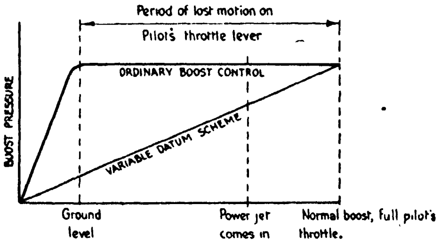


Fig. 46. Boost pressure throttle opening curves.

A refinement to this arrangement is to have the power jet brought into action by the pilot's lever instead of the throttle lever. The difference between the boost pressure-throttle opening curves of the earlier and the later variable datum boost control systems is shown in Fig. 46. In the earlier system the boost pressure rises suddenly to its full value at a comparatively small throttle lever opening, the rest of the lever's movement being lost motion. In the latter method the full range of throttle movement is required for the full boost pressure, there being no lost motion. Further, it renders possible better control of engine speed under certain cruising conditions and full power output on a cruising mixture strength, or without the power jet in action.

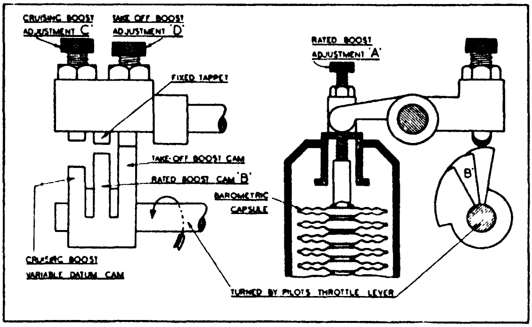


FIG. 47. Three-stage automatic boost control.

With the earlier method, if the pilot left his throttle lever at any position between ground level and the power jet opening one, it was possible to obtain full boost with a weaker mixture. This undesirable state of affairs is associated with excessive cylinder and piston temperatures. The variable datum boost method, however, obviates this disadvantage.

When the engine is to be used for taking-off, it must develop its maximum power for a short period, and for this purpose the carburettor must provide a 15 to 20 per cent. rich mixture; in addition the throttle must be rather more widely open. As the boost control regulates the throttle opening at ground level it is necessary to provide some form of over-riding control to obtain the greater throttle opening required. This control can be effected either by a fairly simple mechanical device or by the provision of an air leak. In the former method the capsule unit is moved mechanically away from the adjustment end.

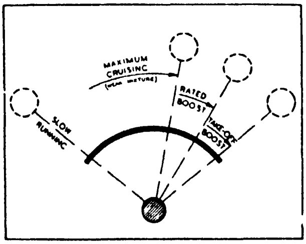


FIG. 48. Arrangement of pilot's throttle lever for three-stage automatic boost control.

The *air leak method* consists in the provision of a controllable leakage from the capsule chamber, thus reducing the boost pressure by a small amount, sufficient to enable the capsule unit to operate the servo motor piston valve and thus to open the throttle a little. The leakage occurs through a pipe leading to the suction side of the blower. By the use of a small jet of the "plate" type on the capsule chamber and a venturi type of jet on the outlet pipe it is possible to ensure an exact drop of pressure in the capsule chamber

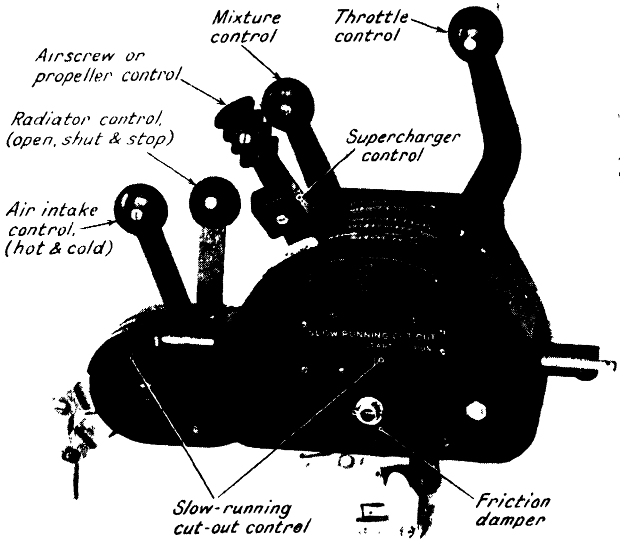


FIG. 49. Pilot's cockpit engine controls, for Hobson carburettor.

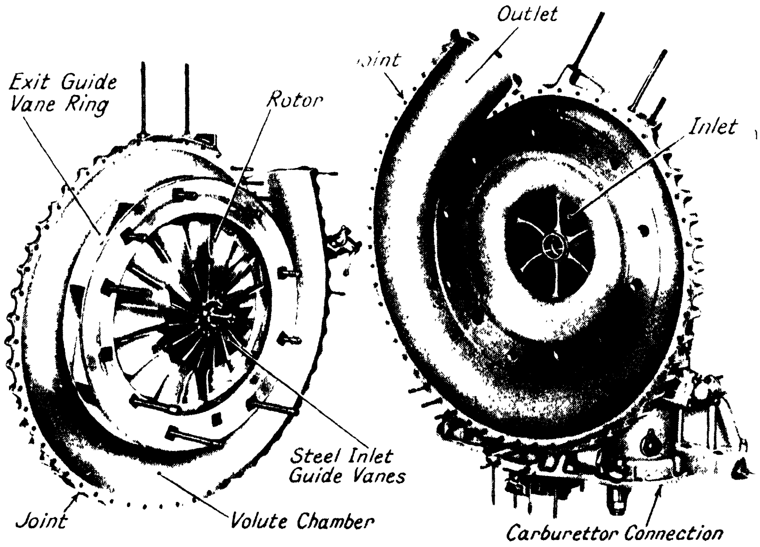


FIG. 53. The Rolls Royce single stage centrifugal supercharger components.

each time the over-ride valve is opened, under varying temperature conditions.

Three-stage Automatic Boost Control. It has been shown that it is necessary to provide three distinct mixture strengths to suit the engine requirements for take-off (extra rich), maximum power (normal rich) and cruising (weaker mixture) ; this has led to the production of a special control system, known as the *Hobson three-phase boost one.* With this system each range of boost pressure is given its appropriate mixture strength. The whole capsule assembly is given three distinct displacements in order to provide the three different mixture ratios. These displacements are obtained by means of three separate cams of varying lifts.

As will be seen from Fig. 47, three cams are fitted to the pilot's throttle lever shaft, and each of the three tappets will, in turn, come into contact with, and ride upon, the cam, depending upon the position of the throttle lever. In the position shown, the take-off boost cam and tappet are in contact and the barometric capsule is compressed by the fork end of the rocker arm to control the take-off boost.

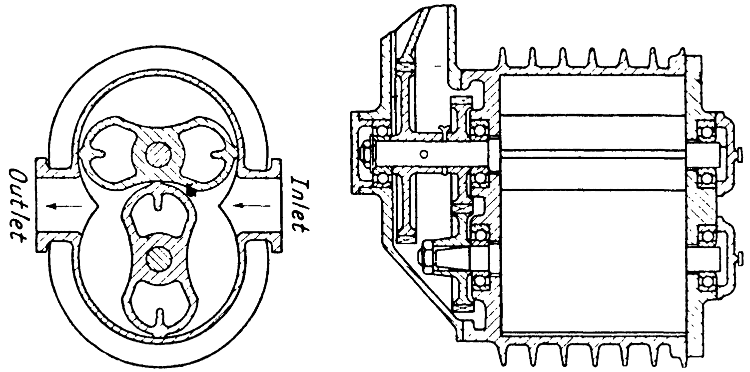


FIG. 50. The Roots type supercharger.

The effect of this arrangement is the same as if an ordinary variable datum boost were fitted with a cam having three definite stages of dwell, corresponding to maximum weak mixture cruising boost, rated boost and take-off boost. The arrangement shown in Fig. 47 enables each of the three boost pressures to be adjusted individually.

Types of Supercharger. The aircraft supercharger, or compressor, must be both light in weight and efficient in operation, the minimum amount of maintenance attention being necessary.

There is a fairly wide range of air compressors available in engineering practice, but for various reasons the only types suitable for aircraft engines are the *displacement* and *centrifugal* compressors.

The *displacement type*, of which the Roots model is a typical example, consists of a pair of similar rotors with two or three lobes or " teeth," which run together like a pair of gear wheels always with line contact of the moving surfaces; the rotors are geared externally and revolve in opposite directions and only one is driven off the engine. The effect of operating these rotors in a double cylindrical casing (Fig. 50) is to draw air in on one side of the casing and to expel it at the opposite side under pressure. In Fig. 50 the lower rotor revolves in a clockwise and the upper one in an anti-clockwise direction. The space between the lower rotor and its casing below contains air drawn in from the inlet opening. As the rotor revolves it sweeps this air around and delivers it to the outlet side; thus at every revolution of the two rotors four times this quantity of air is delivered.

In practice the rotor casing consists of a magnesium or aluminium alloy casting machined to requirements. The rotors, which are either of similar alloys or thin steel, are of involute form or special cycloidal " rolling " curves. They do not actually touch the casing, there being a very small clearance, namely, of the order of a few thousandths of an inch, whilst the flat ends of the rotors have clearances of one- to two-hundredths of an inch.

This type of supercharger, which has been used both in this country and the U.S.A., is usually operated at engine speed or 1½ times this speed.

The principal advantages of the Roots compressor are as follows:—(1) It is of very simple construction and therefore inexpensive. (2) It has no wearing parts other than the end bearings, and thus has a comparatively long life. (3) It has a high volumetric efficiency under maximum discharge pressure conditions. (4) It can deal with comparatively large volumes of air without becoming too bulky for aircraft engine requirements. (5) It can be balanced accurately for high speeds. (6) At lower altitudes by a simple control the air delivered can be by-passed so that the power needed to drive it is reduced, less air being then supplied to the engine.

Its chief disadvantages are that: (1) Pressure pulsations tend to occur owing to the periodic discharges of the displaced air, between the rotor and its casing. (2) The clearances must be kept accurately or leakages will occur. (3) At higher delivery pressure values the operating efficiency tends to fall off. (4) It is not a convenient design for use on radial engines.

More recently, despite its other advantages, the Roots type of supercharger has been superseded by *the centrifugal compressor pattern* in all British and most American and Continental aircraft engines.

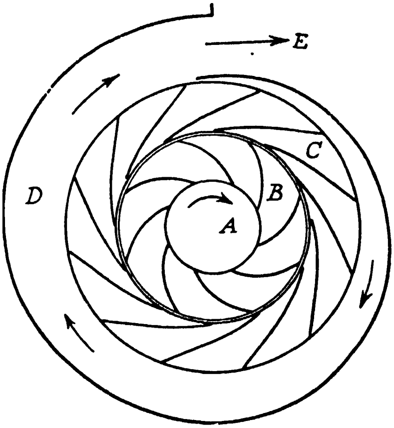


FIG. 51. Illustrating principle of centrifugal compressor.

The compressor consists of a rotor A (Fig. 51), having a series of straight or curved vanes B, which is rotated at very high speeds within a casing of annular or hollow ring shape. Air is thereby drawn in at the central portion of the rotor and expelled by centrifugal action from the ends of the blades, tangentially through curved vanes into the discharge casing D and out to the engine at E. The air has a very high velocity as it leaves the ends of the blades and it is discharged through a set of curved blades C (Fig. 51) which are arranged with their inner ends tangenital to the periphery of the rotor so that the air enters the spaces between them without shock. These vanes, known as *diffusers*, are designed to convert the velocity energy or " head " of the air into pressure " head " as efficiently as possible. In order to obtain the required boost pressures it is necessary to run the rotor at comparatively high speeds, namely, at eight to twelve times engine speed, that is, at speeds ranging from about 15,000 to 25,000 R.P.M. On account of these high speeds any acceleration effects or sudden changes of engine speed would cause serious inertia stresses

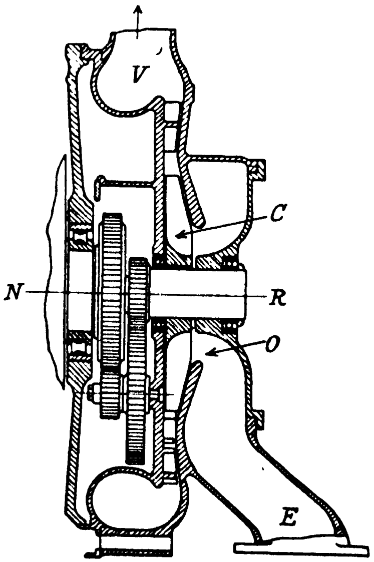


FIG. 52. Method of driving centrifugal supercharger.

C—supercharger rotor. E—air inlet. O—entrance to centre of rotor. V—outlet to engine from volute chamber. N—engine crankshaft. R—rotor shaft.

in the rotor drive so that with gear-driven rotors it is necessary to fit some form of slipping clutch between the engine drive and the rotor.

Fig. 52 illustrates a gear-driven centrifugal type supercharger as used on one of the Bristol air-cooled radial engines. On account of its circular form this type fits in satisfactorily with the design requirements of both radial and "in-line" cylinder aircraft engines.

In regard to *the position of the carburettor*, this is arranged so as to communicate direct with the central inlet side of the centrifugal compressor so that the latter actually compresses the fuel-air mixture. This method has the advantage of providing a cooling action due to the latent heat of evaporation of the fuel, which counteracts largely the heating effect due to the compression of the air which, otherwise, would reduce the charge efficiency.

The centrifugal supercharger usually weighs about one-hundred and fiftieth of the dry engine weight.

The single-speed type has the disadvantage of running at too high a speed for low altitude purposes, although it requires this high speed for take-off purposes. In order to obtain an improved performance superchargers are now fitted with a *two-speed gear system*, which is usually operated by hydraulic means and provides a lower speed for lower altitudes and a higher one for take-off, maximum climb and rated-altitude purposes. The gear-driven centrifugal supercharger is satisfactory for maintaining power up to heights of 15,000 to 20,000 ft., but above these altitudes becomes less effective.

A Typical Supercharger. The Rolls-Royce centrifugal supercharger shown in Fig. 53 * has a 16-bladed impeller of forged aluminium alloy with a separate steel inlet guide member provided with curved vanes; this is seen by the blacker portion in the centre of the left-hand illustration. The rotor shaft, of alloy steel, is carried on a ball-bearing at the front end and on two specially-grooved floating bushes at the rear. The fixed guide vanes (corresponding to those shown at C in Fig. 51) are shrouded, *i.e.*, provided with side shields to prevent end losses; the guide vanes and shrouds can be seen on the left, carrying the stud members. The casing, which is made in two halves from light alloy castings, is of spiral section, to allow for the increasing volume of delivered air (or mixture) towards the outlet. The two halves of the casing are bolted together by means of a relatively large number of bolts and nuts.

The two-speed gear drive used is of the sun-and-planet wheel, or epicyclic gear pattern.

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* Facing page 72.

In cases where *high degrees of supercharging* are necessary the centrifugal compressor can be made in several stages or units, the discharge of the first being taken to the inlet of the second; the discharge of the second to the inlet of the third; and so on. The more recent Rolls-Royce Merlin 61 engine is fitted with a two-speed, two-stage centrifugal supercharger which has two rotors, such that the discharge of the first is directed into the central opening of the second stage. The boost pressure can thus be maintained to much higher altitudes than with the two-speed single stage model. In order to reduce the heat of compression, a mixture cooling device, known as an *intercooler* is fitted between the outlet of the second stage and the induction manifold.

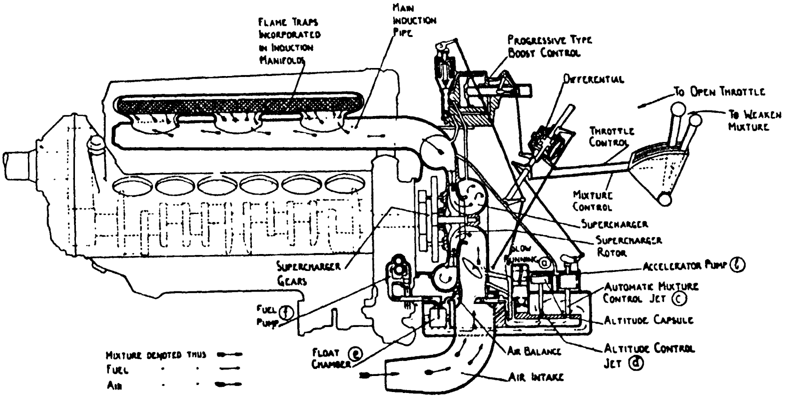


FIG. 54. Complete carburettor and single stage, two-speed centrifugal supercharger installation of the Rolls Royce Merlin engine.

Exhaust-driven Centrifugal Superchargers. The chief drawback of the gear-driven supercharger is that it absorbs an appreciable amount of power from the engine, so that the net supercharged output of the latter is reduced. In addition it tends to be noisy owing to the gearing operating at high speeds. In order to overcome these disadvantages, the rotor of the supercharger is driven by means of a high-speed turbine which derives its power from the energy of the exhaust gases as they leave the cylinders. The turbine used is generally of the Rateau type, consisting of a solid rotor having turbine blades around its periphery; the exhausted gases flow across or through the blade spaces in a direction parallel with the axis of the rotor. With a properly designed exhaust turbine system, not only is no power absorbed, but the efficiency of the engine is increased by the utilisation of some of the exhaust energy that, otherwise, would be wasted. The effect of connecting an exhaust turbine to a petrol-type engine is to increase the back pressure in the exhaust gas system so that there is a small loss of power in the engine, which must be offset against the gain due to the utilisation of part of the exhaust gas energy. Further, as the difference between the exhaust and outside atmospheric pressures increases with altitude the speed of the turbine rotor also increases so that the centrifugal compressor " boost " pressure actually tends to increase. At ground level the exhaust back pressure is usually arranged to be a little higher than the compressor delivery, by about 0·5 to 1·0 lb. per sq. in.; as the machine climbs the boost pressure is practically self-regulating.

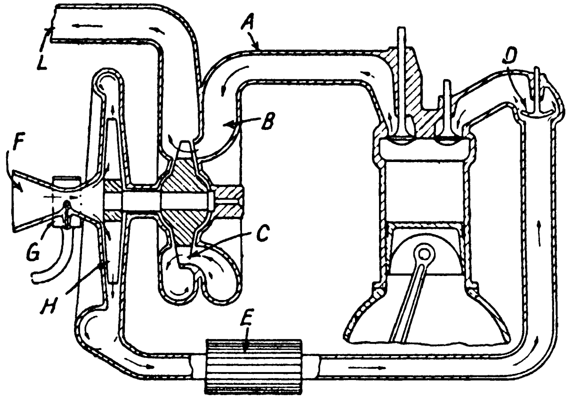


FIG. 55. Arrangement of exhaust gas-driven supercharger.

The design of the exhaust turbine involves the overcoming of distortion and other difficulties due to the high exhaust gas temperatures, namely, from 650° to 750° C., but high strength corrosion-resistance steels are now available for this purpose. The arrangement of a typical exhaust turbine system is shown, schematically, in Fig. 55 in which the centrifugal compressor draws both air and petrol from the carburettor G, having an air intake at F. The mixture is delivered by the rotor H to an intercooler E, whence it passes along a suitable duct, past an automatic blow-back valve D to the engine. The exhaust gases flow through the receiver A and nozzles B to the turbine wheel C and thence to the exhaust pipe L and silencer. In reference to the valve D, the object of this is to isolate the intercooler, supercharger and carburettor from the engine in the event of a backfire.

In regard to the maximum allowable speeds of the turbine rotor, these are limited by the strength of the material employed. With modern high-strength, heat-resisting, non-corroding alloy steels, which will withstand fairly high working stresses at the exhaust temperatures, the maximum tip speeds of the rotor can lie between 1,000 and 1,4000 ft. per sec.

The exhaust turbine centrifugal supercharger has been shown to be superior in performance to the gear-driven one at higher altitudes, namely, 20,000 ft. and above.

CHAPTER V

THE COOLING OF AIRCRAFT ENGINES

Some General Considerations. It can be shown from theoretical considerations of the efficiencies of internal combustion engines, that the maximum thermal efficiencies are obtained when there is the greatest difference between the initial and final temperatures of the working charge.

Thus, if T_0 and T_1 are the initial and final temperatures on the absolute temperature scale, then the theoretical efficiency E is given by the following relation :—

$$E = 1 - \frac{T_0}{T_1}.$$

Thus if the initial temperature is 17° C. (290° absolute) and 533° C. (806° absolute), corresponding to an initial pressure of atmospheric (14·7 lb. sq. in.) and final pressure of 500 lb. sq. in. then :—

$$E = 1 - \frac{290}{806} = 1 - 0{\cdot}36 = 0{\cdot}64 \text{ or } \textit{64 per cent.}$$

In practice, owing to a number of circumstances that include factors such as the variable specific heats of the cylinder contents, modification of the cycle to working conditions, heat losses to the cylinder walls, etc., it is not possible to realise such high efficiencies.

The final temperatures, corresponding to T_1 in the above formula, are much lower in practice, owing chiefly to the heat lost to the exhaust gases, the cylinder walls and by radiation, so that on these accounts the actual efficiencies obtained are lower.

The temperatures of the cylinder walls, cylinder head, piston crown and the *exhaust valve head* must, in practice, be kept down to certain maximum values, in order to avoid detonation with, in some instances, pre-ignition effects ; other associated disadvantages of excessive cylinder temperatures are lubrication troubles and a tendency to " burn " the piston crown and exhaust valve head.

It has been shown that if the *total heat energy of the fuel-air charge* be represented by 100, then in the case of a well-designed high-speed petrol engine having a compression ratio of 7 to 1, the heat energy of the fuel is disposed of as shown on next page :—

Heat Balance Values

Heat utilised as useful mechanical power (I.H.P.)	38·0
Heat lost through the cylinder walls . .	24·3
Heat lost to the exhaust gases . . .	34·5
Heat lost by radiation	3·2
	100·0

As the compression ratio is increased, assuming that there is no detonation, the percentage of heat utilised as useful mechanical power increases and the other losses diminish progressively. Similarly, as the engine speed increases from relatively low to high values, this percentage increases until a certain maximum speed is reached.

Possible Improvement of the Petrol Engine. Although, as will be noted from the preceding table, about 60 per cent. of the energy of the fuel is actually lost in so far as useful work is concerned, it is not possible to recover much of this, except by indirect means, such as by utilising some of the energy of the exhaust gases to operate an exhaust turbine or by exhausting the gases into a second larger diameter cylinder, corresponding to the low pressure cylinder of a compound steam engine.

Some improvement has been effected, in the instance of aircraft engines by the use of special non-detonating (or very high octane) fuels that enable higher compression ratios to be employed; by special designs of combustion chamber that permit higher compressions to be used for a given grade of fuel than for orthodox designs; and by the use of specially cooled exhaust valves which allow somewhat higher cylinder temperatures or rather compression ratios to be employed without detonation. Here, it may be mentioned that the sleeve-valve engine is notable for high efficiency, on account of the absence of hot exhaust valves.

If the heat balance values for various types of aircraft engine are analysed it will be found that between 24 and 30 per cent. of the heat of combustion of the fuel is absorbed by conduction through the cylinder walls and by radiation. Of these "losses," part is transmitted by conduction through the pistons and connecting rods and from the cylinder block to the crankcase, where it goes to heat up the lubricating oil; some of this heat is lost by radiation and convection to the outside air. In this way about 10 per cent. of the cooling losses is accounted for.

The remaining 15 per cent. is disposed of by conduction through the cylinder walls to the cooling liquid in the cylinder jackets, or—in the case of air-cooled engines—to the cooling fins and thence to the air cooling stream. With liquid-cooled engines, the liquid from the jackets is conveyed to *radiators* through which cooling air passes so that in each case *air is the final cooling medium.*

For practical design purposes it may be taken as being sufficiently accurate to assume that from *50 to 60 per cent. of the heat equivalent of the B.H.P. of an aircraft engine must be disposed of by the cooling system.*

The quantity of heat to be dealt with by the cylinder cooling system, whether air- or water-cooled, may be estimated, approximately, as follows :—

Let w = fuel used in lb. per B.H.P. per hour. C_F = calorific value of fuel in B.T.U.'s per lb.

Then total heat energy of fuel = wC_F B.T.U.'s per hour.

Assuming that 25 per cent. of the heat energy is recoverable as useful work on the piston, *i.e.*, as B.H.P., and that 60 per cent. of this represents the heat to be dealt with by the cooling system, we have :—

Heat dealt with by cooling system per minute.

$$= \frac{0{\cdot}25 \times 0{\cdot}6wC_F}{60}$$

$$= \frac{wC_F}{400} \text{ B.T.U.'s per B.H.P. per min.}$$

Thus in the case of an engine using 0·5 lb. of petrol (of calorific value, 18,600 B.T.U.'s per lb.) per B.H.P. per hour :—

Heat dealt with by cooling system = 23·25 B.T.U.'s per B.H.P. per min.

In practice the value in question varies between about 25 and 30 for aircraft engines running on ordinary fuels, but with high octane fuels and high compression ratios, the proportion of the heat to be dealt with by the cooling system diminishes.

Owing to the fact that *compression-ignition engines* have appreciably higher thermal efficiencies than petrol ones, more of the heat energy of the fuel is converted into useful power and there is therefore a smaller proportion to be disposed of by the cooling system. The cooling pins or radiators for these engines can thus be of smaller area than for the petrol engine.

Air-cooled Engines. The cooling method employed in aircraft engines is to provide the cylinder barrel and head with a number of relatively thin metal fins to conduct the surplus heat from inside the cylinder through these fins to the outside air, where it is carried away by a stream of air, due to the forward movement of the aircraft or, when stationary on the ground, to the airscrew slipstream.

It has been shown, as a result of experimental investigation that the heat lost in air-cooled engines varies as :—

(1) The mean temperature difference between the cooling fin surface and the air.

(2) The total area of the fin surface, if the fins are not pitched too close together.

(3) The degree of roughness of the fin surface.

(4) The nature of the metal used for the fins. Thus Dr. Gibson has shown that a steel surface gave from 5 to 10 per cent. greater heat dissipation than an aluminium or copper one, although the two latter metals are much better heat conductors than steel. If the fins of cast aluminium cylinders were given a coating of stove enamel, the heat dissipation was improved over that of the plain metal by about 10 per cent.

(5) The velocity of the cooling air stream.

It has also been shown that the cooling fins should not be too long in relation to their pitch, or distance apart, although their thickness may be reduced to the smallest practical manufacturing limits. In this connection the pitch of the fins should not be less than ¼ to ⅙ in.

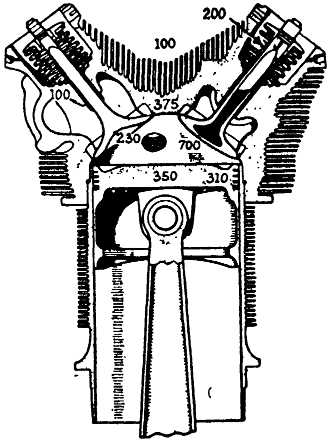


FIG. 56. Temperatures in air-cooled petrol engine.

The cooling areas of modern radial engines usually lies between 22 and 27 sq. in. per h.p., so that a 1,000 h.p. engine would have a total cooling area of 150 to 180 sq. ft.

In regard to fin dimensions, for a cylinder of about 6 in. diameter the steel barrel fins would be about 1 in. long tapering from $\frac{1}{16}$ in. at the root to $\frac{1}{32}$ in. at the tip. The pitch of the fins would be about ¼ in. For aluminium cylinder heads the fins would be from 1¾ to 2¼ in. long tapering from about ⅛ in. to $\frac{1}{16}$ in. ; the pitch would be ¼ in. to ⅜ in.

Cylinder Temperatures. The hottest parts of an air-cooled cylinder unit are the areas around the exhaust valve seatings and the piston crown at the centre; the coolest parts are the barrel and in the vicinity of the inlet valve seating. Fig. 56 will serve to give a general idea of the cylinder temperatures of an air-cooled engine, but it should be pointed out that there is an appreciable variation in the temperature distributions of engines of different designs and under various operating conditions.

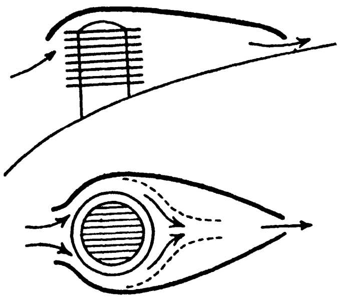


FIG. 57. Method of cooling light aircraft air-cooled engine.

Methods of Air Cooling. In view of the relatively large head resistance of an air-cooled engine it is now no longer the practice to allow the cylinder heads and parts of the barrels to protrude from the fuselage or power unit into the relative air stream, for cooling purposes, as in earlier practice. The greatly improved efficiency of modern high-speed aircraft has been due in part to the results of researches upon different types of engine cowling and baffles for directing the cooling air on to the hotter parts of the cylinders. Thrusting out

In the instance of smaller engines for light low-speed aircraft the cylinder heads are sometimes allowed to protrude from the fuselage nose portion and are cowled with streamline-type sheet metal fairings having entrances and exits for the cooling air as indicated in Fig. 57. The air exits should be chosen to correspond with regions of low pressure on the fuselage surface, in order to reduce the resistance of the cowling. casing directing [illegible] stream

The method of cooling small "in-line" engines is more difficult than with radial ones, as the rear cylinders, being masked by those in front tend to remain hotter. One method of cooling a 6-cylinder "in-line" engine, that provides for a good design of fuselage or power unit nose, is shown in Fig. 58. It employs the method of a pressure region entrance and a lower pressure region exit for the cooling air, with a suitable arrangement of sheet metal baffles at the exit side of the cylinders, to deflect the cooling air around the backs of the barrels and heads.

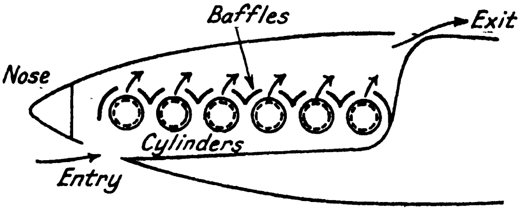


FIG. 58. Method of cooling 6-cylinder "In-line" engine.

In this connection it should be mentioned that it is always more difficult to cool the rear portions of air-cooled cylinders of all types of engines and that baffles are generally employed for this purpose; otherwise, if the fronts and backs are at widely differing temperatures cylinder distortion will occur.

The method of cooling the Gipsy air-cooled 12-cylinder inverted Vee engine is illustrated in Fig. 59 in plan view and Fig. 60 in side view.

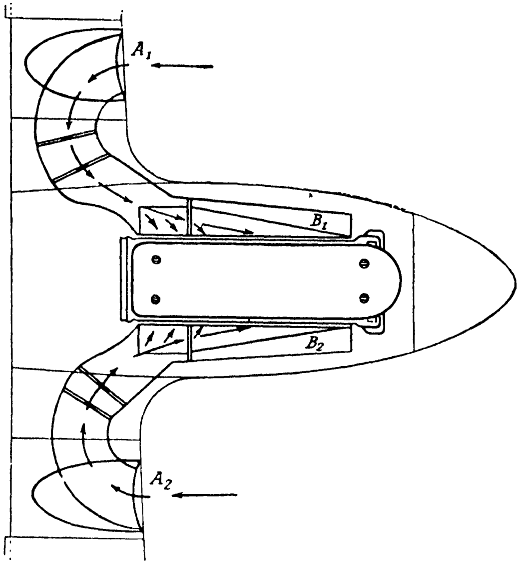


FIG. 59. Cooling system used on "Gipsy Twelve" engine (plan view).

The engine has a circular cowling which terminates at the front in an airscrew spinner, without break of line so as to give an efficient profile or clean entry. The cooling air entry for the engine is located about three-quarters of the radius of the airscrew from the centre, *i.e.*, in the most intense part of the slipstream, by means of orifices made in the leading edge of the wing; this arrangement is equally suitable for fuselage and wing-mounted engines.

The air is forced at pressure to galleries outside the banks of six cylinders through ducts which follow an easy sweep and are unobstructed by auxiliary units. Thence it flows over the fins of the cylinders and cylinder heads to the space between the banks and is exhausted downwards and rearwards. In aircraft of high-speed range *the air flow must naturally be controlled,* for if the cooling is effective when climbing at, say, 100 m.p.h., it will be excessive when cruising at more than 200 m.p.h. and will create unnecessary drag and reduction of speed. Material economy of power is achieved by limiting the air flow to the cooling requirements. Control of the air flow is effected in the case of the Gipsy engine by an air-exit gill located in the most efficient position for minimum interference and drag, namely, on the underside of the engine nacelle. In the fully-open position for take-off this gill induces a suction which assists the slipstream pressure in forcing the air over the engine. In cruising conditions the gill is nearly closed to restrict the airflow to the desired rate, at the same time greatly reducing the drag.

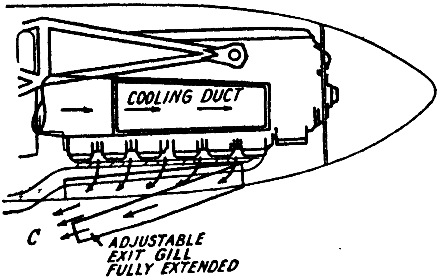


FIG. 60. Cooling system used on "Gipsy Twelve" engine (side view).

Referring to Fig. 59 air enters the openings A1 and A2 in the leading edge of the wing, and from there is led through fixed ducts to scoops or galleries B1 and B2, one on the outside of each bank of cylinders.

These scoops or galleries, which are designed to be removable in the airframe, for access to the sparking plugs, are joined to the fixed ducts in such a way that movement of the engine in the air-frame cannot impose any load on the fixed ducts or on themselves. The joint is made airtight to avoid putting the air in the engine bay under pressure.

After passing between the cylinder and head cooling fins, the air escapes downwards and rearwards through a pipe having a controllable flap valve outlet, shown at C in Fig. 60.

Radial Engines. The efficient cooling of radial engines with their relatively large frontal areas has been effected by the provision of nose cowlings or " rings " of special design which not only ensure the full flow of cooling air but also reduce the total fuselage or power unit air resistance. In addition to these exterior cowlings the cylinder heads and barrels are provided with special baffles for directing the cooling air around the hotter parts of the cylinder units.

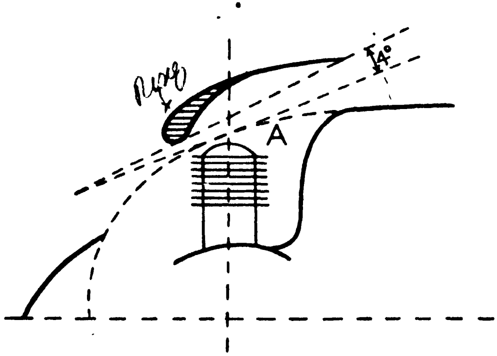


FIG. 61. The Townend ring cooling method.

One of the more efficient radial engine cooling systems is the Townend ring, shown diagrammatically in Fig. 61. This ring, which is shown shaded, is of high lift aerofoil section, with a thick nose and thin tail portion. It is fitted with its mid-chord over the central plane through the cylinder bank A normal to the engine axis and is in the " no-lift " position. The results of tests made upon aircraft show an appreciable increase in the top level speeds as a result of fitting this ring.

Another design of radial engine cooling cowling is that known as the N.A.C.A., developed—in various forms—by the American National Advisory Committee for Aeronautics. As with the Townend ring the air entrance and exit orifices are arranged to provide a minimum amount of cooling air to give the maximum cooling efficiency.

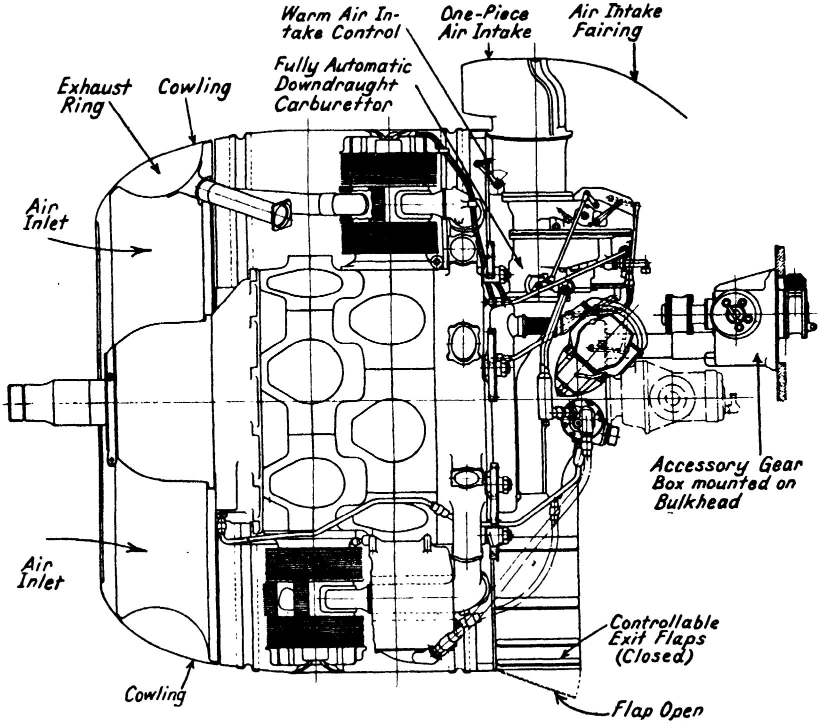
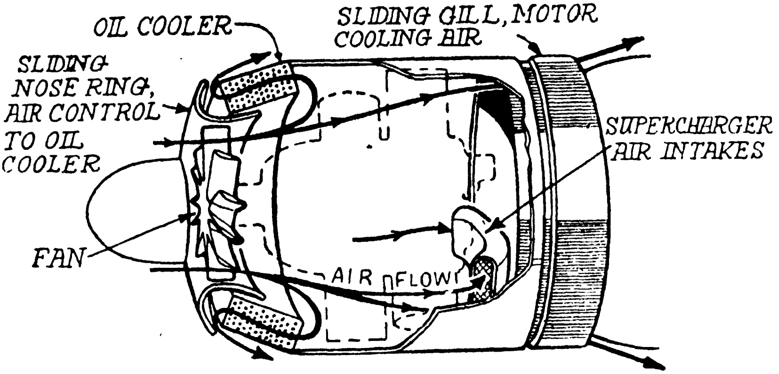


FIG. 62. The Bristol " Hercules " fourteen-cylinder sleeve valve engine cooling arrangement.

The Bristol engines are now fitted with particularly neat and efficient designs of cooling cowling, representing the results of a considerable amount of research work ; as mentioned in Chapter VI, the nose portion of the cowling houses the exhaust manifold and also arranges to cool it.

The cowlings used not only reduce the head resistance of the fuselage or power unit, but also the cooling air speed over the cylinders to about 75 per cent. as compared with the figure for the bare engine in front of a streamlined fuselage. The cowlings are made with short and long chords to suit individual aircraft, and, apart from the inter-cylinder baffles, there is a controllable air exit at the rear. The cooling air after passing through the central aperture of the nose portion, behind the airscrew, flows over the cylinder heads and barrels, being guided by the baffles, and, disregarding the part of the air employed for cooling the exhaust manifold, the rest flows out rearwards through the controllable orifices at the back of the main engine cowling. The hinged exit gills are controlled by the pilot, so that the engine temperatures can be maintained at their most efficient values under all flying conditions or varying aircraft speeds.



[*Courtesy of "The Aeroplane.*"

FIG. 63. Cooling system of B.M.W. 14-cylinder radial air-cooled engine.

The German B.M.W. 14-cylinder radial engine employs a low resistance type of cowling with a central opening around the airscrew hub (Fig. 63). Within this opening there is situated a fan having 12 blades; it is gear-driven from the engine and runs at about three times crank-shaft speed. This efficient system provides air for take-off and slow flying speeds; it is ineffective at high aircraft speeds. Part of the air stream is arranged to flow forward and through the oil cooling radiator; there is a sliding nose ring that can be controlled by the pilot for varying the degree of oil cooling. The main stream of air from the fan after cooling the cylinders escapes rearwards through sliding gills to join the air flowing over the body. Some of the warm-air flows into the supercharger intake as shown in Fig. 63.

Advantages of Air-cooled Engines. This type of engine possesses definite advantages for many aircraft purposes, but at the same time it has certain demerits. The advantages may be summarised briefly as follows :— [illegible]

(1) For military purposes it is less vulnerable, due to absence of radiator, water piping, header tank, etc. For this reason it must also be more reliable, since there is no liquid-cooling system ; moreover, for multiple-engined aircraft each unit can be made independent, although complete liquid-cooled " power units " are now made.

(2) It is lighter than the water-cooled engine. Although there is little to choose between the dry weights, the overall weight of the liquid-cooled type with radiator and water for cooling is appreciably greater per horse power.

(3) It is unaffected by frost conditions.

(4) For certain purposes the radial air-cooled engine is more convenient to instal and maintain than the liquid-cooled type.

(5) For installation in fighter aircraft the radial engine can be brought nearer to the pilot and the moment of inertia about the C.G. of the machine can be made appreciably lower than for a liquid-cooled Vee-type or " flat " engine ; in consequence the machine is more manœuvrable.

The demerits of the air-cooled engine are mentioned in the following considerations relating to liquid-cooled engines.

Liquid-cooled Engines. In this method the cylinder barrels and heads are provided with jackets or casings through which the cooling liquid is circulated by means of a water-type pump. The liquid carries off the surplus cylinder heat continuously whilst the engine is working. It is necessary, therefore, to provide some means for cooling the liquid in order to prevent it from boiling, thereby wasting part of the liquid. This is done by providing a radiator containing a relatively large number of water channels, formed in the thin metal elements, through which cooling air—due to the forward motion of the aircraft or to the airscrew slipstream—passes.

In aircraft engines the hotter parts of the cylinder, namely, the head, valve ports, sparking plug boss and the upper portion of the barrel are jacketed. Instead of cooling each cylinder separately, the cylinder block method of construction is now employed so that there is a common liquid cooling jacket for all of the cylinders and for the head portions ; this greatly simplifies and also lightens the construction.

The principal advantages of the liquid cooling method are as follows :—

(1) More uniform cooling of the whole of the heated cylinder

parts is possible than with the somewhat elaborate air finning and baffle systems.

(2) Much more compact engine units are possible. Thus, in place of the relatively large cooling fins on the barrels and heads, with the outer guide-cowlings, there is a much smaller dimensioned cooling jacket. For " in-line," opposed or Vee-type engines liquid cooling can be arranged to give uniform cooling for all the cylinders, irrespective of their actual positions ; with air-cooling this is always a difficult matter.

(3) With liquid-cooled engines higher compression ratios can be employed for a given grade of fuel and size of cylinder than with air-cooled ones. For this reason, this type has always given a greater power output per litre than the air-cooled one.

(4) Owing to the smaller overall dimensions and greater output per litre the liquid-cooled engine gives an appreciably greater horse-power per square foot of frontal area, even when the additional radiator area is included, so that for machines built for maximum speeds it has, hitherto, always been superior to the air-cooled type.

The extra vulnerability of the liquid system, the additional weight of the jackets, pump, radiator and piping and the risk of freezing of the coolant are the chief disadvantages of liquid-cooled systems.

Liquids Used for Cooling. Hitherto, water has been the most widely used coolant, but for aircraft purposes this liquid has the drawbacks of possessing a limited cooling range and a liability to freeze in very cold weather—with the risk of fracturing the cylinder jackets, pump casing or radiator.

When water is used the amount of heat that can be carried off is given by the following relation :—

$$H = Q\ (T_1 - T_0),$$

where H = number of heat units (B.T.U.'s) dissipated per minute. Q = quantity of water (lbs.) T_1 = outlet water temperature, F.° and T_0 = inlet water temperature, °F.

The quantity of heat to be dealt with has been shown to be 50 to 60 per cent. of the B.H.P. of engine, or—as shown in p. 82, 23·25 B.T.U. per B.H.P. per min.

Thus, for an engine of *x*, B.H.P. the following relation holds :—

$$23{\cdot}35\ x = Q\ (T_1 - T_0).$$

Example. Estimate the quantity of cooling water required for a 500 B.H.P. engine, with cooling water outlet and inlet cylinder temperatures of 180° and 70° F. Using the previous expression and substituting values

$$23{\cdot}25 \times 500 = Q\,(180 - 70)$$

$$\text{whence } Q = \frac{23{\cdot}25 \times 500}{110} = 105{\cdot}7 \text{ lb., } \textit{i.e.}, \ 10{\cdot}57 \text{ gallons.}$$

To maintain this rate of heat elimination the water must be circulated and cooled by the radiator down to the inlet temperature, namely, 70° F.

Ethylene-Glycol. This liquid has a lower freezing-point and also a much higher boiling-point than water, namely, 195° C. (383° F.).

Although it has a somewhat lower heat-absorbing capacity, or, more accurately, lower specific heat than water, namely, 0·725 at 146° C., it has such an increased temperature range that when it is employed as a coolant in aircraft engines not only is a smaller quantity of coolant possible, but *the area of the radiator can be reduced*, roughly to one-half that of a water-cooled radiator.

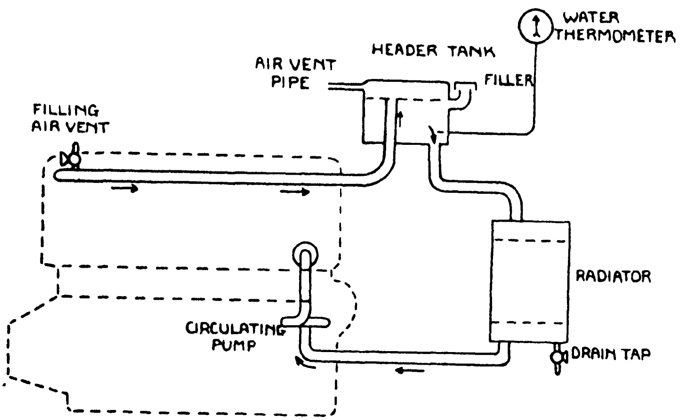


FIG. 64. Liquid-cooled aircraft engine cooling system layout.

Owing to its higher boiling-point, ethylene-glycol permits higher cylinder jacket temperatures (140° to 160° C. instead of 80° to 90° C., with water) to be employed, so that higher octane fuels are necessary than with water cooling in order to avoid detonation.

Ethylene-glycol has a corrosive effect on most metals and alloys, including lead-tin solders, so that in the latter instance cadmium-zinc solders must be used in the construction of the radiators.

Slightly greater piston clearances are required for ethylene-glycol coolant, since the cylinder walls are at a higher working temperature than when water is used.

Typical Liquid Cooling System. The principal components in the cooling system include the cylinder jackets, radiator, circulating pump, a header tank—similar to that employed in automobile radiators for filling purposes and to act as a surplus supply or reservoir—air vents and a thermometer to indicate the temperature at the hotter part of the system, namely, between the jacket outlet and radiator inlet.

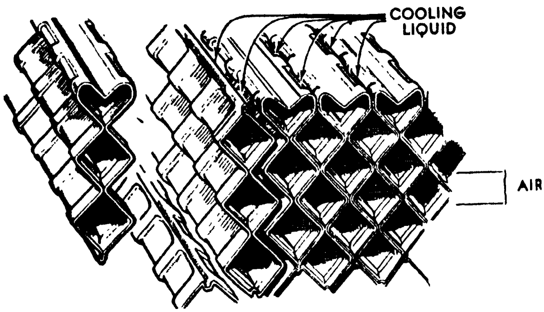


FIG. 65. Aircraft radiator construction.

A suitable lay-out for an aircraft engine cooling system is shown in Fig. 64. It will be observed that the circulating pump is located on the inlet side of the jacket, between the latter and the lower—or cooler—part of the radiator.

Aircraft radiators are of the honeycomb pattern, and made up of thin sheet metal strips shaped in a kind of corrugated pattern such that when assembled and soldered at the front and rear ends they form narrow sinuous water spaces running from the top to bottom of the radiator and leaving relatively large hexagonal or square (Fig. 65) air spaces between for the cooling air stream. At the top and bottom of this nest of " tubes " are arranged reservoirs or tanks. The upper one receives the heated liquid from the cylinder jackets *viâ* the header tank, and the lower one the cooled liquid that flows downwards through the numerous water spaces between the air spaces formed.

In practice honeycomb radiator air tubes have a length equal to about 30 to 50 times the diameter or maximum cross-sectional diameter.

Radiator elements are made from sheet copper, cupro-nickel or brass, and for ethylene glycol coolant are soldered with the cadmium-zinc solder mentioned previously.

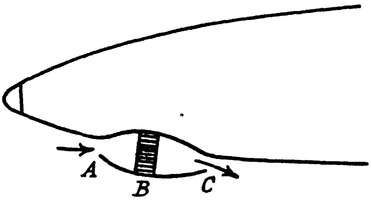
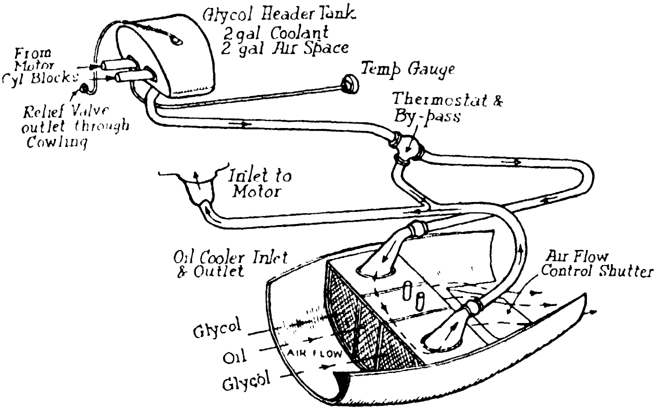


FIG. 66. Principle of duct cooling.

Duct Cooling System. Earlier designs of radiators were usually mounted in front of the engine in a similar manner to the radiators on automobiles; they were sometimes provided with shutters that could be operated by the pilot for regulating the cooling to suit the operating conditions; a radiator thermometer on the instrument panel indicated the cooling water temperature.

The arrangement described was not very efficient and had a high head resistance so that alternative methods were employed. These included (1) Wing radiators made to conform to the shape of the wing and therefore giving a very low resistance. (2) Retractable radiators that could be moved in or out of the fuselage in order to vary the area exposed to the cooling air stream. (3) Duct cooling.

The latter modern method of cooling the radiator contents is to arrange for the small radiator to be cooled by air moving at a lower velocity than the outside relative air stream, by placing it in a duct having an inlet vent A (Fig. 66) facing forwards and an outlet orifice C backwards. The cross-sectional area of the duct increases to a maximum at the radiator B, so that here the air velocity is a minimum and the pressure a maximum. As the air approaches the outlet C its velocity increases until it attains the same value as that of the outside air stream, so that it emerges with the latter smoothly.



[*Courtesy of " The Aeroplane.*"

FIG. 67. Liquid cooling system used on Hurricane aircraft.

It is possible in this way to reduce the cooling head resistance (or drag) considerably, and by careful design it is also theoretically possible to obtain a negative drag effect, so that a forward propulsive effort is actually obtained.

A more recent suggestion is to arrange for the exhaust gases to assist in duct cooling, by utilising the momentum of these gases to create a partial vacuum or low-pressure region which would be utilised for drawing the duct cooling air through the radiator. It has been shown that the total cooling drag could be reduced to zero at 300 m.p.h., by making use of the cooling energy due to the exhaust gases. At higher speeds a negative drag or forward propulsive thrust could be obtained.

A method of combining a duct-cooled radiator with an exhaust gas ejector is illustrated in Fig. 68.

The radiator is shown at A and it is enclosed by a metal casing, the entrance to which is constricted by the curves B and C. At the entrance there are slats D which diverge at an angle of about 7 degrees. In this way the kinetic energy of the air stream is converted into pressure energy within the radiator. The exhaust gases from the engine are collected by the manifold E and conducted to the rear of the radiator casing where they join the air stream and issue by the restricted passage F that converts the pressure energy back into kinetic energy.

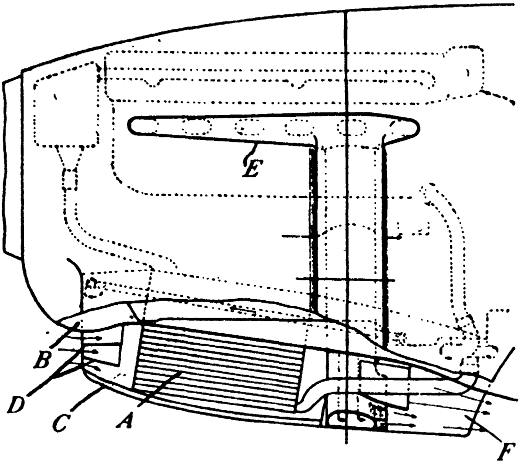


FIG. 68. Exhaust-assisted duct cooling system.

Pressure Cooling Method. A more recent aircraft engine cooling method is that of employing a solution of ethylene-glycol and to seal the cooling system so that the pressure can rise to a certain value before a pressure relief valve in the system opens. In this manner the temperature of the cooling liquid is allowed to rise still higher above the normal boiling-point of water, the temperature increasing with the pressure within the closed cooling system. The system is similar to a normal water cooling one with the addition of a spring-loaded adjustable and double-acting relief valve in place of a vent in the header tank. Its use of a 30 per cent. ethylene-glycol solution also prevents freezing under low temperature conditions of aircraft operation.

If the relief valve is set to open at 5 lb. per sq. in. (gauge) pressure this corresponds to a boiling-point of about 232° F.; if at 10 lb.

per sq. in. 245° F., and if at 25 lb. per sq. in. 272° F., at ground level.

Effect of Altitude. *As the altitude increases the boiling-point diminishes ;* thus for a boiling-point of 212° F. at ground level or zero altitude, the value at 20,000 ft. will be about 175° F. and at 30,000 ft., 157° F.

Similarly the cooling air temperatures fall progressively as the altitude increases ; thus, if the ground temperature is 50° F. (15° C.), at 20,000 and 30,000 ft., the air temperatures will be about — 12·5° F. (— 24·6° C.) and — 48° F. (— 44·5° C.).

As the engine power falls off appreciably with altitude the net effect is that the engine tends to be over-cooled as the altitude increases, if the cooling conditions are correct at ground level, so that theoretically, at least, some means should be provided to reduce the effective area of the radiator during flight.

In duct-cooled systems it is usual to have a variable air outlet in the duct, as shown in Fig. 67, and to provide the pilot with a suitable control for operating this.

With air-cooled engines controllable rear flaps on the ring cowling—in the case of radial engines—provide a simple and effective means of regulating the cooling.

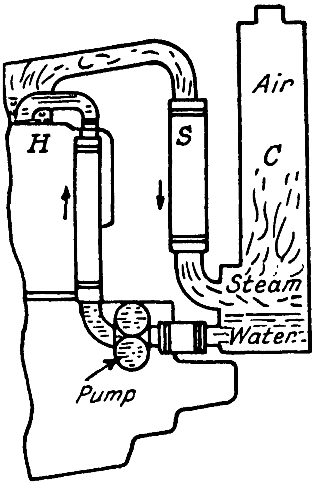


FIG. 69. Principle of steam cooling system.

Most radiators are now designed to give their correct cooling at a certain height, known as the *altitude of minimum suitability ;* below this height the operating temperatures are higher and, above it, lower, but the radiator is so designed that the coolant will not boil under ground level, full-throttle conditions.

Steam or Evaporative Cooling. In this method of cooling the temperature of the water is allowed to reach the boiling-point (100° C.) with the formation of a certain amount of steam. The water is circulated around the cooling system and the steam formed is usually separated and condensed in a radiator.

Apart from the advantage of the higher cooling water temperature in allowing a smaller radiator to be employed, there is also the cooling effect due to the latent heat of evaporation to be taken advantage of. Thus, for every pound of water converted into steam at 100° C., 537·5 C.H.U.'s* (966 B.T.U.'s) are absorbed by the cooling system at the expense of the heat conducted through the cylinder walls; only a certain proportion of the water is allowed to evaporate however.

The principle of the steam-cooling method is illustrated in Fig. 69. The steam formed in the jacket spaces at the tops of the cylinder head H is led to separator S and thence to the bottom of a condenser C, in which the steam is cooled by air flowing through tubes in a similar manner to the ordinary radiator. The condensed steam water flows to the bottom of the condenser and is returned to the jacket spaces by means of a gear-wheel type of pump.

In more recent applications of steam-cooling to aircraft the condensers have taken the form of wing radiators conforming to the profile of the wing portions adjoining; this results in a very low cooling drag.

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* Centigrade heat units.

CHAPTER VI

COMPONENTS OF THE ENGINE

It has previously been stated that the aircraft engine represents the highest standard of development of the petrol type engine. It is not only the lightest form but combines maximum operating efficiency with the greatest wear resistance and reliability; moreover, it will run for long periods with minimum maintenance attention.

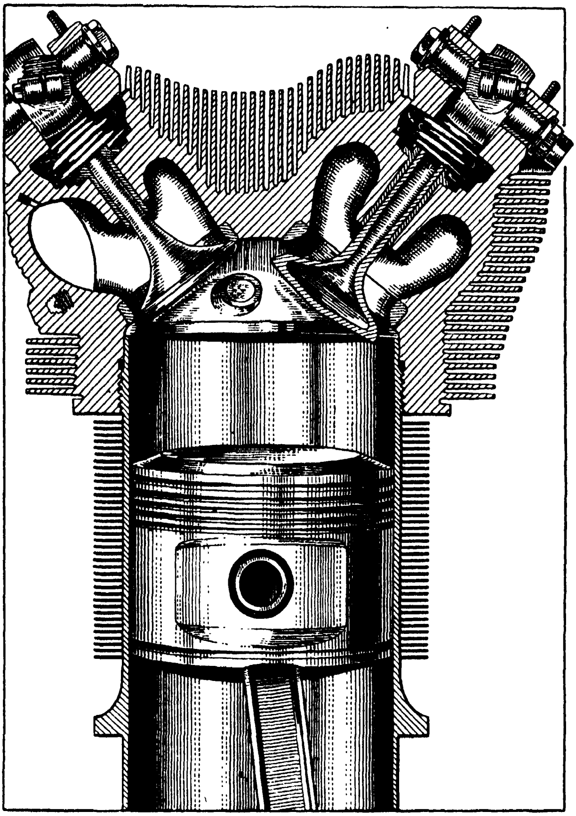


Fig. 70. Cylinder of Wright "Cyclone," G. 200 radial engine, showing piston, valves, fins, etc.

The careful design of the engine components is the greatest factor in the achievement of these results, since every part must be able to perform its special function under minimum weight conditions, without trouble or breakdown.

The simple example of an air-cooled engine shown in Fig. 11, on page 25 whilst useful for explanatory purposes, in no way represents the practical interpretation of the principles outlined to modern aircraft engines, as the examples considered elsewhere in this book will indicate.

It is proposed, therefore, to give a brief account of some of the more important engine components, with special reference to the four-cycle multi-cylinder types.

The Cylinders. The cylinder has to withstand the maximum combustion pressures, which may amount to about one-third of a ton for every square inch of cross-sectional area. At the same time it must be designed so as to get rid of a relatively large proportion of the total heat of the mixture, namely, from one-quarter to one-third, by conduction of this heat through the cylinder head and walls, there to be carried off by the cooling air or liquid, according to the engine cooling system employed; a small part of the heat is got rid of by the piston to the cylinder walls and oil in the crankcase.

In addition the cylinder must provide the best possible working surface for the reciprocating sliding movement of the piston and it must also give efficient housings for the inlet and exhaust valves and sparking plug; it is sometimes necessary to carry part of the valve operating gear on the cylinder head, as with overhead camshaft engines. The cylinder, in liquid-cooled engines, must be provided with double walls over the greater part of its surface for the cooling liquid. Finally, the cylinder unit requires suitable means for securing it rigidly to the crank chamber.

The cylinders of air-cooled engines were previously made of cast iron, a typical example being the eight-cylinder Renault engine (80 h.p.) used in large numbers during 1914–1918 on British and French aircraft.

Although cast iron is ideal in its wearing qualities and can be cast to very clean and sharp forms it is, relatively to steel, very weak in tension and bending; the tensile strength in the best cylinder irons is only about one-fifth that of alloy steels used for modern cylinders so that it must be made in relatively thick sections to withstand the cylinder pressures. Another disadvantage as compared with aluminium alloys is its relatively low heat conduction properties, which make it more difficult to get rid of the surplus heat.

Air-cooled Cylinders. Cast iron has therefore been replaced by steel or aluminium alloy (with steel liners). An early application of steel to cylinders is the classic example of the Gnome rotary engine in which the cylinders (barrels and heads in one unit) were machined from nickel steel ingots or forgings, complete with their cooling fins and flanges. The thickness of the cylinder barrel was only 2 to 3 mm. and the original engine, of 50 h.p., weighed 3·44 lb. per h.p.

In all the later rotary engines the cylinders were either entirely of forged steel or, as in the last of these engines, namely, the Bentley or B.R. engines, of aluminium alloy shrunk on to cast-iron liners.

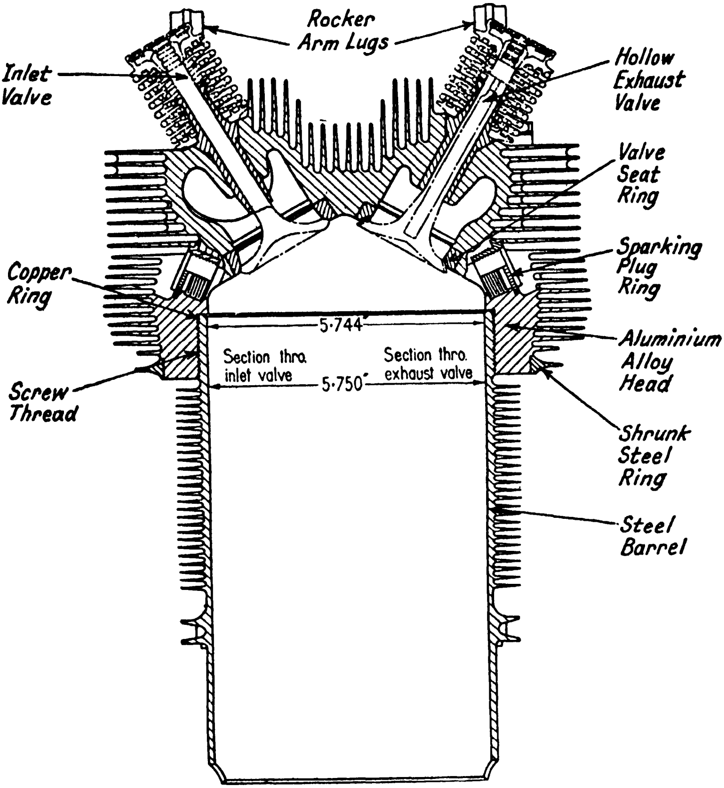


FIG. 71. Bristol " Mercury " cylinder unit.

The air-cooled engines which have superseded the rotary types are now made with alloy steel barrels, suitably finned for cooling, and aluminium alloy cylinder heads. A typical example is the Bristol radial engine cylinder unit (Fig. 71) as used on the " Mercury " and " Pegasus " engines. This unit has an alloy steel barrel and an aluminium alloy head.

In order to provide the maximum wearing action the barrel is made from a special nickel-chrome-molybdenum steel which, after machining, is given a glass-hard surface by heating it to about 500° C. in a stream of ammonia gas ; this is known as the *nitriding process* of surface hardening. The cylinder head is machined from a Y-alloy forging, which leaves it with the clean-cut intricate cooling fin system shown in Fig. 72 ; and also the valve ports and seatings for the valve inserts. The latter consist of screwed-in rings of hard bronze or a special nickel-chrome-manganese steel having the same expansion coefficient as the Y-alloy. This is important since, otherwise, when the cylinder head heats up the valve rings will tend to loosen and cause engine trouble. In order to give the valve seating areas of these rings the greatest wearing effect, they are given a deposit—by means of the welding torch—of a glass-hard substance known as Stellite. It may be of interest to mention that the weight of the Bristol cylinder head before forging (or stamping) in a typical instance was 49 lb. ; after all of the machining operations this was reduced to 15 lb.

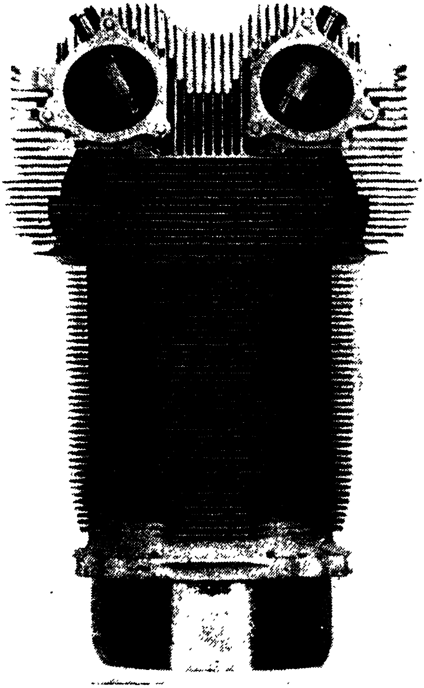


FIG. 72. The Bristol "Mercury" and "Pegasus" cylinder.

Other aluminium alloys used for cylinder heads are R.R. 53, and R.R. 59—sometimes known as Hiduminium alloys.

The cylinder head is secured to the barrel, by making a screw thread on the outside of the upper part of the barrel and screwing the head internally to suit. The barrel thread is made a very tight fit in the head and is fitted by heating the head to 400° C. and quickly screwing in the cold barrel ; the expansion of the hole in the head enables the barrel to be screwed into place with no undue effort. Hitherto, and until 1942, the aluminium alloy heads of the Wright Cyclone engines were made as castings, these being of a high degree of casting accuracy and cleanliness with the fins 1½ in. long and about ⅛ in. thick spaced at $\frac{7}{16}$ in. apart. More recently, however, forged and machined cylinder heads have been fitted and tests have shown that the power output is increased by 12 to 15 per cent. and the weight per cylinder reduced by 3½ lb. on this account.

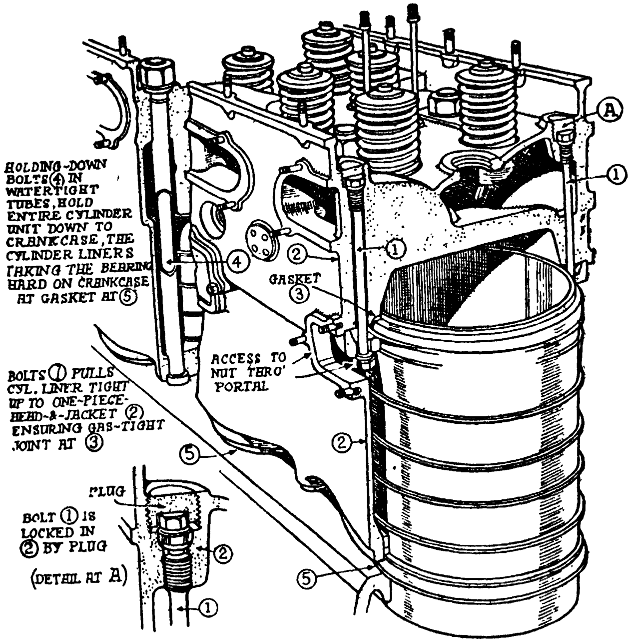


FIG. 73. Rolls Royce cylinder construction.

Liquid-cooled Cylinders. In distinction to the air-cooled cylinders which are invariably made as separate and usually interchangeable units, liquid-cooled cylinders are made in groups or blocks of 4 or 6 cylinders. The earlier engines used cylinders of steel with the thin steel water jackets welded in position. Later, the cast aluminium alloy cylinder block with inserted steel liners was employed as this construction is a very light one, easier to manufacture and gives excellent heat dissipation through the aluminium alloy; moreover, for the same weight an aluminium alloy casting can be made much stiffer than a built-up steel cylinder block.

The usual practice in modern liquid-cooled engines is to employ strong aluminium alloy castings for the cylinder blocks with aluminium-bronze or special alloy steel valve-seating rings shrunk into position. The alloy steel liners can either be shrunk into position or bolted down, using long cylinder clamping bolts for this purpose.

The Rolls-Royce method (Fig. 73) is to use a cylinder block of R.R. 50 aluminium alloy with high carbon steel liners having flanges at the tops which seat against soft aluminium joint rings in the cylinder casting. The lower end of the liner is made water-tight by means of a spring-loaded rubber ring located between the outside of the liner and inside of the cylinder casting ; this provides for relative movement without any liability of water leakage. There is a water space between the outside of the liner and inside of the cylinder barrel so that the water is directly in contact with the steel liner ; this method of fitting the liner is known as the *wet liner* one. The alternative, or *dry liner* method, is to make the liner a tight fit in the aluminium cylinder barrel and arrange for the water jacket on the outside of the aluminium barrel portion.

In the Rolls Royce cylinder the inlet valve-seating consists of an aluminium-bronze ring shrunk into the aluminium alloy, whilst the exhaust valve-seating, which is subjected to a much higher temperature, is of a silicon alloy steel, known as Silchrome. The sparking plug is screwed into a bronze adapter ring shrunk into the cylinder casting. In order to reduce wear in the valve stem guides to a minimum the inlet and exhaust guides are made separately and shrunk into the cylinder casting. The inlet guide is of cast iron and the exhaust of phosphor bronze.

The cylinder block castings for liquid-cooled engines are necessarily complicated as they have to accommodate the valve seatings, sparking plugs and cylinder liners besides providing spaces around these parts for circulation of the cooling liquid. In addition, with the usual overhead valve gear, the upper part of the block must accommodate the bearings or guides for the valve operating gear.

The Crankcase. This is usually the largest engine component, as it is required to accommodate the main crankshaft bearings, the cylinders or cylinder block, the lubricating oil sump, and, in the case of supercharged engines, the air compressor casing. In radial engines the crankcase is provided with a rear end cover which is employed for housing the bearings of the power-driven shafts for the auxiliary components, and it is also used for holding certain external accessories such as the magneto.

The crankcases are often made of cast aluminium alloy, such as R.R. 50 or R.R. 53 or, alternatively, in a strong magnesium alloy such as the casting grade Elektron or Magnaminium. These alloys

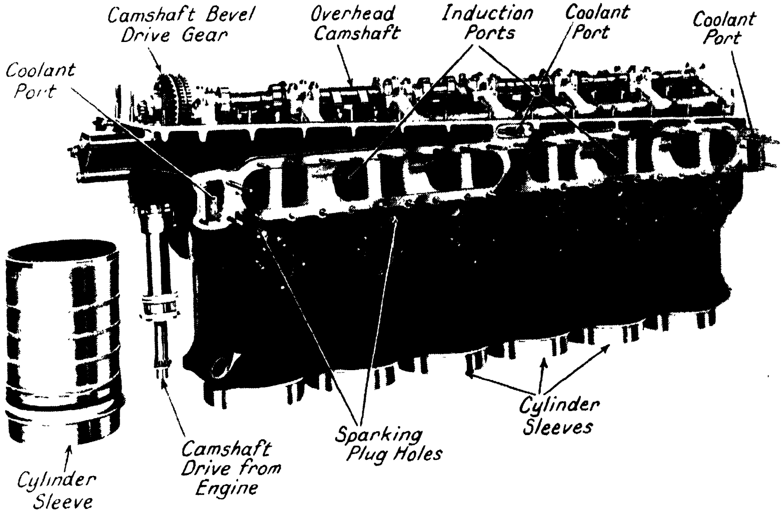


FIG. 74. One cylinder block of the Rolls Royce "Merlin" engine, showing principal parts, and (*on left*) one of the cylinder sleeves.

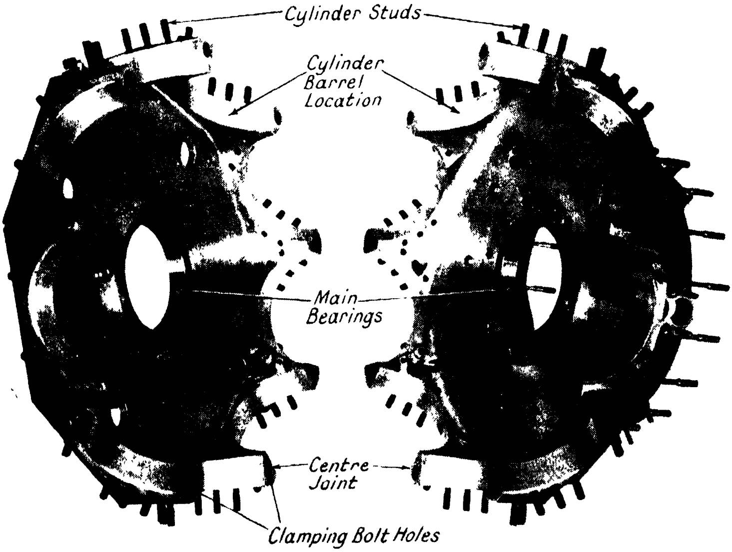


FIG. 75. The two crankcase half members of the Bristol 9-cylinder radial engine.

are appreciably lighter for a given strength and rigidity than the aluminium ones, but their strength diminishes more rapidly as the temperature increases, so that they cannot be used for parts exposed to appreciably high temperatures, namely, of the order 250° C. and above ; at this temperature the tensile strength is reduced to about one-third of that at normal air temperature (20° C.).

In some instances the crankcase and cylinder block is made in the form of a single aluminium alloy casting ; the Napier " Culverin " engine employed such a unit for its six double-opposed cylinders.

The crankcases of radial engines which for the single row of cylinders have only two main crankshaft bearings are made in two principal parts (Fig. 75) bolted together. It will be observed that the joint is arranged at the centre lines of the cylinder barrels.

The Bristol radial engines crankcases are made from aluminium alloy forgings, machined all over, as this construction enables a lighter unit to be built than with the sand cast crankcase construction.

The crankcases of all radial aircraft engines are provided with high tensile steel screwed studs for the purpose of attaching the cylinders or cylinder blocks, the end covers and other attachments.

The cast designs of crankcases are stiffened by means of special ribs located where the greater loads are applied.

The Piston. This is of hollow construction and made as light as possible in order to reduce the stresses due to the effects of its reciprocating movement and to minimise engine vibrations.

In modern aircraft engines pistons of aluminium alloy are invariably used, typical metals being those known as R.R. alloy 53 and Y-alloys, which are very strong for their weight and excellent conductors of heat. Magnesium alloys of only about two-thirds the weight of aluminium have been used experimentally in engines, but as these alloys lose their strength properties as the temperature increases more than the aluminium alloys special precautions must be taken to prevent failure from this cause. It should be remembered, also, that the piston is subjected to the full shock of the explosion and at a high rate of repetition. Thus in the case of an aircraft piston of 4½ in. diameter, used in an engine running at 2,700 r.p.m., the piston has to withstand a total load of about 4 tons which occurs suddenly and at the rate of 22½ times every second. In addition it is momentarily subjected to the high explosive flame temperature previously mentioned.

Aircraft pistons are made appreciably shorter than automobile ones, the ratio of the length-to-diameter being from 0·6 to 0·75, whereas in car engines the pistons have a length equal to or greater than the diameter.

The top or crown of the piston, which has to withstand the explosion load, is made much thicker, relatively, than the walls or skirt ; sometimes ribs are provided below the crown, *i.e.*, inside the piston to strengthen it, although the British tendency (Fig. 76) is towards the ribless design. The favoured American practice is to employ ribs for both stiffening and also for cooling purposes ; the ribs conduct the heat from the crown to the cooler inside walls, the surplus heat being eliminated by the lubricating oil within the crank chamber.

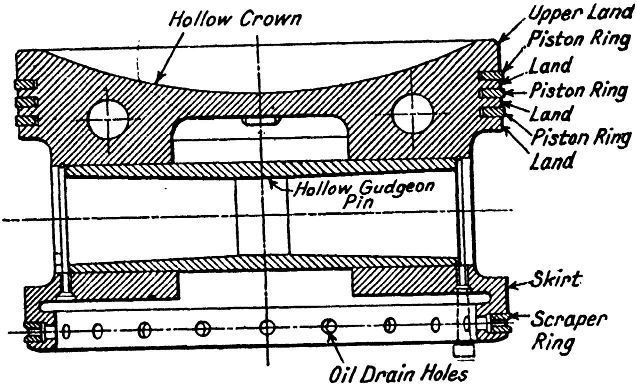


FIG. 76. Piston used on certain Rolls Royce aircraft engines.

The various names employed in connection with pistons are shown in Fig. 76.

The piston is made gas-tight within the cylinder by means of cast-iron or alloy steel split rings which fit into grooves machined in the cylindrical portion ; these are termed *gas* or *compression piston rings* to distinguish them from another type of ring used on the piston, known as an *oil control* or *scraper* ring.

The piston contains also the bearings or bosses for fixing the pin upon which the small end of the connecting rod rocks or oscillates. This pin is known as the *gudgeon*, *wrist* or *piston pin*, and is made hollow for lightness. It is sometimes secured within the piston gudgeon pin bosses by making it a tight, light driving or thermal fit and the small end bearing then rocks on the central portion of the pin. In other instances the gudgeon pin is made a floating or bearing fit in both the small end bearing and the piston boss. In

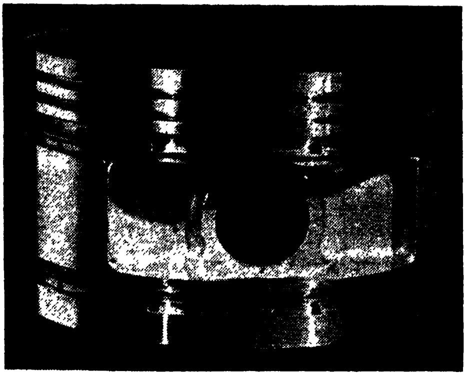


FIG. 77. Aircraft engine piston of Hiduminium R.R. 59 aluminium alloy.

either case the pin is prevented from moving endwise by means of spring rings at each end, engaging with grooves turned within the holes in the piston bosses. A much used ring for this purpose is that known as the *Circlip* ; it requires only a pair of round-nosed pliers to insert or remove the ring (Fig. 78).

The Bristol piston has a light spring ring and washer device to retain the gudgeon pin in endwise direction. Usually the gudgeon pin is made of nickel or nickel-chrome low carbon steel, and is case-hardened to give an almost glass-hard wearing surface.

The gudgeon pin in aircraft pistons has an outside diameter of one-fifth to one-quarter of the piston diameter and a length of about four-fifths of the diameter.

Notes on Pistons. Aircraft pistons in aluminium alloys are either sand-cast or die-cast, but are seldom if ever machined from solid metal. The die-cast piston is both harder and stronger in tension at all operating temperatures than the sand-cast one and for this reason is generally preferred. It has the further advantage of requiring much less machining, since the die castings can be made to within very fine limits and the surfaces—some of which do not require machining—are left in a clean and smooth condition.

As the pistons have to work within steel cylinders, in most instances, and aluminium alloys have a coefficient of heat expansion about 2½ times that of steel, it is necessary to make due allowance for this fact when the pistons are machined and fitted. If, for example, the piston was of the same steel as the cylinder it would only be necessary to provide a fine clearance

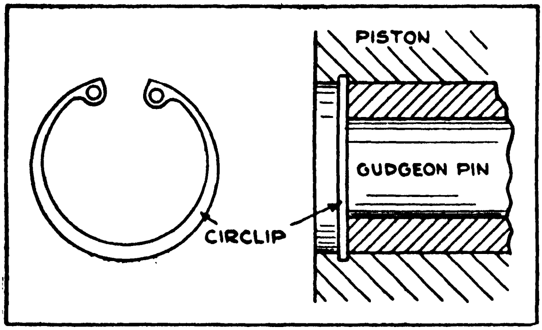


FIG. 78. The Circlip ring.

between it and the cylinder sufficient for the lubricating oil film, *i.e.*, a bearing fit. Any increase in temperature would affect both the piston and cylinder to a somewhat similar extent and would not alter the clearance to any perceptible degree. If, however, the same clearance were given to a piston of aluminium alloy, when the engine warmed up the piston would expand to a greater extent than the cylinder and seizure would probably occur. It is usual, therefore, to allow a skirt clearance, of 0·003 in. per inch diameter of piston for plain (un-split) skirts. As the top of the piston is much hotter than the bottom it is necessary to allow a greater clearance at this end, so that in effect the piston is of tapered form, being smaller at the top than the bottom (see Fig. 79).

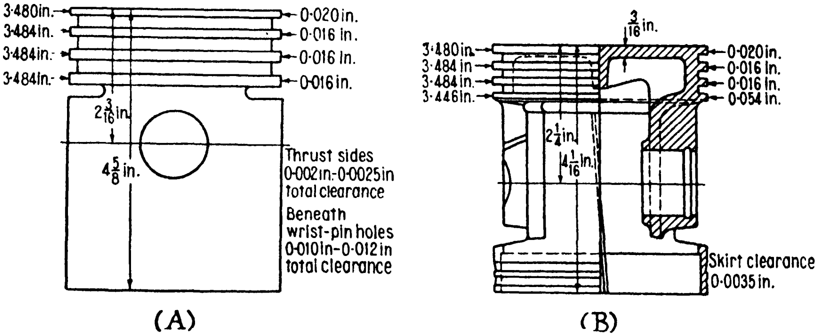


FIG. 79. Showing clearances for (A) plain and (B) split skirt pistons.

In order to prevent the piston from " knocking " or " slapping " on the cylinder wall when starting and warming up the engine, due to the appreciable amount of clearance, when cold, the skirt of the piston is sometimes provided with a diagonal slit and is lightly sprung into the cylinder ; it cannot therefore seize up when heated.

Another favoured method is to make the piston, as seen in plan view, very slightly elliptical instead of round, the smaller diameter being that containing the gudgeon pin axis and the larger one, that between the thrust faces. When the piston attains its working temperature the differential expansion causes the smaller diameter portion to expand more than the larger part so that the section becomes cylindrical.

Figs. 79 (A) and (B) illustrate aluminium alloy pistons of the elliptically (or cam) ground and split skirt types respectively, the clearances in each instance being indicated by the dimensions given ; the examples shown refer to automobile engines.

In many recent pistons it has become the practice to give the

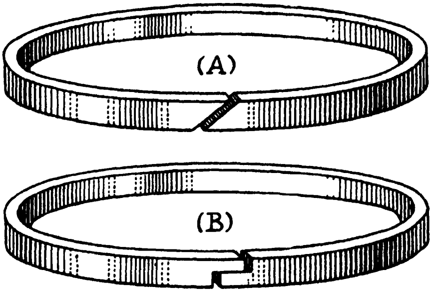


FIG. 80. Types of piston ring. A—Diagonal-cut. B—Step-cut.

aluminium alloy outer sliding surfaces a *fine coating of tin or aluminium oxide* in order to reduce the initial wearing effect or " scuffing " action. The tin coating results in a high degree of polish and gives a low frictional resistance. The oxide method provides a very hard, fine texture surface of marked resistance to wear and capable of retaining some of the lubricating oil in its interstices. Sometimes the pistons are treated with a solution of colloidal graphite, such as Aquedag, in water, allowing the solution to dry off, when the extremely fine graphite particles remain embedded in the pores of the metal and thus reduce greatly any risk of seizure during the initial running-in stages.

Piston Rings. Pistons used on aircraft engines are generally fitted with two or three compression and also two or three oil control rings. The piston rings are of a special grade of cast iron, or alloy steel, and are designed and machined to give uniform radial pressure, thus bearing against the cylinder walls evenly. The amount of this pressure is about 7 lb. per sq. in. for piston rings of 4 in. diameter, diminishing to about 5 lb. per sq. in. for those of 8-in. diameter.

The rings must be sliding fits in the ring grooves with side clearances of 0·003 to 0·005 inch.

Usually the rings are machined from cylindrical castings, parted off and split by means of a 45° slot (A) or made with a step as shown at (B) in Fig. 80. If, however, such a ring were sprung into a cylinder it would assume the oval form indicated in Fig. 81, in which the diameter B C is less than A D. The gases would then leak past the ring at B and C whilst excessive wear would occur at A.

To overcome this drawback the cut rings are clamped between two circular steel discs with their gaps closed, or nearly so, and their cylindrical surfaces projecting a little above the (smaller diameter) discs. They are then ground to truly cylindrical shape so that they will fit

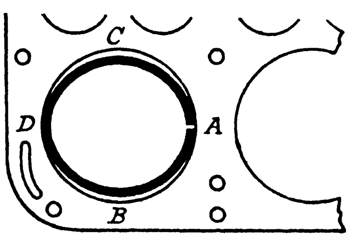


FIG. 81. Concentric piston ring inserted in cylinder.

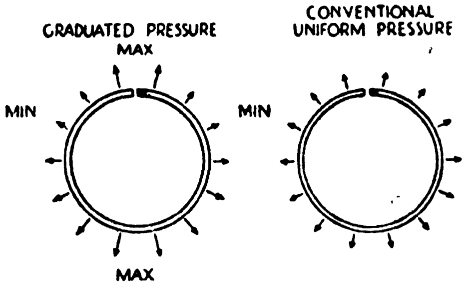


FIG. 82. Piston-ring pressures.

into the cylinder evenly all round.

This, however, is not entirely satisfactory, although it gives a much better result than for the ring shown in Fig. 81. To ensure even pressure the ring is subjected to a hammering or "stretching" process at certain places so as to give the required distribution of wall pressure. A typical ring employs a graduated pressure (Fig. 82) such that it is a maximum at the slot and also at the portion opposite the slot—as indicated by the lengths of the pressure arrows in Fig. 82 and a minimum between these positions. This method, it is claimed, prevents ring vibration and provides a more effective seal between the combustion chamber gases and the crankcase; at the same time oil leakage past the rings is reduced to a minimum. The rings used for aircraft pistons are thinner than for automobile ones; the widths range from 0·09 in. for 4 in. to 5½-in. pistons up to 0·15 in. for pistons of 7½ in. to 8 in. diameter.

The rings are diagonally cut with free gaps of 0·25 in. for 4-in. pistons to 0·53 in. for 8-in. ones. The actual radial widths vary from 0·134 in. for 4-in. pistons to 0·230 in. for 8-in. ones.

Oil control rings are provided for the purpose of regulating the amount of oil on the cylinder wall and preventing the excessive consumption that would otherwise occur if compression rings only were used.

The principle of the oil control ring is that of scraping the surplus oil off the cylinder wall on the down-stroke of the piston and returning it to the crank chamber *viâ* holes made from below the scraping edges through the wall of the piston. These holes are generally drilled obliquely through the wall at or below the control ring slot (Fig. 83).

Two types of oil control rings are shown in the latter illustration and in both cases the bearing area of the ring on the cylinder wall has been reduced so that a greater bearing pressure results. The ring shown at A has its

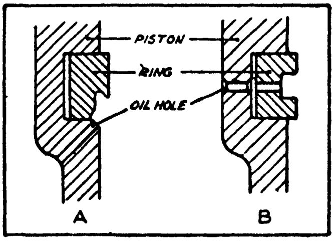


FIG. 83. Oil control rings. A—Single. B—Grooved.

lower side machined away, whilst that shown at B has a central groove turned in it; slots have been cut right through this ring groove at intervals, in order to provide for the flow of the surplus oil from the walls into and through the drilled holes in the back of the ring groove; this is shown more clearly in Fig. 84.

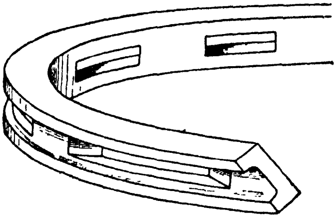


FIG. 84. Grooved or slotted oil control ring.

Aircraft pistons are fitted with both double- and single-control oil rings. A typical example is that of the Bristol piston shown in Fig. 85 which has four piston rings above the gudgeon pin, namely, two compression rings above, and a "double" oil control ring in the third groove down. There is also a fifth single oil control ring fitted near the bottom of the piston skirt.

The Wright air-cooled radial engine pistons, e.g., the "*Cyclone*" ones, have six and the *Pratt and Whitney "Twin Wasp" engines*, five. In the former instance (Fig. 70) there are five rings above the gudgeon pin and a single oil control ring in the lowest groove, inverted so as to act as an oil pump. The five upper rings all exercise a scraping action, the two lower ones being located in separate grooves of extra width to allow the oil pumped by the bottom ring to drain away through holes into the interior of the piston. The method of actually supplying oil to the walls by means of the bottom ring and scraping off the surplus with the upper ones ensures adequate lubrication with, however, a minimum oil consumption—since the latter is suitably regulated.

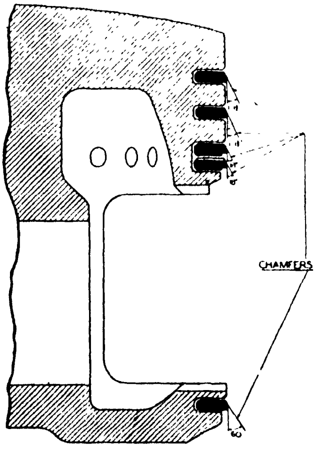


FIG. 85. The Bristol "Mercury" piston ring arrangement.

Piston rings are often coated with a surface of tin, iron-oxide or iron and manganese phosphates in order to reduce the wear and prevent piston ring scuffing. The results of tests made upon such coated rings have shown that the wear is about one-half that of untreated rings.

Valve Operation Mechanism. It has been explained in Chapter II how the inlet and exhaust valves are operated by means of cams, through the agency of push rods and rocker arms, for the particular engine shown in Fig. 11.

Before proceeding to describe other valve-operating mechanisms it is proposed to devote a small amount of space to considerations of valve areas and valve cams wherewith the inlet and exhaust valves of each cylinder of an engine are opened and closed by the correct amounts during a working cycle.

The actual times of the valve movements or *events* have been ascertained by the manufacturers largely as a result of research work and practical experience, and it has been found that for the maximum engine output the valves should (1) Have as large an area in relation to the piston as possible; (2) Remain open during the cycle as long as possible.

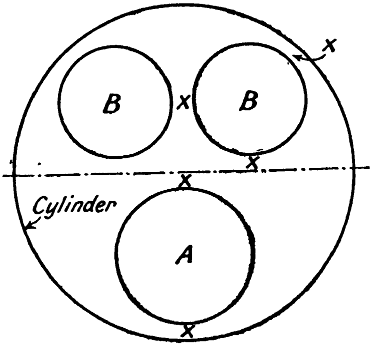


FIG. 86. Valve areas.

The valve area is limited by the size of the cylinder, as it is necessary to make the valves circular in shape and to leave ample metal for the seatings and ports. For single valves the diameter is usually made equal to about 0·4 times the piston diameter, or, alternatively, the valve diameter is chosen so that the average gas velocity past the valve does not exceed 220 to 240 ft. per second at maximum engine speed.

A formula based upon gas velocity considerations is as follows :—

$$\text{Diameter of valve} = \sqrt{\frac{D^2 l \,.\, N}{43{,}200}} = \frac{D}{208}\sqrt{lN} \text{ inches.}$$

where D = diameter of piston (inches) l = stroke of piston (inches). N = r.p.m. for maximum engine speed.

The lift of the valve is usually made equal to one-quarter or one-fifth of the valve diameter.

The valve seating is made at 45°, although angles of 60° have been used on certain engines.

In order to obtain the greatest area for the valves, it is not unusual to employ two inlet and two exhaust valves per cylinder. The reason why this arrangement gives a greater area than for a single valve will at once be apparent from the example illustrated in outline in Fig. 86, which illustrates, to scale, two possible valve arrangements, each giving the maximum area as governed by the minimum clearances indicated at X.

If the area of the piston be denoted by 100, then the area of the single valve arrangement A will be 16·5 and the total area of the two valves B by 23·4. Thus, the latter arrangement gives about 42 per cent. more valve area than that of the single valve A.

The diameters of the valves A and B are 40·6 and 34·1 per cent. of the piston diameter respectively.

The Valve Cams. The maximum amount of valve lift and the period of valve opening are determined by the shape of the valve cam. The maximum valve lift is given by the difference in radii of the top of the cam and the plain or concentric circular part. The period of the valve opening is given by the angle between the radii drawn from the centre of the cam circle to the points of intersection of the cam curves with the cam circle.

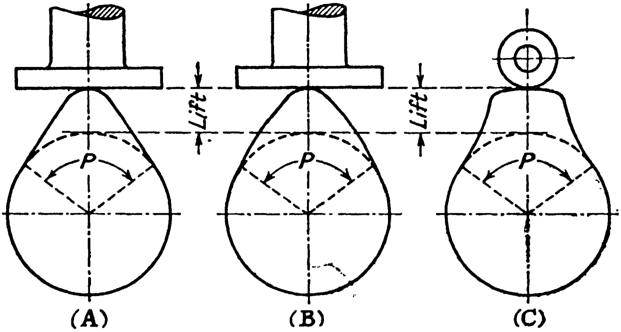


FIG. 87. Type of valve cams.

Referring to Fig. 87, the cam shown at A is known as a *tangential* one as the sides are tangents to the cam base and lobe circles. This type gives a quick lift when used with the flat-ended or mushroom tappet shown. It is apt to be noisy, requires a stronger spring than other cam shapes and wears more appreciably. The cam shown at B is a *convex-sided* one and gives a more gradual lift to the valve *viâ* the mushroom tappet. Both of the cams A and B can be used with roller-ended tappets and then give a more gradual lift and fall; the convex shape of B results in a greater valve opening area during the valve period, denoted by the angle P. The type of cam shown at C is known as the *constant acceleration* one and, when used with a roller ended tappet gives a constant rate of acceleration and deceleration as it is opened and closed respectively. It does not need so strong a valve spring as A or B and gives a greater valve opening area, since the valve is kept open at its full lift for a longer period. With this shape of cam the exhaust valve can usually be distinguished from the inlet cam by its broader lobe.

It should be mentioned that the shape of the valve lift curve, as plotted on a base representing the valve opening angles, is determined by the shape of the cam follower, *e.g.*, mushroom or roller-ended tappet.

Two typical examples of aircraft engines employing four valves per cylinder are the Rolls Royce 12-cylinder water-cooled " Merlin " series and the Bristol " Mercury " and " Pegasus" 9-cylinder radial engines.

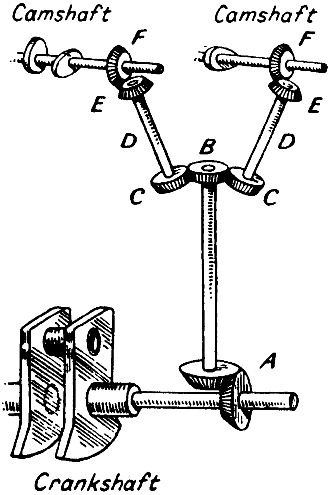


FIG. 88. Camshaft driving mechanism of Rolls Royce " Merlin " engine.

The method of operating the valves in the former example is by means of a camshaft mounted in suitable bearings disposed along the top of each 6-cylinder block, as indicated in Fig. 74. The camshaft carries a series of cams arranged at different angles, each cam is duplicated so that the two inlet valves are operated by a pair of identical cams, whilst the two exhaust valves have another and similar pair to operate them.

The "Merlin" engines are arranged with two sets of 6 cylinders inclined at an angle. The camshafts are driven from a bevel gear A on the engine crankshaft which drives a short vertical shaft (Fig. 88) having a bevel gear B which engages with the bevel gears C attached to the lower ends of the inclined shafts D ; the latter have bevel gears E which engage with similar bevel gears F on the camshafts.

The smaller 4- and 6-cylinder air-cooled vertical engines are usually provided with a camshaft running in bearings mounted within the crankcase. The cams engage with mushroom-ended plungers or tappets which move up and down in suitable guide bushes in the crankcase. The upper ends of these tappets have spherical cups in which rest ball-ended rods that convey the tappet movement to similar ball-and-socket joints at one end of the rocker arms, the other ends of which operate the valves. The rocker arm has a fixed position central bearing mounted on the cylinder head casting.

Fig. 89 illustrates a typical aircraft engine overhead valve mechanism, the engine in question being of the opposed-cylinder type for light aircraft. The same cam, it will be observed, operates a pair of tappets for opposing cylinders.

The method of operating all four valves in the case of air-cooled separate cylinder engines is well illustrated by the example of a motor-cycle engine shown in Fig. 90; it utilises the same principles as the aircraft engine. There are two cams, driven at one-half engine speed and each cam operates its own push rod; both rods are housed in a single tubular casing. The upper end of each rod engages with the outer end of a lever arm which forms a solid part of a lever unit having a central bearing on a shaft and provided with a pair of similar lever arms which operate the two valves. The right-hand support for the left rocker arm shaft has been omitted for clarity reasons in Fig. 90.

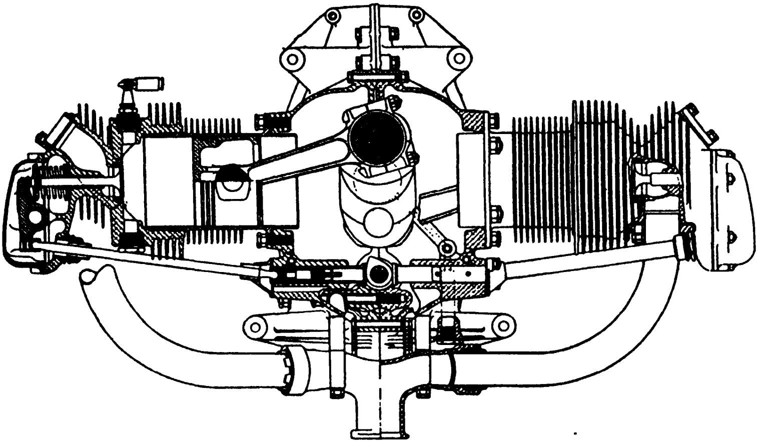


FIG. 89. Opposed cylinder aircraft engine showing valve operating mechanism.

Fig. 91 shows the Bristol valve gear as seen in plan view on the cylinder head, and illustrates the neat and compact arrangement of the pairs of operating rocking lever arms, each pair, viz., inlet and exhaust, being actuated by a separate push rod. Both rods are enclosed in a light tubular housing, the latter being located at the front of the cylinders as viewed when the engine is mounted in an aircraft.

The *radial aircraft engine,* instead of using a camshaft, employs *cam rings,* as in the example of Fig. 92, to operate the valve tappets. There is a separate cam ring for the inlet and exhaust valves and the ring combination is driven by gearing from the crankshaft by a pair of external gears, one of which drives a smaller gear meshing internally with an annular gear formed within one of the cam rings ; the latter are mounted concentrically with the axis of the crankshaft.

In order to give the correct number of valve operations for each revolution of the crankshaft, it is usual to run the cam rings in the *opposite* direction to that of the crankshaft and to provide each ring with one cam lobe for a 3-cylinder radial ; two lobes for a 5-cylinder ; three lobes for a 7-cylinder and four lobes for a 9-cylinder engine. The cam rings in these examples rotate at $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{6}$ and $\frac{1}{8}$ engine crankshaft speed. It is, however, possible to run the cam rings in the same direction as the crankshaft, but in this case one more cam lobe per ring will be needed and the cam ring will require to be rotated at a lower speed. Thus, in the example of a 9-cylinder engine a five-lobe ring would be needed and it would run at $\frac{1}{10}$ engine speed. The disadvantages of this alternative method are the additional cam to be machined and the larger reduction gear, both of which give an increased weight.

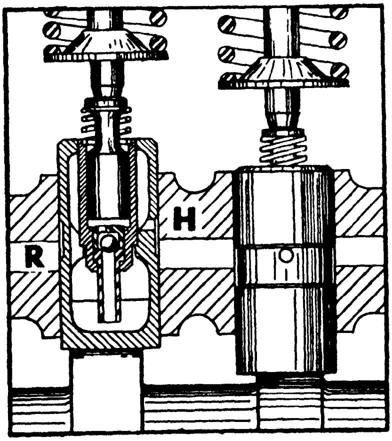
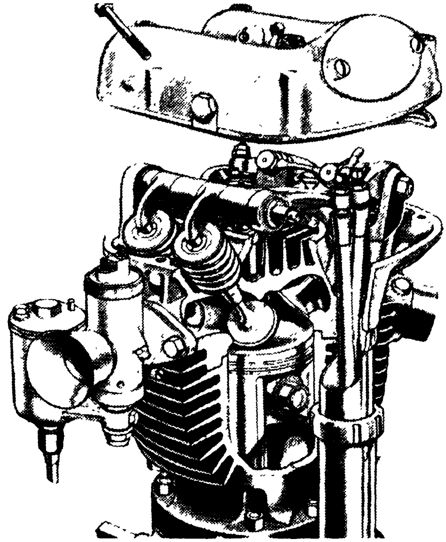


FIG. 93. Automatic valve clearance adjuster.

Valve Clearances. Normally with side-by-side valves, as used on automobile engines, and push-rod operated overhead valve engines it is necessary to provide a definite but small amount of clearance between the valve stem end and its operating mechanism, in order to allow for cylinder and valve expansion effects. This clearance tends to alter after an engine has been in operation for an appreciable period so that a screw adjustment with a locking nut is provided for the purpose of re-adjusting the clearance. If the latter is too great valve operation will not only be noisy but the engine will lose power, owing to the reduced valve lift. If the clearance is too small the valve may not close properly when the engine warms up and the compression pressure will then be reduced so that the power output will be lowered ; further, in the case of the exhaust valve, this will tend to become burnt on its seating face. The usual valve clearance for push-rod operated overhead exhaust valves is about ·004 to ·006 in. and for the inlet valves ·003 to ·004 in. For overhead camshaft engines temperature effects



[*Courtesy of "The Motor Cycle."*

FIG. 90. Method of operating four overhead valves.

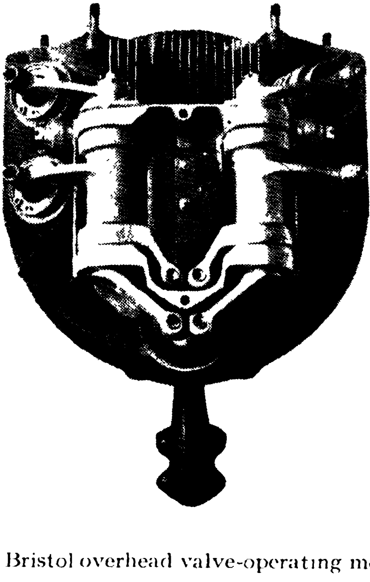


FIG. 91. Bristol overhead valve-operating mechanism.

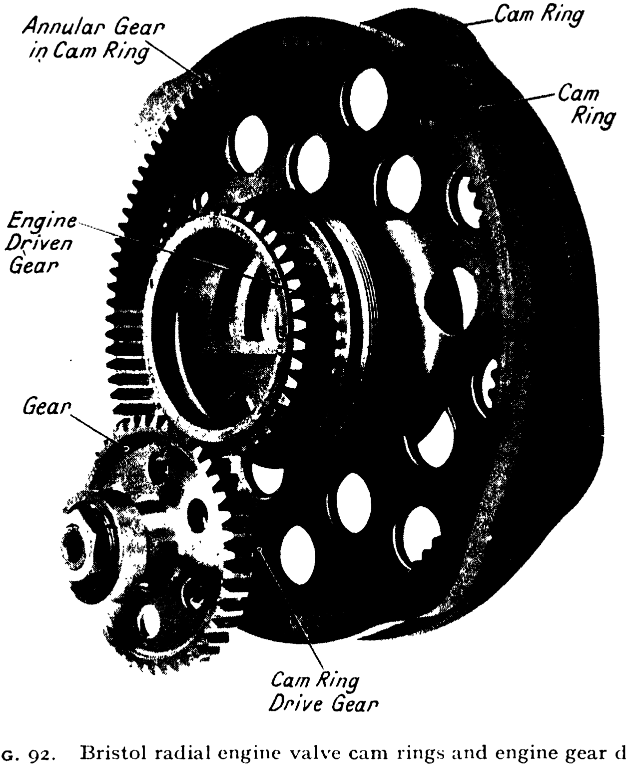


FIG. 92. Bristol radial engine valve cam rings and engine gear drive.

do not vary the clearances, so that these can be set to rather finer limits, namely, ·003 to ·004 in. for both types of valves.

There are several *automatic devices*, one of which—known as the "Zero Lash"—is shown in Fig. 93. It operates upon the hydraulic principle. The valve tappet is made hollow and has a plunger member which abuts against the end of the valve stem. Oil under pressure is delivered to a reservoir R, whence it passes through a hole H into the hollow tappet, up a central tube and past a non-return valve into the adjusting chamber below the end of the plunger. Oil also passes from the reservoir through a hole in the upper end to lubricate the tappet guide and to help get rid of any air in the system. This adjuster maintains zero clearance under all conditions.

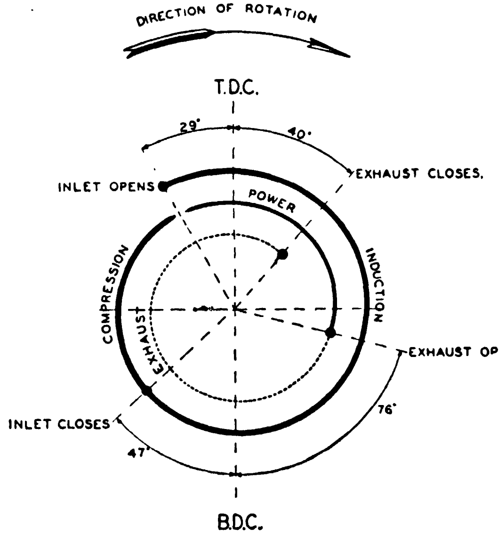


FIG. 94. Bristol "Pegasus" valve timing diagram.

The Bristol air-cooled engines are provided with an automatic valve clearance compensation device in which the position of the front rocker bracket pivot is kept constant by means of a tie rod from the cylinder head to the crankcase. The rear rocket bracket pivots, however, are free to rise as the cylinder expands outwards. The pivots are so arranged in relation to the push rods and rockers that the resultant effect on the valve stem clearances is negligible.

Valve Timing. It is usual to indicate the opening and closing positions of the valves by means of a crank circle upon which the corresponding positions of the crank of the cylinder in question are shown. Fig. 94 illustrates the valve-timing diagram of the Bristol "Pegasus" engine. In this example the inlet opens at 29° before T.D.C., whilst the exhaust valve does not close until 40° after T.D.C. Both valves are therefore open at the same time over a period of 69° ; this period is known as the *valve overlap*. The object of overlap is to allow the outgoing exhaust gases to create a partial vacuum, in virtue of their inertia, so that the incoming charge will flow in more readily. The inlet and exhaust valve clearances for the Pegasus engine are ·004 and ·006 in. respectively.

Valve Materials. As the inlet valve is to some extent cooled by the fresh charge of fuel and air flowing past it during the induction stroke it is not actually necessary to employ a non-corrosive steel as in the case of the exhaust valve which has to withstand the full effects of the very hot corrosive gases that sweep past it. Each valve, however, is subjected to impact stresses, the most severe ones occurring when the valve is rapidly closed or brought back on to its seating by the valve spring ; the latter holds the valve on its seating during the " closed " periods.

The inlet valve is generally made of an alloy steel, such as high nickel-chrome, tungsten or silicon-chrome, as these steels retain a high proportion of their normal air temperature strength and hardness at the engine working temperatures, namely, from 220° to 260° C. for inlet valves.

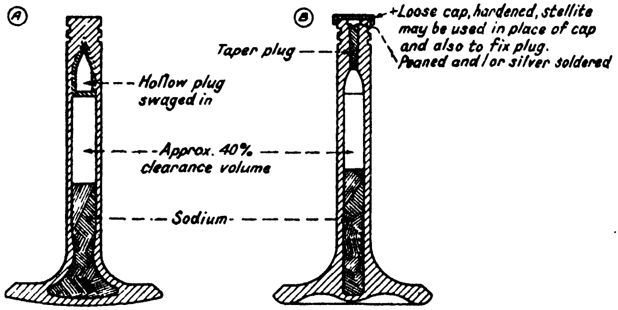


FIG. 95. Sodium-filled exhaust valves.

The exhaust valve head, which is usually the hottest part of the combustion chamber, requires special cooling means, since its temperature has a marked influence upon the possible power output ; the lower this temperature, the higher the working compression can be made, within limits, and the greater the efficiency.

The modern exhaust valve is made in hollow form (Fig. 95) of a silicon-chrome or cobalt-chrome steel ; these are noted for their high heat and corrosion resistance. The hollow space in the valve stem (or stem and head) is partly filled with the chemical element *sodium*, which under working conditions vaporises and acts as a heat conductor between the valve head and stem, thus getting rid of the surplus heat to the better cooled regions. Another illustration of a hollow exhaust valve is shown in Fig. 70 on p. 97. It is usual to give the valve seating and stem end a deposit of *Stellite*—an extremely hard synthetic material used for tipping the cutting edges of machine tools. Another substance used on Rolls Royce valves is *Brightray*, an alloy consisting of 80 per cent. nickel and 20 per cent. chromium.

The valve insert rings are sometimes coated on the seating faces with Stellite.

Valve Springs. These have to withstand continuously the repeated compressions and expansion effects of the valve movements. They are often made of two or sometimes three concentric springs (Fig. 96) in order to prevent spring vibration effects that might otherwise cause fracture of the coils. Modern valve springs are made of medium carbon steel (0·7 to 0·08 per cent. carbon) or chrome-vanadium steel. In order to obviate any risk of fatigue failure due to surface defects such as pits or scratches, valve springs are now treated by a shot-blasting process ; this both hardens and smooths the surface.

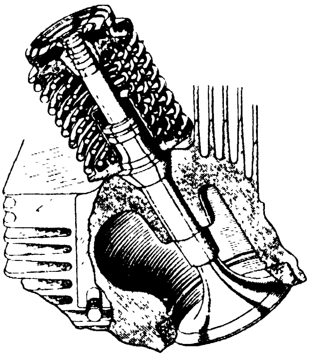


FIG. 96. Bristol " Mercury " engine valve, showing triple valve springs, valve stem guide and valve seating insert.

The Crankshaft. This important engine component transmits the engine power from the reciprocating pistons to the airscrew in the form of energy of rotation. It is subjected to severe loads, namely, a combined twist and bending load—between each consecutive pair of main bearings and must also provide both the crank pin and main journals for the connecting rod big-end and main bearings, respectively.

When the piston descends on its firing or expansion stroke the turning effort or torque on the crankshaft varies from a maximum value down to a minimum one during the stroke. In the case of a single cylinder engine this maximum value may be as great as 8 to 9 times the average value of the torque throughout the complete cycle. A 4-cylinder engine with similar cylinders and piston stroke gives a marked reduction in this ratio of maximum to mean torque, namely to about 2. A 6-cylinder engine gives a ratio of only 1·3 to 1·5 so that the turning effort is a very steady one and the crankshaft can be made much lighter, relatively, than for the other types of engines mentioned.

The corresponding ratios for a straight 8- and a 12-cylinder vee-type engine would be about 1·2 to 1·3 and 1·1 to 1·15 respectively. These values indicate the smooth running advantages of engines with a relatively large number of cylinders. Another merit of the multi-cylinder engine is that as the variations of torque are much smaller the flywheel—which serves to smooth out the irregularities in the torque, by storing up the surplus energy and restoring it during the idle periods—can be reduced in weight or actually dispensed with in the case of engines with more than 6 cylinders; actually, in aircraft practice, flywheels are not employed, the airscrew and its gearing acting as a kind of torque-smoothing device.

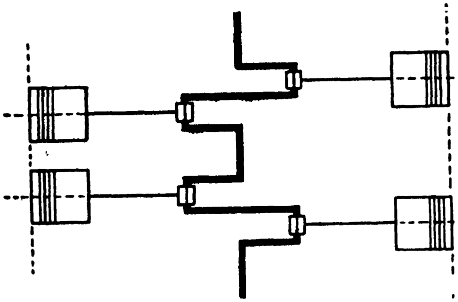


FIG. 97. Opposed 4-cylinder crankshaft arrangement.

Torsional Vibrations. A crankshaft may be regarded as a kind of helical spring which can twist and untwist slightly under varying torque action about its axis. The variations of torque on the crankshaft also tend to cause similar angular oscillations about the axis of the shaft. These occur at the engine-firing frequency, *e.g.*, at one-half engine speed for a single-cylinder engine and at N/2 times engine speed for an engine having N cylinders. If this frequency happens to coincide with or to be a multiple of the natural vibration frequency of the crankshaft a resonance effect will occur, tending to set the shaft vibrating dangerously. Unless checked by, say, a change of engine speed, these oscillations may eventually cause fracture of the crankshaft. The engine cruising and maximum speeds are always arranged to be well away from the natural or "critical" speeds of the crankshaft, for this reason.

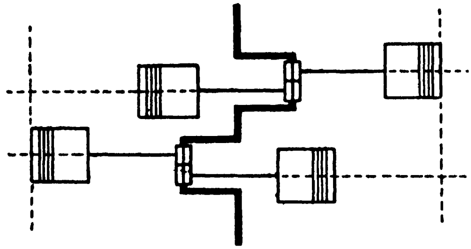


FIG. 98. Simplified crankshaft for opposed 4-cylinder engine.

Crank Arrangements. Omitting the opposed two-cylinder engine with its cranks at 180° apart, the 4-cylinder opposed engine may have its cranks arranged either as a four-throw crankshaft, as shown in Fig. 97, or as a two-throw one, as in Fig. 98. The latter arrangement is a more simple and compact one; it has been used in certain designs.

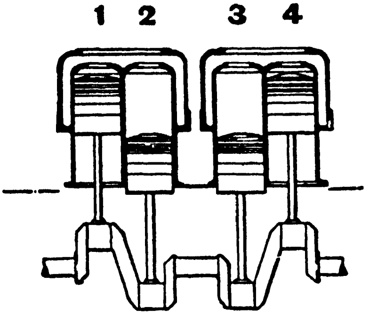


FIG. 99. Four-cylinder vertical engine crank arrangement.

The 4-cylinder vertical engine—used in the inverted form in aircraft engines such as the Cirrus "Minor" and "Major" and the American "Menasco," has its cranks arranged as indicated in Fig. 99, namely, with the two inside cranks together and the two outside ones also together but at 180° to the inside ones. This arrangement gives good engine balance and equal firing intervals, namely, at 180° apart.

The 6-cylinder vertical engine, which is employed in the inverted form in aircraft engines, *e.g.*, the "Gipsy Six" and "Menasco Six," has its cranks located as shown in Fig. 100. The corresponding pairs of cranks, it will be seen, are at one-third of a revolution or 120° apart. The pairs of corresponding cranks in line are the two inside ones, the two outside ones and the second and fifth. This crank lay-out gives excellent engine balance and equal firing intervals, namely, at 120° apart.

The straight eight-engine is not used for aircraft purposes, but the Vee-eight has been used in the past, and with this type several alternative crank arrangements were possible; these included the ordinary 4-cylinder vertical engine crankshaft.

The 12-cylinder vee-type engine employs a similar crankshaft to that of the 6-cylinder vertical one. A typical example is that of the Rolls Royce "Merlin" engine, shown in Fig. 101. This light but strong crankshaft is provided with balance weights for the crank

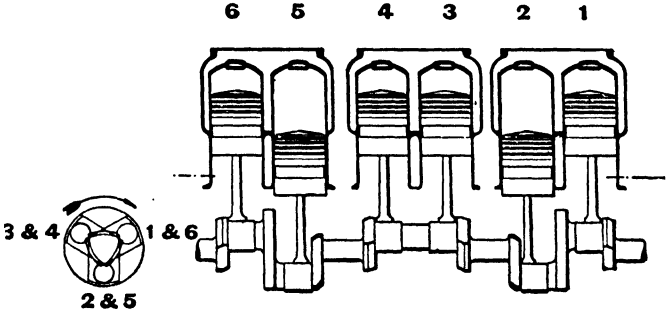


FIG. 100. Six-cylinder vertical engine crank arrangement.

pins, as otherwise these would be out of balance and tend to cause vibration effects. Both the main and crank-pin portions of the shaft are made hollow, for lightness reasons, the ends of the lightening holes being closed by light metal plates held in place by bolts and nuts. The webs of the shaft are drilled so as to connect the spaces in the crank pins and main journals. The reason for this is that the lubricating oil for the main and big-end bearings is supplied to the insides of the journals.

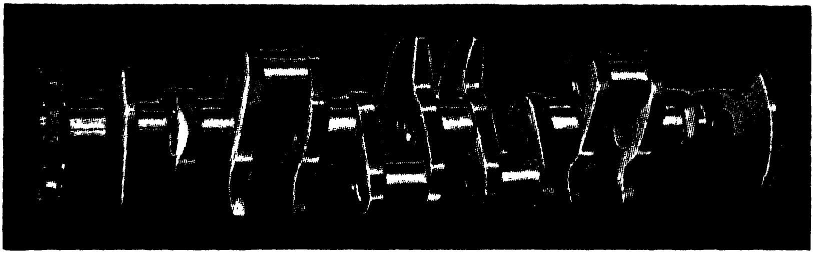


FIG. 101. The six-throw crankshaft of the Rolls Royce " Merlin " engine.

It will be observed that the 12-cylinder engine crankshaft (Fig. 101) has only six crank pins, although there are twelve connecting rods, each with its own big-end bearing. Accordingly, opposite pairs of rods work upon the same crank pin, one rod being forked and the other left plain so as to work within the fork. The forked rod has its bearing directly on the crank pin, whilst the plain rod bears upon a larger diameter cylindrical member formed between the two forked members. In this way, it is possible to give equal

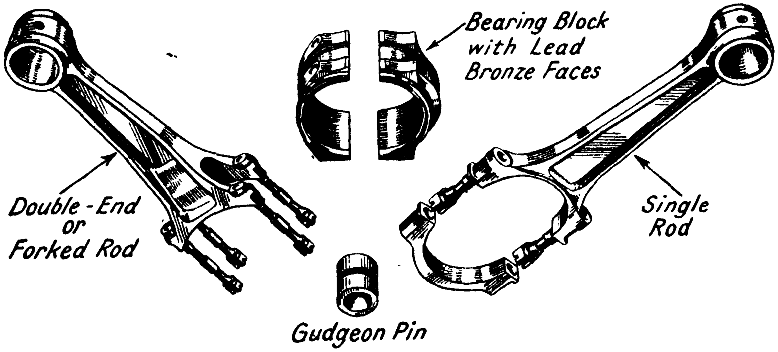


FIG. 102. An opposite pair of connecting rods and their bearing block, for the Rolls Royce " Merlin " engine. These two rods work on the same crank pin.

bearing areas for the plain and forked rod big-end bearings (Fig. 102).

The connecting rods are made from a special nickel or nickel-chrome steel suitably heat-treated to give a high tensile and impact strength.

The crankshafts of *radial engines* are comparatively simple in design as compared with those previously described. Thus, for a single row, 5-, 7- or 9-cylinder radial engine a single-throw crankshaft only is needed ; for a two-row radial (14 or 18 cylinders) a two-throw crankshaft with its cranks at 180° apart is employed.

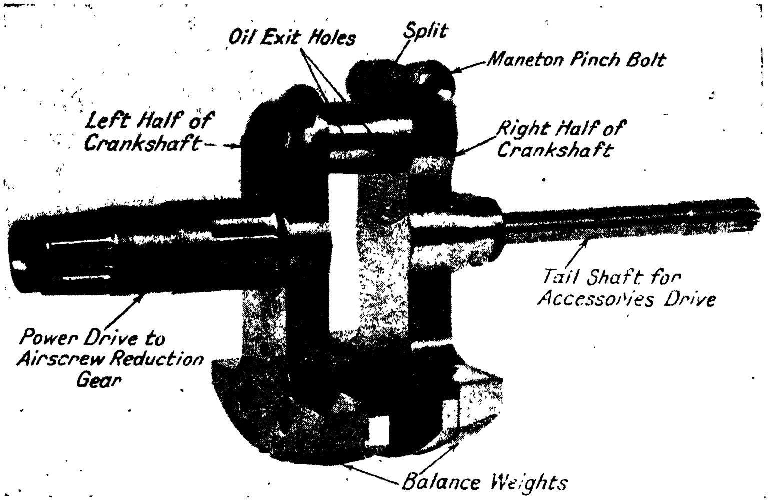


FIG. 103. Bristol radial engine crankshaft.

The crankshaft of the Bristol single-row radial engines (Fig. 103) is made in two parts, consisting of one main journal member with its crank web, counterweight and crank pin and the other main journal member having a crank web and counterweight only. The crank pin is clamped to the web of the latter member by means of a pinch bolt and nut ; the web is split at its upper end for this purpose. An advantage of this method of construction is that a special highly efficient type of crank pin bearing can be used. This consists of a phosphor bronze bush having a number of oil holes drilled right through it. This bush is a bearing fit on the crank pin and floats between the latter and the inside cylindrical or bearing surface of the master connecting rod, to which reference is made later. The Bristol crankshaft is machined from forgings in a special alloy steel, such that after machining the whole of the wearing surfaces can be hardened by the nitriding process. The crankshaft is drilled for lightness and also for lubricating oil passages to the inside of the crank pin. It is carried on one ball bearing and two roller bearings. The crankshaft carries also a tail shaft for the purpose of providing a drive for the engine accessories ; this shaft is provided with splines which engage with similar internal splines in the end of the crankshaft ; it is given a certain amount of universal movement in order to relieve the crankcase cover of any side stresses due to the non-alignment of the drive.

The Wright radial engine crankshaft embodies a special device for damping out any torsional vibrations that may occur. It is known as a "pendulum damper" and utilises the principle illustrated in Fig. 104, in which diagram A shows a simple pendulum subjected to regular impulses at its natural frequency ; these impulses cause the pendulum to commence swinging and, in time, to build up a big amplitude of swing. These conditions are analogous to those of the torsional impulses occurring at the natural torsional vibration frequency of the crankshaft thus causing a relatively large amplitude of vibration and increased stresses.

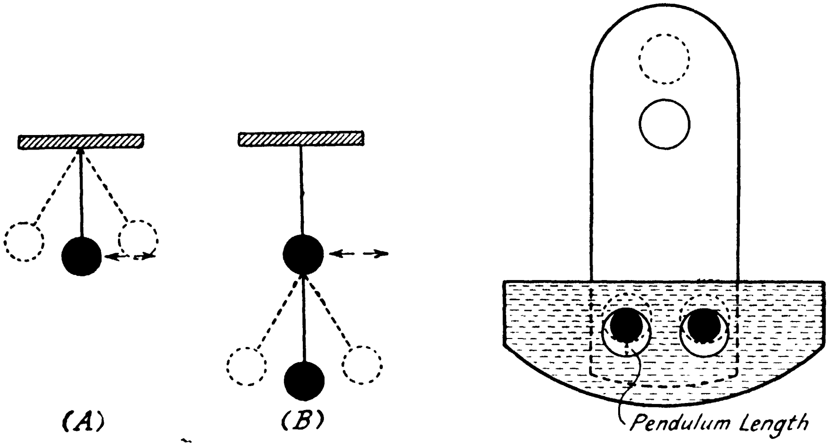


FIG. 104. (A) and (B) Principle of pendulum damper. (*Right*) Application to crankshaft.

Diagram B (Fig. 104) shows how the vibration of the pendulum can be brought to a standstill by providing a second pendulum of equal weight and length, *i.e.*, of equal vibration frequency.

The dynamic damper shown diagrammatically in Fig. 104 (right) is a short pendulum hung on to the crankshaft and tuned to the frequency of the normal speed power impulses so as to absorb the vibrations in a similar manner to that shown in diagram B, Fig. 104.

In the case of the 9-cylinder radial engine torsional vibrations are set up by the firing impulses four and a half times each revolution. To damp out these vibrations in the Wright engines the rear crankshaft counterweight is suspended on the crank cheek in such a manner that it forms a free swinging pendulum oscillating in the plane of the crankshaft rotation and of such short radius that its frequency corresponds to that of the power impulses.

Radial Engine Connecting Rod System. With the single crank-pin arrangement used for single-row radial engines it would obviously not be a very satisfactory proposition to have all of the connecting rods working on this single crank pin. Apart from the fact that it would not be possible to provide sufficient bearing area for each connecting rod big-end, the rods or the cylinders would have to be staggered in order to allow the big-end bearings to operate side by side.

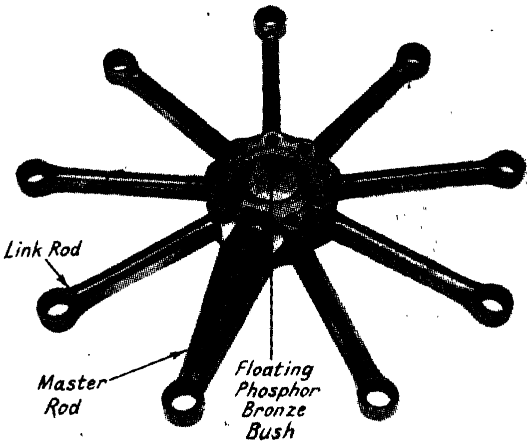


FIG. 105. Radial engine connecting rod system.

To overcome these objections the arrangement illustrated in Fig. 105 was devised. This consists of one main connecting rod, known as the *master rod*, having a big-end portion of special design so that it carries a number of bearing pins for each of the other connecting rods. The latter, known as the *link rods*, have plain phosphor bronze bush type bearings on the master rod pins. The latter are rigidly secured to the flanges of the master rod. In the operation of the engine the link rods merely rock upon the pins, whilst the master rod main bearing—which was previously described —has a relative motion of rotation to the crank pin ; actually, it is the crank pin that rotates whilst the master rod bears upon it. The link rod bearings are pressure lubricated by means of oil collected from the big-end bearing through suitable passages.

The connecting rod small-end bearings in aircraft engines are very similar to those of automobile engines. Usually, they consist of phosphor bronze bushes bearing upon the outer surfaces of the gudgeon pins. The latter are made hollow and are provided with holes to convey oil to the small-end bushes.

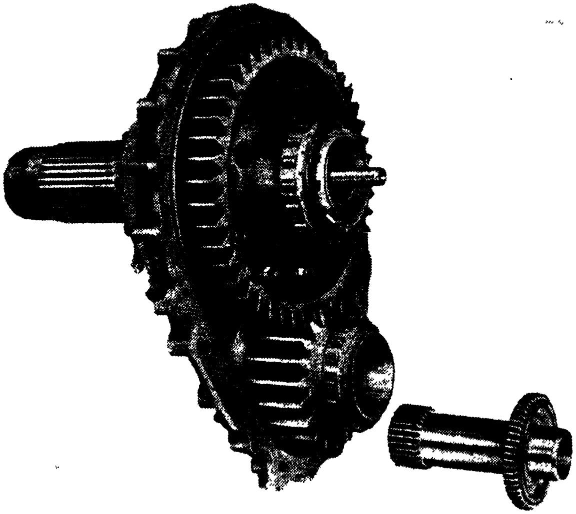


FIG. 106. Rolls Royce engine airscrew reduction gear.

The Bristol master rod is machined from a nickel-chrome steel forging weighing in its initial state about 42 lb. After machining, the rod, with its small-end bush, has a weight of about 9½ lb. When suitably heat-treated the nickel-chrome steel has a breaking (tensile) strength of 100 tons per sq. in. The link rods are made of another grade of nickel chrome steel of 65 to 70 tons per sq. in. tensile strength. In machining each of these rods the weight is reduced from 9½ lb., for the rough stamping, down to just over 2 lb. for the final rod.

The Airscrew Drive. In order to obtain high power outputs from aircraft engines of given cylinder capacities it has been found necessary to increase the engine speeds to values well above the most efficient airscrew speeds. Thus, in a typical modern example, the engine and airscrew speeds when the engine is giving its full power are 3,000 and 1,430 r.p.m. respectively. The airscrew must, therefore, be geared down in order to run at the lower speed, and the ratio of the reduction gearing must be that of the airscrew to the engine speed ; in the example mentioned this is 0·477.

The usual range of reduction gear ratios in British engines is from 0·3 to 0·6 ; the former is for high-speed engines running at 4,000 to 4,500 r.p.m. and the latter for slower speed ones, namely, from 2,300 to 2,600 r.p.m.

The simplest airscrew reduction gear is that of a pair of gear wheels of the required ratio, the smaller one on the front end of the engine shaft driving the larger one on the airscrew hub immediately above (Fig. 106). In some instances epicyclic gears are employed, as these enable the airscrew shaft to be co-axial with the crankshaft. The Bristol, Wright and Pratt-and-Whitney radial engines use the epicyclic reduction gear method. The former engines have bevel reduction gears (Fig. 107) and the two latter straight pinions and internal-toothed wheels.

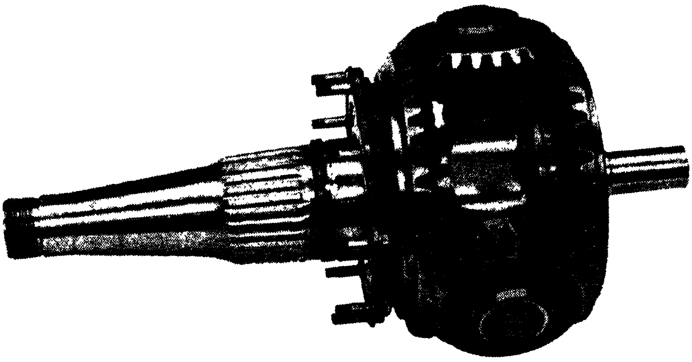
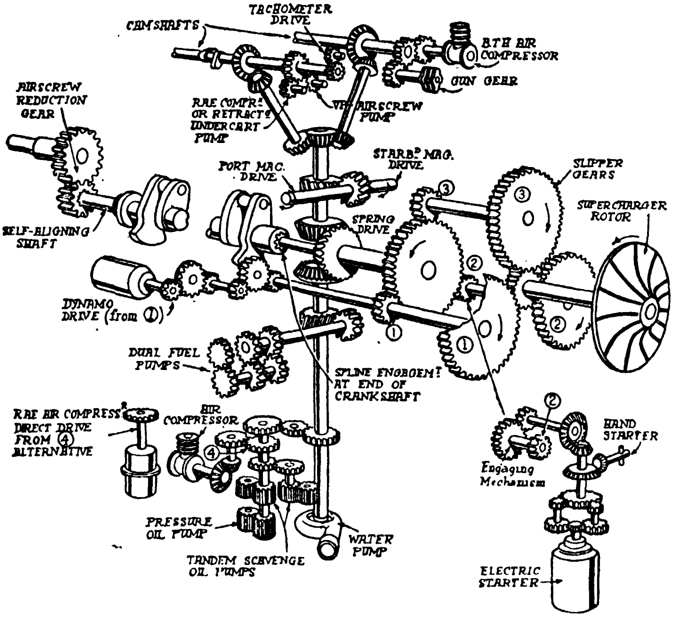


FIG. 107. Bristol epicyclic airscrew reduction gear.

Engine Accessories. The total power output as measured at the crankshaft of an aircraft engine is not wholly available for the purpose of driving the airscrew, since a number of accessories that are necessary for the operation of the engine and certain other items aircraft are driven from the engine.

The engine accessories requiring power-drive include the following : (1) The magnetos ; (2) The fuel feed pumps and, in fuel-injection type engines, the fuel-injection pumps ; (3) Liquid-cooling pumps for the cylinders ; (4) Supercharging air compressors, when fitted ; (5) The tachometer ; (6) Engine lubricating oil pumps.

The external aircraft accessories deriving their operating power from the engine include, according to the type of aircraft, some or most of the following : (1) Air compressor, high and low pressure ; (2) Vacuum pump ; (3) Electric generator for charging batteries ; (4) Hydraulic pumps for operating aircraft devices, *e.g.*, retractable undercarriage gear, wing flaps, bomb doors, gun turrets, etc. These accessories are usually mounted on, and at the rear of, the engine and are driven from the engine crankshaft by means of trains of spur gears. The lay-out of a typical gear system for driving the accessories is well illustrated by the example of the " Merlin " engine shown in Fig. 108. All of the accessory drive gears derive their power, initially, from a short drive shaft at the rear end of the crankshaft. This, through the bevel gears shown, drives a vertical and also a horizontal shaft. The former, in turn, drives the port and starboard magnetos, the two camshafts for operating the valves, air compressor, gun mechanism, tachometer, water and lubricating oil pumps, and the dual fuel-feed pumps for supplying fuel to the carburettor.



[*Courtesy of " The Aeroplane."*

FIG. 108. Arrangement of accessory drives in the " Merlin " engine.

The horizontal rear spring drive shaft rotates the supercharger at a considerably higher speed than the engine crankshaft ; also the electric generator. Special gears (shown at the lower right-hand side) are provided for connecting the hand starter for the engine and also the electric starter ; in each case a large reduction gear ratio is arranged so that the engine can be turned over slowly.

In the case of radial engines the accessories are all driven off the rear cover, but more recently there has been developed a method of grouping all of the external power-driven accessories together in a single unit mounted upon a bulkhead and driven from a single rear extension shaft of the engine. This gearbox then provides, by its internal gear trains, the correct speeds for the various accessories. The Bristol Aeroplane Company has developed this type of separate gearbox, and it has proved satisfactory under aircraft operating conditions. In the case of very large engine installations of future machines, a separate petrol or compression-ignition engine will no doubt be fitted in a convenient part of the fuselage, to drive most of the accessories and thus simplify the main aircraft engines.

The Exhaust System. When the exhaust valve opens just before the end of the firing stroke the gases in the cylinder are usually at a pressure of three to four atmospheres and a temperature of about 700° to 750° C., namely, that of a dull red heat for steel. The effect of discharging the exhaust gases at these pressures and at relatively high frequencies, due to the large number of exhausts per second directly into the air, is to cause sound waves of great intensities, which result in the characteristic and objectionable exhaust noises of open exhausts.

It is necessary, therefore, to provide aircraft engines with a system of pipes and reservoirs for the purpose of reducing the exhaust temperatures and silencing, to a comfortable degree, the noises that otherwise would occur. Whilst it is a relatively easy matter to silence an aircraft engine in the ground test house by means of a somewhat bulky and heavy system of pipes and expansion chambers, it is a difficult matter to do so on aircraft owing to space and weight considerations, so that some compromise must be effected.

The principle of efficient exhaust silencing is (1) *to cool the gases*, (2) to *reduce the pressure pulsations* causing the sound waves, down to steady pressure or flow effect, and (3) *to reduce the back pressure* in the exhaust system to its lowest practicable value ; further, for aircraft purposes the head resistance of the silencer must be as low as possible.

Whilst the process of silencing the exhaust gases involves an appreciable amount of cooling effect, for aircraft purposes there should be ample overall cooling so that no visible flame can occur.

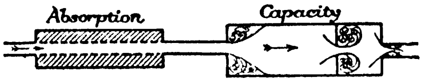


FIG. 109. Ideal silencing system for the exhaust gases.

The efficient silencing of an engine involves a study of the frequencies of the sound waves emitted from an open exhaust, and in this connection it has been found that, in general, the exhaust noise may be regarded as being made up of two parts, namely, (1) *A low-to-medium frequency* band of 50 to 600 cycles per second, and (2) A high frequency band of 3,000 to 10,000 cycles per second, causing the high pitch exhaust noises.

In order to silence the lower frequency band mentioned it is necessary to use what is known as a *capacity type of silencer*, namely, a plain silencer, or reservoir of large capacity and big changes of section.

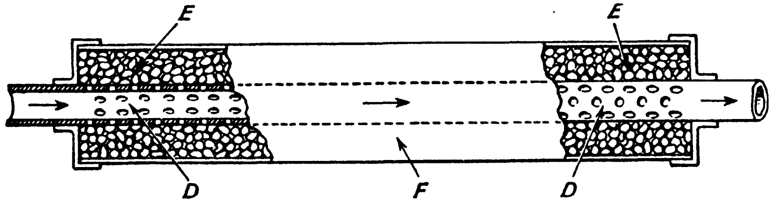


FIG. 110. The Burgess absorption-type silencer

To silence the high frequency noises requires another type, known as the *absorption silencer*, consisting of a straight-through perforated tube surrounded by an outer chamber filled with a sound-absorbent material such as steel wool, glass fibres or bundled wires, which damp down and absorb the high frequency noises.

In order to silence both high and low frequency noises a combination capacity-absorption silencer (Fig. 109) must be employed.

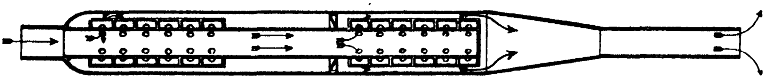


FIG. 111. The Burgess-Farnborough aircraft engine silencer. The arrows show paths of the gases.

A typical absorption-type silencer is the Burgess one shown in Fig. 110. This consists of a perforated steel tube D within an outer steel container F, the space between the two being filled with steel wool or wire.

An improved design of silencer, based upon a somewhat different acoustical principle, is the Burgess-Farnborough one (Fig. 111). The silencer is a full resonator consisting of two resonant chambers, the first one, namely, at the inlet having re-entry to the exhaust passage and the second one an outlet to the atmosphere. Surrounding the exhaust pipe and within these chambers there are acoustic filters communicating through holes with the exhaust pipe and the exterior reservoir. The principle employed in this example is that of "sound reflection," in which the sound waves are reflected out of phase so that the high pressure peaks coincide, after reflection, with the low pressure troughs and cancel out.

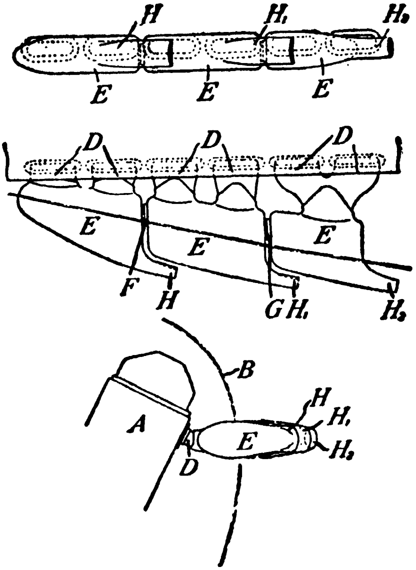


FIG. 112. Rolls Royce ejector type of silencer.

The Rolls Royce Merlin engines employ an exhaust manifold silencing system, known as the *ejector type*, which has the advantage of giving reasonably good silencing combined with low weight, small bulk and minimum head resistance. In addition, the exhaust gases are discharged through injector nozzles, rearwards, in such a manner that their kinetic energy is utilised to exert a forward thrust on the aircraft. In this connection it may again be mentioned that the exhaust ejector action has more recently been utilised to assist in the duct cooling of the radiator. The principle of the ejector type silencer is shown in Fig. 112. which illustrates the exhaust system of an engine having two banks of cylinders arranged in a vee, one of the banks being shown at A. The engine is contained in a cowling B. Each bank has 6 cylinders, the exhaust gases from which pass into short pipes D. Three expansion boxes E are connected together by short lengths of piping F and G, and each of these collects the gases from two of the pipes D. Each box has a rearwardly projecting nozzle H, H_1, and H_2 with orifices shaped as shown, those of nozzles H, H_1 being crescent shaped and that of H_2 being oval. These nozzles are tapered and restricted and operate to increase the kinetic energy of the gases at the point of discharge. The group of boxes together forms a member of flattened streamline shape except for the necessary departure therefrom due to accommodating the discharge orifices. In the example shown only a part of the streamline member lies outside the cowling. It can, however, be wholly outside.

The weight of this silencer for a 12-cylinder Vee-type engine of 800–1,000 h.p. is only 17½ lb. per side, *i.e.*, 35 lb. for the complete system. The back pressure is also very low and at speeds above about 350 m.p.h. the exhaust system actually gives an increase in speed of the machine.

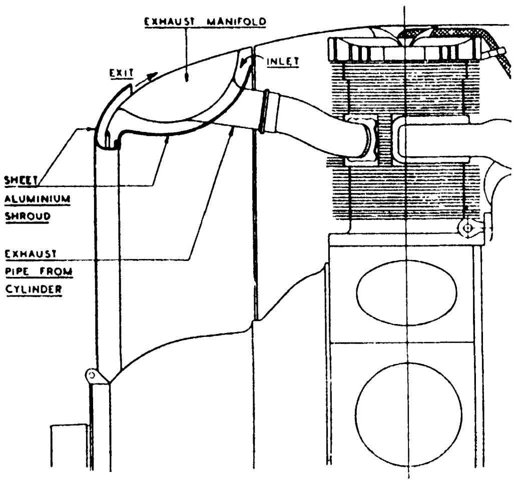


FIG. 113. Bristol radial type exhaust manifold.

The exhaust system used on radial engines is generally that of a hollow ring into which the exhausts from all the individual cylinders are directed; the annular silencer has either one or two rearward exits to the atmosphere.

Fig. 113 illustrates the Bristol shrouded exhaust manifold which utilises the method of reverse flow cooling. It consists of a shield or shroud fitted around the nose and inner surface of the exhaust manifold. The annular outlet aperture between the shroud and the manifold is located near the nose in a region of relatively low air pressure, whilst the inlet aperture is at the rear of the shroud, in the high pressure region which exists immediately in front of the cylinders. A proportion of the air flowing through the cowl therefore diverges from the main stream and flows forward through the channel between the shroud and the manifold, rejoining the outer air stream at the nose aperture. With this arrangement it has been shown that the cooling power loss, based on the product of the volume flow and pressure drop, is reduced, whilst the capacity for adequate cooling of higher-powered engines inside a given diameter cowl is increased. The collector ring volume is usually made about one-half the total cylinder capacity, in radial engines.

Fig. 114 shows the cowling, cooling and exhaust arrangements of the German B.M.W. 801A, 1,600 h.p., 14-cylinder air-cooled radial engine. In particular it indicates the method of damping the flames that, otherwise, would occur at the exhaust outlet pipes. The ribbed exit members tend to cool down the gases sufficiently so as to prevent flames from occurring. It will also be observed that the exhaust pipes from the engine are provided with sleeves, or muffs, through which air is drawn for the purpose of heating before supplying it to the cabin. A sliding type of ring around the periphery of the cowling, at its rear end, enables the temperature of the cooling air to be regulated.

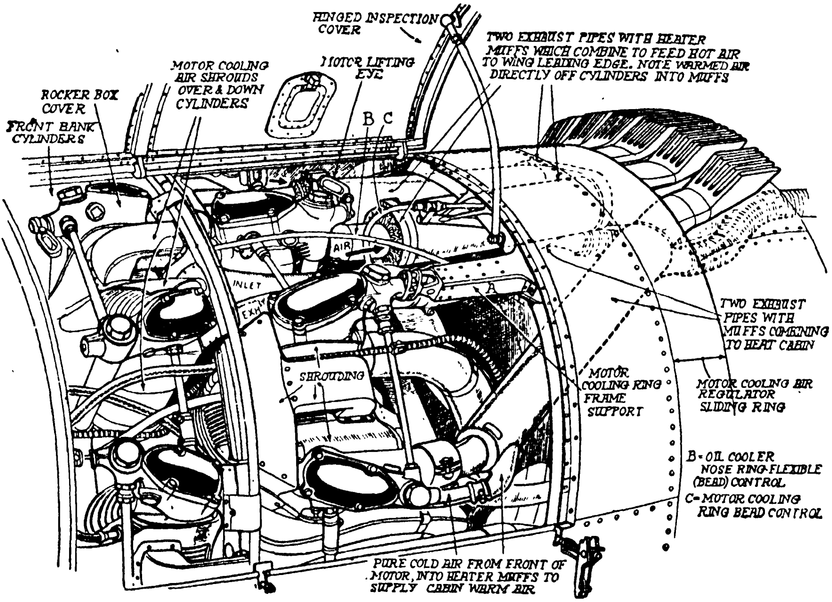


FIG. 114. The B.M.W. 801A German 14-cylinder radial engine exhaust and cooling arrangements.

[*Courtesy of " The Aeroplane."*

Exhaust manifolds are generally made of sheet steel with riveted instead of welded joints, and it is necessary to protect the inside and outside surfaces against corrosion by spraying with aluminium or by nickel plating. More recently heat- and corrosion-resisting nickel chromium steels and stainless steels have been used for exhaust manifolds. Another very satisfactory material is Inconel, consisting of 80 per cent. nickel, 14 per cent. chromium and the rest mainly of iron ; this alloy is strong, ductile and highly resistant to corrosion, whilst retaining a relatively high percentage of its cold strength properties at exhaust temperatures; it is generally used in thicknesses of 18 to 20 S.W.G.

Engine Mountings. The engine mounting serves to take the weight of the engine and to attach the latter to the frame of the fuselage or wing structure (in the case of multiple engine aircraft); it also transmits the airscrew thrust and the engine torque reaction to the aircraft framework.

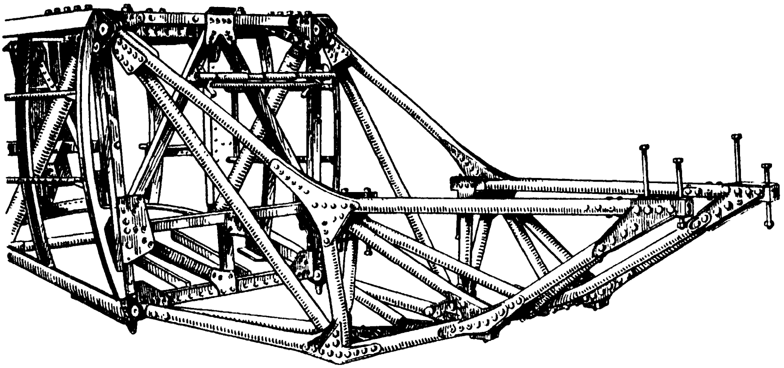


FIG. 115. Rolls Royce "Merlin" engine mounting as used on fighter aircraft.

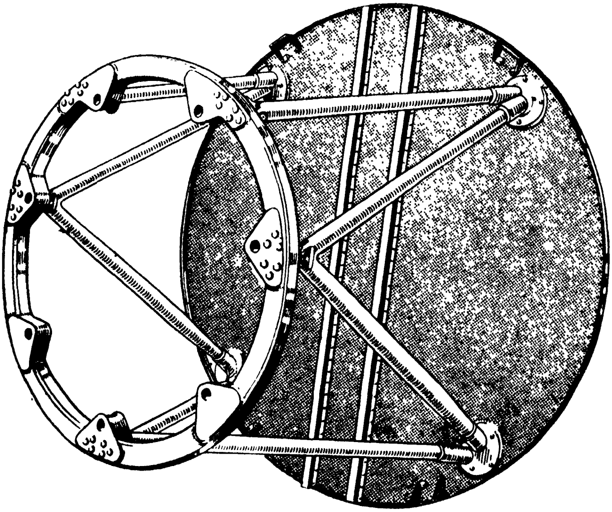


FIG. 116. The Bristol radial sleeve-valve engine mounting, with bulkhead on right.

The design of mounting depends, largely, upon the type of engine, but it usually consists of a framework built up of steel tubes welded together and to common bracket or plate members; is provided with suitable bearers or flanges for bolting on the engine

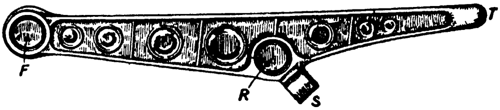


FIG. 117. Elektron engine bearer.

crankcase unit and separate attachment lugs, plates or flanges for fixing the engine and mounting frame to the aircraft structure.

Typical illustrations of engine mountings for a 12-cylinder Vee-type engine and a high-power radial one are given in Figs. 115 and 116. Another type of engine mounting used on certain German aircraft is shown in Fig. 117. It consists of two forged Elektron magnesium alloy bearers, one on either side of the engine; the latter is connected to trunnion bearings at F and R respectively. The bearers are in their turn connected to the bulkhead frame of

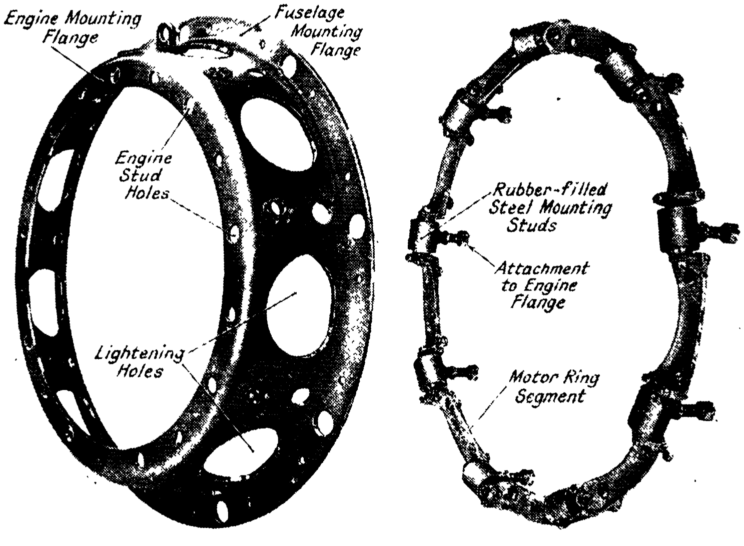


FIG. 118. Bristol radial engine flexible rubber-filled stud mounting.

the aircraft by a socket fitting to take the rounded end portion T and a strut to connect the lug S to the frame. The engine bearers in question are both strong and light, weighing only about 26 lb. each for a 1,000-h.p. engine.

The Bristol radial engines are usually mounted on a double-flanged steel plate pressing, provided with holes for the bolting of the engine crankcase unit on one side and others for the attachment bolts of the aircraft bulkhead or power "egg" member on the opposite side. Suitable lightening holes are provided around the cylindrical portion.

In many instances, instead of bolting the engine direct to the metal of the engine mounting, rubber blocks are interposed in order to insulate the engine vibration effects, or damp them out in a similar manner to that of the flexible mountings used for motor car engines. A typical example is that of the Bristol mounting shown in Fig. 118. An artificial rubber, immune from the effects of ordinary aircraft engine temperatures and from oil, petrol and moisture, is employed for this purpose. Usually, the rubber is encased in cylindrical metal containers in such a manner that any failure of the rubber would not result in any serious engine movement.

CHAPTER VII

TYPES OF AIRCRAFT ENGINE

SINCE the earliest days of power-driven aircraft there has been a wide range of different types of engine. The majority of these are now of historic interest only, so that the present section will be confined to a consideration of engines that have been employed in civil and military aircraft in recent years.

A convenient method of classifying such engines is to arrange them into power groups, indicating at the same time their usual applications, as follows :—

(1) 50 to 100 b.h.p. Light touring aeroplanes, 2-seater club and light commercial machines, etc.

(2) 100 to 250 b.h.p. Civil training machines, first stage military tuition aircraft, light touring machines.

(3) 250 to 700 b.h.p. More advanced military training machines (single and twin engine), commercial medium speed aircraft, higher performance single engine civil aeroplanes.

(4) 700 to 1,200 b.h.p. Larger commercial multi-engine machines, flying boats, single engine military fighters, multi-engine bombers, twin-engine long distance fighters.

(5) 1,000 to 2,000 b.h.p. High performance commercial multi-engine aircraft, high performance military single engine fighter machines, twin-engine bombers, heavy load-carrying, long distance machines.

The selection of the most suitable type of engine for each of these groups is to some extent governed by the power output and also a number of other minor factors concerned with particular purpose for which the aircraft is to be employed.

In some instances the question of first cost is of primary importance, notably in the case of small commercial aircraft in Group (1). In other instances the main considerations are low fuel and maintenance costs, as with long distance commercial machines. Military aircraft, on the other hand, require the maximum outputs for minimum weight, combined with relatively low fuel consumption. In long distance military aircraft, whilst relatively high power-per-unit-weight is important, low fuel consumption and the ability to operate over long periods with the minimum of maintenance attention are the ruling factors.

The selection of an engine for any particular type of aircraft is generally a matter of determining (1) *The number of cylinders.* (2) *The best arrangement of these cylinders for satisfactory torque and good engine balance,* combined with *low frontal area* and (3) Whether the engine is to be *air- or liquid-cooled.*

(1) **Number of Cylinders.** Experience and experiment have both shown that the bore and stroke of an aircraft engine cylinder should lie within certain limits.

If *the cylinder size is too small* this will mean a greater number of cylinders for a given power output, and therefore an all-round increase in the number of working parts. The maintenance attention will also be increased and, with the greater number of working parts, there will be a greater possibility of breakdown.

On the other hand, *if the cylinders are too big,* fewer will be needed for a given power output, but it may not be possible to arrange the best torque and engine balance except in the instance of the very high output engines. For smaller outputs the increased cylinder dimensions will mean a greater frontal area and therefore increased head resistance and a larger engine housing unit. On the other hand, the number of working parts will be reduced giving greater reliability and reduced maintenance time.

It has been ascertained as the result of experimental work that the cylinder bores for aircraft engines should lie between 3¾ in. and 6 in., with an average of 5 in. to 5½ in. as representing the most favoured dimensions. The smaller bore engines are those running at the highest speeds. Thus, the Napier " Dagger VIII " engine has a bore and stroke of 3·82 in. and 3·74 in. respectively, and gives its maximum power output at 4,200 r.p.m., whereas the Bristol " Perseus " engine has cylinders of 5·75 in. bore and 6·50 in. stroke, and gives its greatest output at 2,600 r.p.m.

It has also been shown, as a result of laboratory tests, that as the cylinder bore of an engine is reduced, the compression ratio, for a given grade of fuel, can be increased progressively, before detonation occurs. This increased compression means that the *power output per unit volume can be increased* as the cylinder bore is reduced.

An example of this is given by the results of tests on cylinders of 4 in., 5½ in. and 6½ in. bore, under similar conditions of operation, which showed that the power output per litre (1,000 cu. cm.) was 40 per cent. greater for the 4-in. bore cylinder and 65 per cent. more than for the 6½-in. bore one.

If the average size of cylinder be taken as 5 in. to 5½-in. bore with a stroke of 5¾ in. to 6¼ in., then the maximum power output of a modern design of cylinder would be about 80 to 100 brake horse power (b.h.p.) and the average range of engine speeds from 2,500 to 3,000 r.p.m. It will thus be apparent that a 1,000 h.p. engine would require twelve cylinders of about 5-in. bore.

In the case of engines of about 300 h.p. and less, it is not feasible to use large cylinders, as these would necessitate the employment of too few for proper engine balance and torque. It is usual, therefore, to adopt cylinders with bores of 4 in. to 4½ in. for the smaller engines.

In regard to the *piston strokes of aircraft engines*, for small cylinders and therefore high engine speeds, the strokes are made equal to or slightly greater than the bores. For the larger sizes of cylinders, namely, from 5 in. to 6-in. bore, the stroke is usually made greater than the bore by 15 to 20 per cent.

(2) **Arrangement of the Cylinders.** It has been shown that there is a limited range of sizes for the cylinders of aircraft engines, thus governing the number of cylinders, and it follows that the smallest number of cylinders is therefore associated with the lowest power outputs, whilst the greatest number is employed on engines of the highest power outputs. Thus, for outputs of 50 to 100 h.p., engines with either 2 or 4 cylinders would be used. For power outputs of 2,000 h.p. and above, 18 cylinders or 21 cylinders, for radial engines, and 24 cylinders for Vee-type, X-type and H-type liquid-cooled engines would be employed.

Considering the 1,000 h.p. class engine this will be a 9- or 14-cylinder air-cooled radial, or a 12-cylinder Vee-type liquid-cooled; a possible alternative to the latter would be a 12-cylinder opposed liquid-cooled engine similar to the American Lycoming engine.

The various modern types of engines can conveniently be classified into groups of different horse power range similar to those referred to on p. 135. Particulars of these engine types are given in the table on p. 138.

A study of the results given in the table on p. 138 reveals the interesting fact that all of the engines in the lower power groups, with one exception, are of the air-cooled class, whilst in the higher power groups there are both air- and liquid-cooled types. Actually there are at present considerably more types and numbers of high-powered air-cooled engines in service than liquid-cooled ones. In this country there is only one originating firm of liquid-cooled engine manufacturers, as compared with eight firms of air-cooled engine manufacturers. In the U.S.A., with the exception of the Allison and Lycoming liquid-cooled engines, all the rest were of the air-cooled kind.

Classification of Engines by Horse Power Ranges

Class (h.p.)	Number of Cylinders	Arrangement of Cylinders		Typical Commercial Examples
		Air-cooled	Liquid-cooled	
50–100	2	Opposed, cranks at 180°	—	Continental (50 h.p.).
	4	Vertical, in line and inverted	—	Gipsy Minor (100/110 h.p.), Cirrus Minor (90 h.p.).
	4	Opposed (double 2-cylinder opposed)	—	Continental (50 and 75 h.p.). Aspin Rotary Valve (90 h.p.)
100–250	4	Vertical, in line and inverted	—	Gipsy Major II (140 h.p.) Cirrus Major 150 (150 h.p.)
	6	Vertical, in line and inverted	—	Gipsy Six II (205 h.p.) Menasco Super Buccaneer (250 h.p.)
	7	Radial	—	Genet Major IV (180 h.p.) Lynx IVC (240 h.p.)
250–700	7	Radial	—	Cheetah X (350 h.p).
	9	Radial	—	Alvis Leonides (440 h.p.) Bristol Aquila IV (540 h.p.)
	12	Vee-type. Inverted	—	Gipsy Twelve (425 h.p.)
	12	—	Vee-type. Upright	Rolls Royce Kestrel XVI (745 h.p.)
	16	H-type. Four rows of 4-cylinders	—	Napier Rapier VI (365 h.p.)
700–1,200	24	H-type. Four rows of 6-cylinder	—	Napier Dagger VIII (935 h.p.)
			H-type. Four rows of 6-cylinders	
	9	Single Row Radial	—	Bristol Pegasus XVIII (1,000 h.p.)
	14	Two rows of 7-cylinders, Radial	—	Pratt and Whitney Twin Wasp (1,100 h.p.)
	12	—	Vee-type. Upright	Rolls Royce Merlin X (1,145 h.p.)
	12	—	Vee-type. Inverted	Junkers. Juno 211A (1,200 h.p.)
	12	—	Horizontally opposed	Lycoming (1,000 h.p.)
1,000–2,500	14	Two rows of 7-cylinders. Radial	—	Bristol Hercules II (1,300 h.p.) Wright Cyclone (1,600 h.p.)
	18	Two rows of 9-cylinders. Radial	—	Wright Duplex Cyclone (2,000 h.p.)
	24	—	X-type or double 12-Vee	Rolls Royce Vulture (2,000 h.p.) Mercedes Benz DB-605 (2,000 h.p.)
	24	—	H-type	Napier Sabre.

Note. The h.p. values given in the r.h. column are nominal values for maximum ground h.p.'s.

Modern aircraft engines belong to certain definite types, or arrangements of cylinders and crankshaft, the principal ones being shown diagrammatically in end view in this chapter; these views are of interest, also, since they denote the relative frontal areas of the engines in question. The following notes are intended as a guide to the advantages and applications of the engines in question.

✓ (1) **"In-line" Engines.** Although Fig. 119 depicts a single-cylinder engine in end elevation, it may also be regarded as an end view of a 4- or 6-cylinder engine, a fact which indicates that the frontal areas of the 1-, 4- or 6-cylinder engines are approximately the same, so that by arranging the cylinders in a line the head resistance may be kept down to a minimum. Actually, the resistance of a 6-cylinder engine will be rather higher than that of a 4, owing to its greater length, unless the complete engine can be enclosed within the fuselage or a power unit cowling.

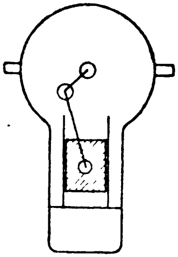


FIG. 119. Arrangement of "In-line" engines.

As mentioned previously, the single-cylinder engine is not used on full-scale aircraft, but it may be of interest to note that *tiny model engines* of the single-cylinder 2- and 4-cycle pattern are used on the smallest power-driven model aircraft. These engines are made in cylinder capacities of 5, 10, 15 and 20 c.c., and operate at maximum speeds of 5,000 to 10,000 r.p.m. A typical engine has a bore of 0·875 in., and stroke of 1 in., and develops 0·2 h.p. at 10,000 r.p.m. Its weight, complete with fuel tank, battery for ignition and airscrew, is 20 oz.

The 4- and 6-cylinder "in-line" aircraft engines are arranged to operate in the inverted position, chiefly in order to give a better view ahead for the pilot, since the crankcase is of much smaller frontal area than the cylinder units. In the inverted position the cylinders are more accessible for attention to the valves and sparking plugs. The cooling of this type of engine is also more satisfactory than if the cylinders were on top.

Although, at first, it might be thought that lubrication difficulties would be experienced with the inverted type of engine, as distinct from the automobile pattern with its oil reservoir in the bottom of the crankcase, this is not the case since the dry sump method of lubrication is employed with inverted types of aircraft engines.

The 4-cylinder aircraft engine employs the same arrangement of cranks as for the automobile engine; this is described in Chapter VI. The engines are all of the air-cooled pattern with cylinder baffles to direct the cooling air due to the forward motion of the machine on to the hotter parts of the cylinders. The 4-cylinder engines usually develop between 80 and 150 b.h.p. at normal engine speeds of 2,000 to 2,500 r.p.m.; no airscrew reduction gear is fitted.

The dry weights per maximum (take-off) horse-power of these engines is from 2·1 to 2·6 per h.p. for unsupercharged engines operating on 80-octane fuel. The compression ratio for the same fuel is about 6·5 to 1. The fuel consumption lies between 0·5 and 0·6 lb. per b.h.p., and the oil consumption from 0·010 to 0·015 lb. per b.h.p. per hour.

A typical 4-cylinder engine is the Cirrus Major (shown in Fig. 120).* This has a bore and stroke of 4·72 in. (120 mm.) and 5·5 in. (140 mm.) giving a cubical capacity of 386 cu. in. (6,330 c.c.). The compression ratio is 5·8 : 1 and maximum output, 150 b.h.p. at 2,450 r.p.m., with cruising output of 138 b.h.p. at 2,200 r.p.m. The features include steel cylinders machined from forgings located in the crankcase by spigots each secured at its base by four bolts so that no cylinder head distortion can occur by this clamping-down method. The cylinder heads are made from Y-alloy castings, spigoted and clamped by eight studs to the cylinder flange. The cylinder head forms one-half of the valve gear-box and has an Elektron (magnesium alloy) cover which acts as an oil bath for the valve mechanism. Y-alloy pistons of the slipper type with fully-floating gudgeon pins, located by circlips, and fitted with two compression and one scraper ring, are employed. The connecting rods are made from the light aluminium alloy, Hiduminium, and the big-ends have white metal bearings in steel shells. The crankshaft is of the five main-bearing type with a ball-thrust bearing at one end to take the thrust of the airscrew. The camshaft also has five main bearings, and is driven from the crankshaft by means of a train of gears at the front end.

Overhead type push-rod and rocker valves are employed; double ball-ended push-rods are used and the tappets are cup-ended and in one piece, passing through Duralumin guides.

The whole of the valve rocker mechanism is enclosed. The valve clearances are easily set by means of an adjustable ball-cup in the rocker with lock-nut and tab washer. Instead of a hardened pad on the rocker a ball is fitted in the cup-ended rocker and a flat on the ball makes contact with the valve stem. The ball being free to turn in its housing offers a constant large wearing surface, whilst

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* Messrs. Blackburn Ltd.

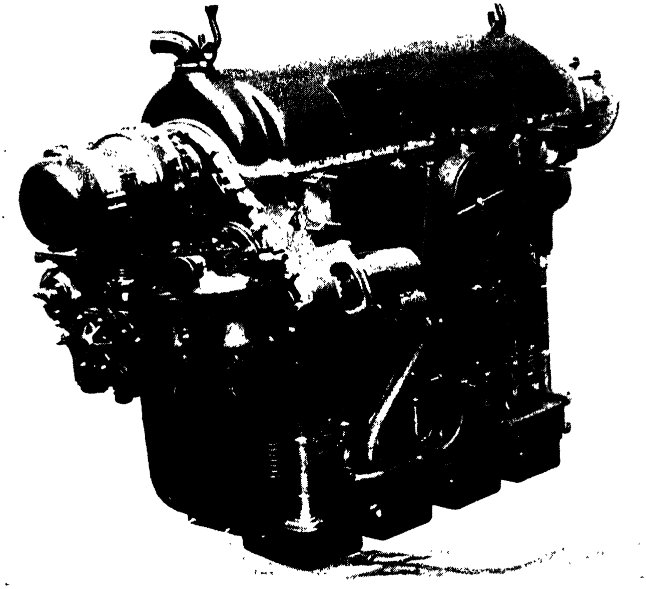
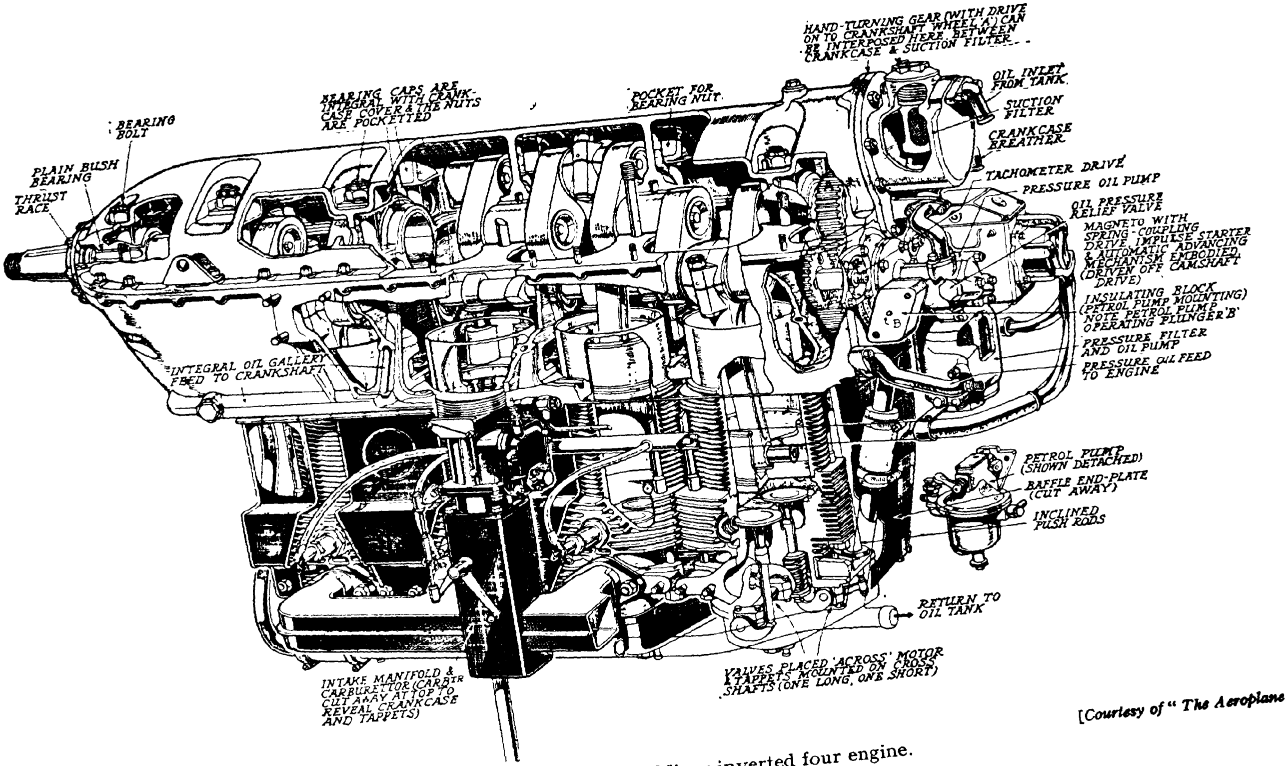


FIG. 120. The "Cirrus Major" four-cylinder inverted engine, showing carburettor and rear-end accessories.

[*Facing p.* 140.



[Courtesy of "The Aeroplane."

FIG. 121. The Gipsy Minor inverted four engine.

the flat maintains correct relative position on the valve stem and eliminates all wear.

The crankcase is made in the form of an Elektron casting with all the pressure oil-ways embodied. Two Amal fuel pumps can be fitted to it, the usual arrangement being one on either side at the rear, operated by cams on the separate magneto vertical driving shafts. Hand-priming levers are fitted to these pumps for starting purposes. The rear end of the crankcase has a breather located centrally, whilst on one side the tachometer drive is taken off.

The engine is fitted with a Claudel Hobson down-draught carburettor with an independent altitude control.

Ignition is by two B.T.H. S.G.4 magnetos of the spigot-mounted type, one having an impulse starting device ; the distributors face upwards, for easy access ; two 14 mm. sparking plugs are fitted to each cylinder.

The engine cylinder cowling has detachable inspection panels to facilitate removal of the sparking plugs for cleaning.

Another example of the inverted four engine is the Gipsy Minor,* which has a bore and stroke of 4·016 in. (102 mm.) and 4·528 in. (115 mm.), giving a cylinder capacity of 229·29 cu. in. (3·76 litres). It has a compression ratio of 6 : 1 and weight, less the airscrew boss, of 205 to 215 lb. The take-off power is 80 b.h.p. at 2,250 r.p.m. and normal cruising power 60 b.h.p. (66·6 per cent.) at 2,250 at sea level.

The 6-cylinder " in-line " engine resembles the four in its main constructional details, but may be regarded as an inverted version of an automobile type of engine, modified to suit aircraft requirements. Its crankshaft is of the same type as that illustrated in Fig. 100 on p. 119. The addition of 2 cylinders to the 4-cylinder arrangement, as previously mentioned, does not appreciably affect the frontal area, so that this engine gives a higher horse-power per sq. ft. of frontal area and is therefore relatively more efficient than the 4-cylinder one.

A typical engine of this class is the Gipsy Series II, which has a bore of 4·646 (118 mm.) and stroke of 5·512 in. (140 mm.), giving a cylinder capacity of 9·186 litres. It has a compression ratio of 6·0 to 1.

Fig. 20 on page 39 shows the full throttle, throttled power and consumption curves obtained during official type tests with a fuel not inferior to 77-octane. The fuel consumption under the previously stated cruising conditions is 0·5 pints per b.h.p. hour ; for fuel of 0·75 S.G. this is equivalent to 0·375 lb. per b.h.p. hour.

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* De Havilland Aircraft Co. Ltd.

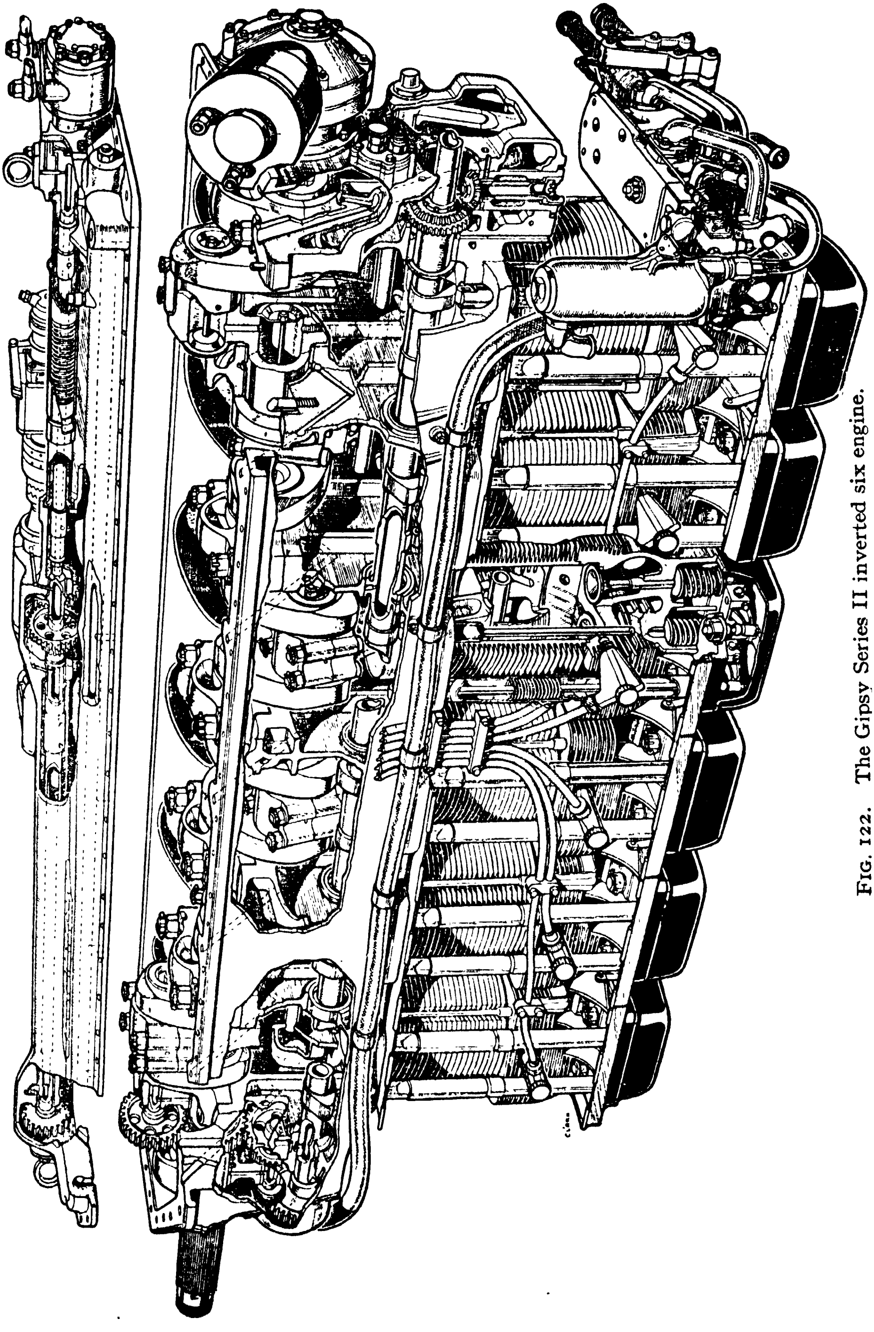

FIG. 122. The Gipsy Series II inverted six engine.

The engine is suitable for use with controllable pitch airscrews and it will give about 153 b.h.p. at 6,000 ft. altitude with such airscrews, used in conjunction with the de Havilland constant speed governor; as the altitude increases to 14,000 ft. the power falls progressively to 112 b.h.p. The maximum ground level output is 205 b.h.p. at 2,400 r.p.m. The minimum fuel consumption for low level weak mixture conditions is about 0·47 lb. per h.p. hour; for all-out level flight at full throttle with mixture control in the fully rich position this figure is increased to about 0·49 lb. per h.p. hour. The dry weight of this engine is 470 lbs., corresponding to 2·3 lbs. per h.p.

Special features of the engine include the use of steel cylinders machined all over and the special treatment of exposed surfaces to prevent corrosion; aluminium alloy cylinder heads; slipper-type pistons of aluminium alloy, with fully-floating gudgeon pins and two compression and one scraper ring below the gudgeon pin; aluminium alloy connecting rods with four bolts to each big-end and white-metal lined split steel shells; eight-bearing crankshaft with white metal main bearings and ball-thrust bearing at the front end; Elektron crankcase; fully enclosed overhead valve gear with one inlet and one Stellited exhaust valve per cylinder; high expansion steel valve seat inserts; light alloy tubular push rods and steel tappets operated off seven-bearing camshaft; twin Claudel Hobson down-draught carburettors, each supplying three cylinders; lubrication at 40 to 45 lbs. per sq. in. pressure; dual ignition by two B.T.H. magnetos and Rotax electrical engine starter.

In connection with the auxiliary drives the camshaft and all auxiliaries are driven off the gear wheel on the front end of crankshaft between the ball thrust-bearing and the first crank-throw. A train of hardened gears with profile-ground teeth drives the camshaft; also the shaft in top cover which runs at 1·5 times crankshaft speed to drive the magnetos. There is an alternative type of crankcase top cover which incorporates a drive for an electric generator of (up to) 500 watts output. Accommodation has also been made for an oil pressure-increasing valve and hand-control, for use when 2-position controllable airscrews are fitted. Fuel and oil pumps are driven off the vertical shaft at the back of camshaft. Tachometer drives and starter are fitted at the bank of crankcase. The fuel feed supply to the carburettors is by an Amal Duplex engine-driven diaphragm type fuel pump.

A more recent supercharged version of the Gipsy Six engine known as the "Gipsyqueen IV" has a bore of 120 mm. and stroke of 150 mm. giving 10·18 litres capacity. Its cruising power output at 12,000 ft. is 180 B.H.P. and dry weight without the engine starter and other accessories, 560 lb. The centrifugal type supercharger runs at 11·16 times crankshaft speed; the compression ratio is 6·2 to 1.

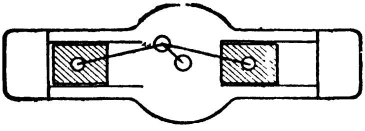

FIG. 123. Arrangement of opposed-cylinder engine.

(2) **Opposed Cylinder Engines.** This type has always offered attractions to engine designers on account of its practically perfect engine balance and equal firing intervals. Moreover, it enables a " flat " shape of engine to be made, which is ideal for housing within deep-section aircraft wings, although not as good as the " in line " engine of equal output for ordinary fuselage mounting.

The schematic layout of this engine is shown in Fig. 123. In this diagram the two connecting rods are shown connected to the same crank pin; in practice a pair of cranks at 180°—as shown in Fig. 98—is used, in order to obtain correct balance for the reciprocating forces, *i.e.*, the pistons and part of the connecting rods.

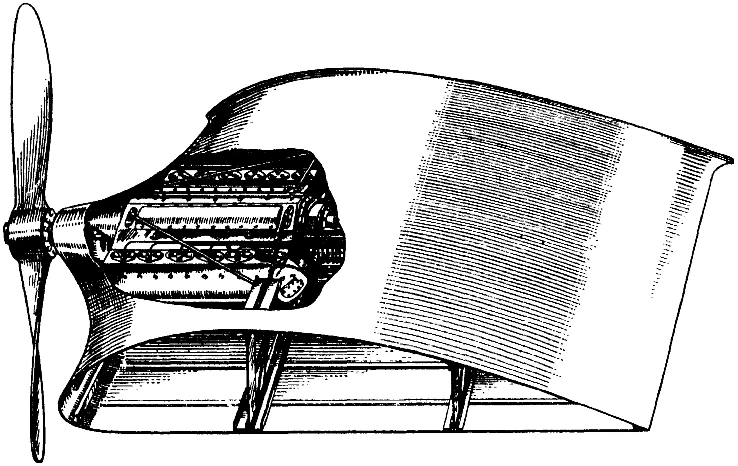

FIG. 124. Showing how an opposed-cylinder engine can be fitted into the wing of an aircraft.

The two pistons therefore move inwards and outwards together just as if one piston was the looking-glass image of the other.

The opposed 2-cylinder engine was used for very light aeroplanes and power-assisted gliders some years ago; a typical example was the 30-h.p. A.B.C. engine which was fitted to the front of the fuselage with its air-cooled fins exposed to the cooling draught of the machine. An example of this and several other early aircraft engines can be seen in the Science Museum, South Kensington, London.

The smallest opposed-cylinder engines used to-day are the 50- to 80-h.p. 4-cylinder ones, with two cylinders in line on each side of the crankshaft, namely, at 180° apart. This arrangement, however, gives about 75 per cent. greater frontal area than for the 4-cylinder in-line of similar output. An example of this engine is the Continental 4-cylinder opposed one, Model A (Fig. 89, p. 113), which has a bore and stroke of 3·875 in. and 3·625 in., giving a cubical capacity of 171 cu. in. (2·8 litres). The compression ratio is 5·4 : 1 and the rated h.p. is 50 at 1,900 r.p.m. on 73-octane fuel.

The finned cylinders are made from steel forgings shrunk and screwed into heat-treated aluminium heads. The pistons are also of aluminium alloy cast in permanent moulds. They are fitted with two compression and one scraper ring. The H-section connecting-rods have a bronze bush at the small end, while the big-end bearing is copper-lead lined and of the replaceable thin steel shell backed type. The forged four-throw crankshaft has also steel-backed copper-lead bearings. Plain thrust faces are formed on the propeller end throw and on a shoulder near the propeller, enabling the unit to be used either as a pusher or tractor.

A cast camshaft with six hardened cams and three journals is employed. At the propeller end the shaft is extended to carry an eccentric which drives the fuel pump. The overhead valves are driven through rockers and tappet rods fitted with hydraulic tappets of the automatic adjustment type. The entire rocker box mechanism is lubricated automatically. Aluminium-bronze valve seat inserts and sparking plug bushes are fitted. The crankcase is of aluminium alloy cast in two pieces and bolted together. It is reinforced with a central web supporting the middle crankshaft and camshaft bearings. The timing gears are at the opposite end to the propeller shaft, the casing forming the support for the dual ignition units, oil pump, tachometer drive, starter and generator. A Stromberg updraught carburettor is fitted to the smaller engines ; also an aluminium manifold with exhaust hot-spot. Steel inlet pipes connect this manifold to all the four inlet pipes.

It is of interest to note that this and certain other models of Continental opposed-cylinder engines may be fitted alternatively with fuel injection equipment instead of carburettors.

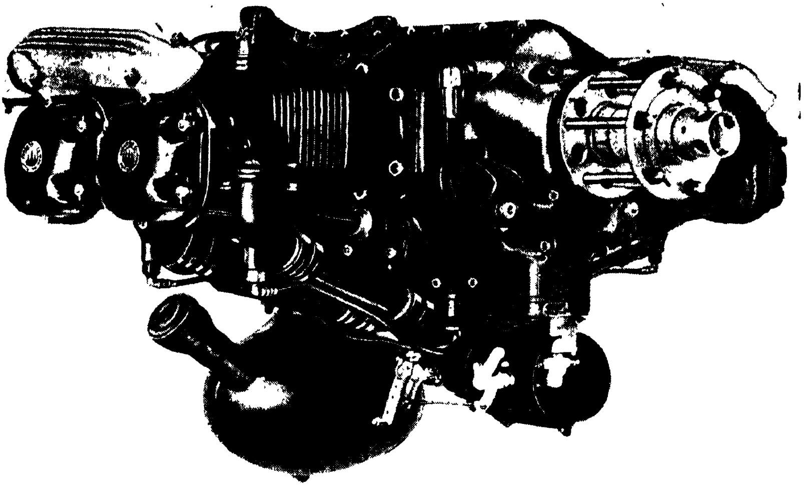

FIG. 125. The Continental 4-cylinder opposed engine. (Petrol injection model.)

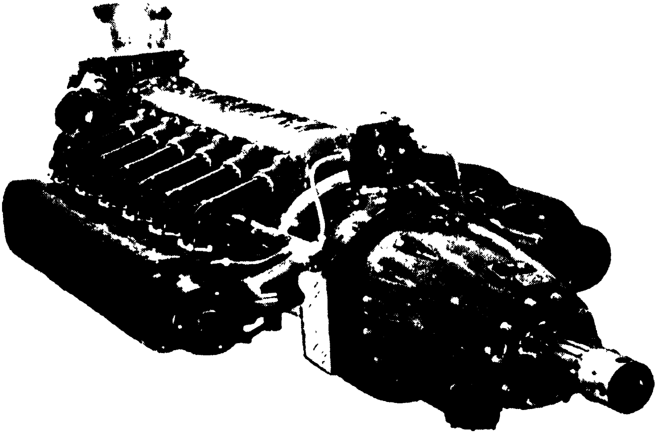

FIG. 126. The Lycoming 12-cylinder liquid-cooled opposed engine (1,000 h.p.).

The weight of the engine is 150 lbs., *i.e.*, about 3 lbs. per h.p.; the overall length is 30$\frac{13}{32}$ in., width 31$\frac{11}{16}$ in. and height 23 in.

Although most of the opposed-cylinder aircraft engines that have been built or are in use have been of low power, there appear to be certain advantages in using 12 cylinders in two banks of 6 cylinders each at 180° apart. This "flat" engine arrangement would be particularly adaptable for fitting within deep wing aircraft of the multi-engine pattern, since this would *do away with the relatively high air resistance* of the ordinary exposed engine units in machines using Vee-type or radial engines.

A production model engine of the 12-cylinder type has been built by the Lycoming Division of the Aviation Manufacturing Co., U.S.A., in recent times. It is a liquid-cooled pattern and has a bore of 5·25 in. (133·2 mm.) and stroke of 4·75 in. (120·7 mm.), giving 20·6 litres capacity. The engine is supercharged by means of an exhaust-driven turbine coupled to a centrifugal air compressor using a 10-in. diameter impeller and operating at a maximum speed of 25,000 r.p.m. The engine is rated at 1,000 h.p. at 3,100 r.p.m. at sea level, but gives 1,200 b.h.p. at 3,400 r.p.m. for take-off purposes. At 25,000 ft., owing to the well-known fact that power falls off as the altitude increases, the engine develops 570 b.h.p. at 3,400 r.p.m. The dry weight is 1,325 lbs., *i.e.*, 1·325 lb. per h.p. The engine has a low frontal area, namely, about 7 sq. ft., thus giving 143 h.p. per sq. ft. The fuel consumption, using 100-octane fuel, is 0·5 lb. per b.h.p. per hour. A 185 h.p. six-cylinder opposed air-cooled engine is also made by the same firm.

(3) **Vee-type Engines.** In this arrangement the cylinders are in two banks, consisting usually of 6 cylinders per bank, and the two banks are inclined to one another at an angle of 60° to 90°. This type has always been popular from the early days of the 2-cylinder Anzani, the J.A.P. engines, 8-cylinder Antoinette, Simms, Curtiss, Renault (8-cylinder air-cooled), R.A.F. (similar arrangement to the Renault), to the later Wolseley-Viper, Rolls Royce Eagle, and the more recent Gipsy Twelve, the Merlin and Allison engines.

The reasons for the popularity of the Vee-type engine are its excellent engine balance and torque, compactness, low frontal area and weight per h.p. It gives about the lowest frontal area of any type, the Merlin later models giving over 300 b.h.p. per sq. ft. of frontal area.

It is not possible to describe the various Vee-type engines of modern design owing to space limitations, but mention should be made of the two distinct classes of Vee-type engines, namely, the upright (Fig. 127 (A)) and the inverted ones (Fig. 127 (B)). All of the earlier Vee-type engines were of the former class and recent models include the Rolls Royce Kestrel and Merlin engines and the American 1,000-h.p. class Allison 12-cylinder engine.

The upright Vee is considered more convenient for mounting in an aircraft and accessible, but the removal of the engine from its mounting is easier in the inverted type. It is further considered to be a disadvantage to leave the whole of the underneath side unmasked by any other features of the installation than the cowling, in the case of the inverted engine. Lubrication of the upright engine is also less difficult to arrange than that of the inverted model.

The main object of inverting the cylinders is to obtain a better view for the pilot, more particularly in fighting aircraft, but whilst this is true for engines of smaller horse-power, it has been shown that engines, such as the Merlin, are so compact that they do not occupy the full cross-sectional area, the latter being governed in size by other practical requirements; indeed there is usually sufficient room in the same fuselage for a larger engine without impairing the pilot's vision.

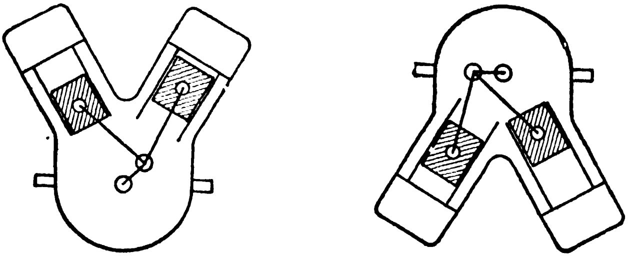
(A) (B)

FIG. 127. Upright (A) and inverted (B) Vee-type engine.

Typical examples of inverted engines are the Gipsy Twelve and the German Junkers 1,270-h.p. type DB–601N. petrol-injection engine; there are several other modern German inverted engines.

The Gipsy Twelve is an air-cooled supercharged engine of relatively low cooling losses; it has a frontal area of only 1·75 sq. in. per h.p., *i.e.*, 82·3 h.p. per sq. ft. of frontal area. This supercharged engine, of 4·646 in. bore (118 mm.) and 5·512 in. (140 mm.) stroke has a cylinder capacity of 1,121·2 cu. in. (18·372 litres). The compression ratio is 6 : 1 and the fuel used, namely, D.T.D. 230, has an octane value of 87. The maximum power rating is 410/425 b.h.p. at 2,450 r.p.m. at 7,750 ft. with zero boost * ; the

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* *Vide* p. 67.

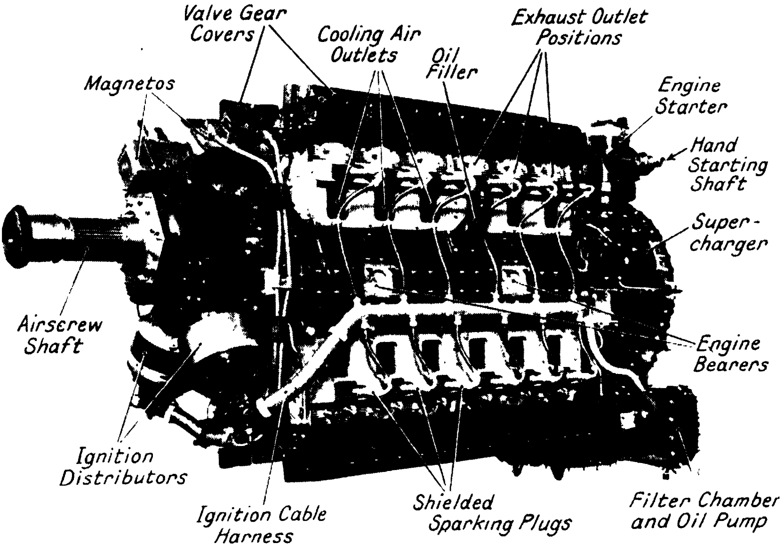

FIG. 128. The Napier "Dagger" 24-cylinder air-cooled engine.

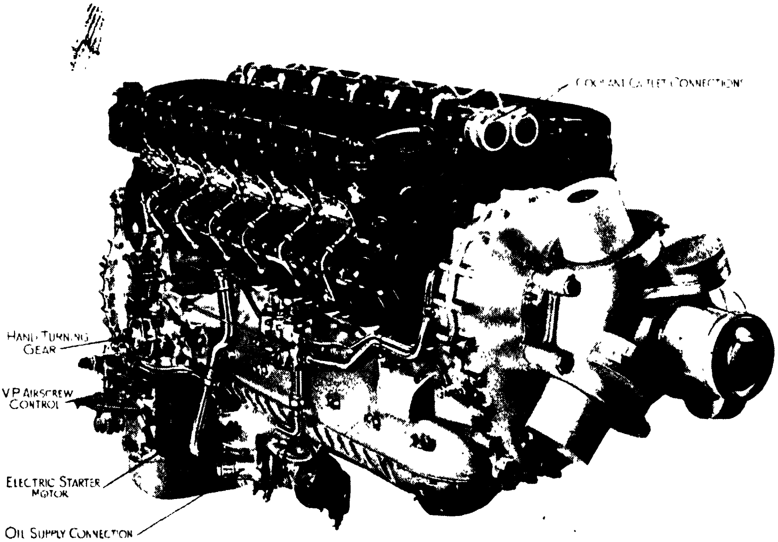

FIG. 129. The Rolls Royce "Merlin" engine, showing starting gear, variable pitch airscrew and other details.

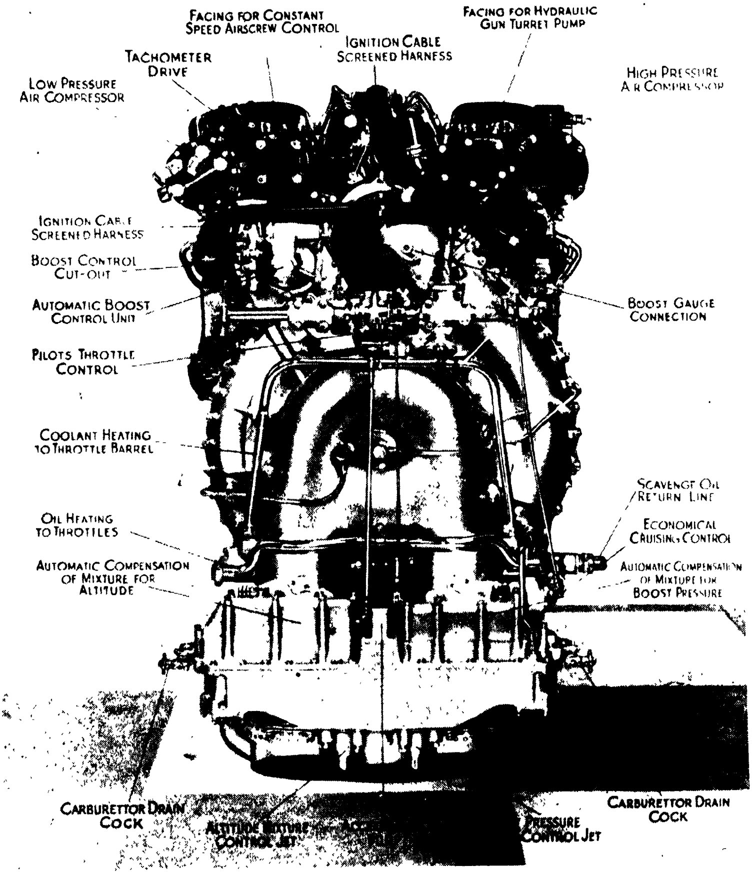

FIG. 130. Rear-end view of Rolls Royce "Merlin" engine, showing principal components.

[*Facing p.* 149.

International rating is 405/420 at 2,400 r.p.m., at 7,500 ft. with zero boost. The maximum take-off power is 505/525 B.H.P. at 2,600 r.p.m. at sea level, at + 3½ lb. per sq. in. boost pressure.

The engine employs a gear-driven centrifugal supercharger, with a gear-ratio of 7·14 to 1, giving supercharger rotor speeds of 17,000 to 18,500 r.p.m. The airscrew is geared down, the gear ratio being 0·677 to 1. The dry weight of the engine is 1,058 lbs., which is equivalent to about 2 lbs. per h.p. The engine design details resemble those of the other Gipsy engines, but several improved features are embodied.

Of special interest is the method of cooling the cylinders by means of the airscrew slip-stream ; this is shown in Figs. 59 and 60.

The Rolls-Royce Vee-type engines have always adopted the 12-cylinder grouping for normal horse-powers of 360 (for the Eagle IX) to over 1,300 (for later developments of the Merlin types).

The performances of the various engines up to the beginning of the War of 1939 are given in the following table :—

Performances of Various Rolls-Royce Engines

TYPE	Bore × Stroke, inches	Swept vol., litres	Normal r.p.m.	Normal Power, h.p.	Rated alt., feet	Approx. ground Power (*potential*) h.p.	Dry Weight, lb.	Specific (*potential*) Power, h.p./litre	Specific Weight (*potential*) lb./h.p.
EAGLE IX	4·5 × 6·5	20·2	1,800	360	0	360	965	17·8	2·68
CONDOR IIIB	5·5 × 7·7	35·3	1,900	665	0	665	1,364	18·8	2·05
(2) BUZZARD	6·0 × 6·6	36·6	2,000	825	0	825	1,510	22·5	1·83
(1) KESTREL IIS	5·0 × 5·5	21·2	2,250	480	10,000	(670)	910	(31.6)	(1·36)
(1) KESTREL V	5·0 × 5·5	21·2	2,500	600	11,000	(870)	945	(41·0)	(1·08)
(1) KESTREL XVI	5·0 × 5·5	21·2	2,600	690	11,000	(1,000)	970	(47·1)	(0·97)
(1) MERLIN II	5·4 × 5·0	27·0	2,600	990	12,250	(1,500)	1,335	(55.5)	(0·89)
(3) MERLIN X	5·4 × 6·0	27·0	2,600	960	13,000	(1,500)	1,394	(55·5)	(0·93)
(1) PEREGRINE	5·0 × 5·5	21·2	2,850	860	13,500	(1,365)	1,106	(64·4)	(0·81)

(1) Fully supercharged. (2) Moderately supercharged. (3) With two-speed supercharger in ***high*** gear.

It should also be noted that a later model, namely, the Merlin XX, developed 1,280 h.p. when supercharged and at its rated altitude.

The Merlin X engine has a bore and stroke of 5·4 in. (137 mm.) and 6·0 in. (152·4 mm.) respectively, giving a cylinder capacity of 1,650 cu. in. (28 litres). It has two blocks of 6 cylinders each, arranged at 60°, and is provided with a two-speed supercharger of the centrifugal compressor type driven by means of gears from the engine. The airscrew is driven by means of a simple spur reduction gear having a ratio of 0·477 to 1.

In regard to some of the more interesting constructional features, reference is made in Chapter VI to the cylinders, camshaft, valves etc. ; it may also be mentioned that the exhaust valve and ring seating faces are coated with a hard heat and corrosion resisting alloy, known as "*Brightray*," and that each valve has two concentric springs retained by a collar and split wedge. There is also a spring circlip at the upper end to retain the valve in its guide in the event of valve fracture ; if this were not done the valve head would drop into the cylinder, break the piston and score the cylinder walls.

The crankcase is an aluminium casting in two halves bolted together. The upper half, which is cast integral with the rear half of the reduction gear casing, carries the cylinder blocks, and, in addition, incorporates the seven main bearings and caps, the engine mounting feet, slinging points, etc. The lower half carries the oil pumps and filters, and drives for a hydraulic undercarriage pump or low-pressure air compressor.

The main bearings are split mild steel shells lined with lead-bronze and fitted into recesses machined in the crankcase. The bearings are held in position by caps and bolts which pass through the caps and across the whole width of the crankcase, a design allowing the withdrawal of the lower half of the crankcase without disturbing the bearings.

The camshafts are nickel steel forgings machined all over, being case-hardened and ground on the cam and bearing surfaces. Seven brackets, centrally disposed along the top of the cylinder block and secured to it by studs, carry the camshaft and rocker mechanism, the rocker spindles being located one on each side of and parallel to the camshaft. The camshafts are driven through the spring drive by an inclined shaft and bevel gears from the wheelcase at the rear end of the engine. Each valve is operated by a separate steel rocker having a spherical-headed tappet screw and lock nut at the valve end for tappet adjustment. The camshaft operates above, and acts directly on, a hardened rocker pad in the centre of the rocker shaft.

In order to damp out irregularities in angular velocity and torque, the drive from the crankshaft to the supercharger, timing gears, and auxiliary components, is taken through a torsionally flexible shaft which provides a spring drive. The twisting of this shaft is limited by a hollow sleeve connected to its outer end by a damper clutch ; the drive is then taken up by the sleeve. (See also Fig. 108 on p. 126.)

The wheelcase is an aluminium alloy casting, secured by studs to the rear face of the crankcase and having the supercharger unit mounted on its rear face.

It houses also the drives to the camshafts, magnetos, water- and oil-pumps, fuel pumps, supercharger, hand and electric starters and the electrical generator.

The carburettor fitted is the twin-choke vertical model of Rolls Royce S.U. design referred to in Chapter III.

The fuel pumps for supplying the carburettor are of the dual gear pattern operating in parallel and having one inlet and one outlet connection. Each pump can supply enough fuel to meet the full engine demand and any excess fuel delivery is returned through a relief valve to the suction side of the fuel pump.

The ignition system consists of two 12-cylinder magnetos driven by means of a skew gear from the upper vertical drive shaft (see Fig. 108) through serrated couplings allowing a fine (vernier) adjustment for ignition timing purposes. Each magneto supplies a spark to one plug in each cylinder. The ignition wiring system is of the enclosed metal-braided pattern forming a " screen " for preventing interference with the aircraft radio equipment.

The engine cooling liquid, namely, ethylene glycol, is circulated through the cooling system by a large capacity centrifugal vane-pattern pump located on the base of the wheelcase and driven at 1½ times engine speed by means of a vertical shaft from the main bevel wheel driving the auxiliaries. Two bends on the pump casing, fitted with gland type connections, deliver the coolant through pipes into the rear lower end of each cylinder block. The coolant circulates through the jackets and cylinder heads, finally leaving through three outlets along the upper side of the cylinder block, inside the Vee, which connect with a main outlet pipe discharging either forwards or rearwards, depending on the method of installation of the engine.

The lubrication system is dealt with in Chapter VIII.

The Merlin engine can be started either by means of a hand-turning gear or an electric starting motor obtaining its power from a suitable battery ; the arrangement of these two starting devices is shown in the lower right hand portion of Fig. 108 on page 126.

The engine drives a 12-volt, 500-watt electric generator mounted on the left hand side of the upper half crankcase ; it runs at 1·914 times engine speed and is driven by means of a gear train from one of the supercharger planet wheels.

The Rolls-Royce Merlin 61, referred to on page 77, is an improved and more powerful version of the Merlin XX and Merlin X engines.

The only other modern design of upright vertical Vee-type engine is the 12-cylinder Allison model made in the U.S.A. It has a bore of 5·5 in. (139·7 mm.) and stroke of 6·0 in. (152·4 mm.), giving a cylinder capacity of 1,710 cu. in. (28 litres). The engine has a compression ratio of 6·65 : 1 and operates on fuel of 90 to 100 octane rating. The V–1710–C15 model is rated at 1,060 b.h.p. at 3,000 r.p.m. for take-off and 960 b.h.p. at 2,600 r.p.m. at 12,000 ft. An output of 1,090 b.h.p. for five minutes is developed at 13,200 ft. The fuel consumption on 100-octane fuel is 0·6 lb. per B.H.P. hour. The dry weight of 1,325 lbs. gives a specific weight of 1·25 lbs. per h.p., reckoned on the take-off rated power.

The engine is supercharged, a geared centrifugal blower with step-up gear ratio of 8·77 : 1 being used for this purpose. The output per litre works out at 38·90. The maximum B.M.E.P. is 169 lbs. per sq. in. and maximum piston speed 3,000 ft. per min.

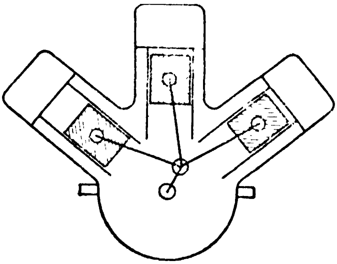

FIG. 131. The arrow-type engine.

The Arrow-type Engine. In this type the cylinders are arranged in three blocks so as to give an arrow formation, as shown in Fig. 131. Usually there are 4 cylinders per block, thus making a more compact and shorter engine than the equivalent 12-cylinder Vee-type. An example of this arrangement was the well-known Napier "Lion" of 450 h.p. (Series V). It had a bore of 5·5 in. and stroke of 5·125 in. and developed 460 B.H.P. at 2,000 r.p.m. (ground level) for a dry weight of 900 lb. The airscrew was geared to run at 1,320 r.p.m. An interesting feature of this engine was the employment of five roller bearings for the crankshaft main bearings.

The Air-cooled Radial Engine. This is now the most widely used of any aircraft engine as it possesses several notable features and advantages and has, moreover, been developed to a very high degree of efficiency and reliability. The modern radial engine is represented in this country by the Armstrong Siddeley series, *e.g.*, the "Genet," Lynx, Cheetah and Tiger models—the latter being a 14-cylinder twin-row radial; by the Bristol Series, including the Mercury, Pegasus, Perseus, Hercules, etc.; and the Alvis Leonides and Pelides—the latter being a 14-cylinder twin-row radial. The American engines include the Wright Cyclone Series of single- and double-row radials, and the Pratt and Whitney single- and double-row radials, *e.g.*, the Wasp, Hornet, Twin Wasp, Twin Hornet, etc.

A typical modern German engine is the 14-cylinder twin-row radial, known as the B.M.W.801A. (1,580 h.p.).

✓In regard to the merits of the air-cooled radial engine it is *the lightest of any type* for a given power output and since it requires no separate cooling system, is entirely self-contained and ideal for rapid production in the works. It is insensitive to climatic extremes and therefore does not require the same precautions as liquid-cooled engines in extreme winter conditions. Another important factor is the comparative rapidity with which it gives its full power after starting from the cold, as compared with liquid-cooled engines, owing to absence of cooling liquid, etc.

The radial engine has excellent engine balance qualities, and with its short crankshaft is very less prone to torsional vibration effects than engines with long crankshafts, *e.g.*, the "in-line" and Vee-type ones. Many of the design features of the radial engine are simpler than the corresponding ones of the other engines mentioned ; in particular, the crankcase, cylinders, crankshaft, main bearings (which are relatively few in number), connecting-rod assembly and valve operating gear. The engine is easy to install, maintain and overhaul ; moreover, injury to any particular cylinder does not necessitate the replacement of a cylinder block but as all of the cylinders can be made to similar design, replacement is an easy and relatively inexpensive matter.

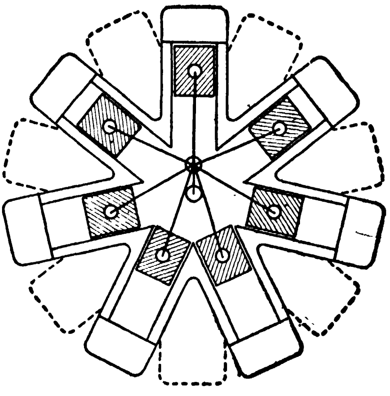

FIG. 132. The air-cooled radial engine. Full lines show 7-cylinder and full and dotted lines 14-cylinder units.

The radial engine, with its cowling, has a higher head resistance than the Vee-type liquid-cooled engine, including its ducted radiator for cooling the liquid. The two-row radial engine has an appreciably lower resistance than the single-row one, as reckoned in frontal area per h.p.

Frontal Areas. In regard to *frontal areas of engines*, it may here be of interest to quote some comparative figures for typical arrangements of cylinders. If the 9-cylinder radial engine is taken as the standard of comparison and its frontal area is represented as 100 per cent., then the relative frontal areas of the other types, described in the first column will be as shown in the third column.

If the power outputs of these engines are assumed to be proportional to the number of cylinders, then the outputs can be represented by the figures in the second column. Finally, the power outputs per unit of frontal areas or the *relative* h.p.'s per sq. ft. of frontal area will be as shown in the fourth column.

Comparative Power Outputs per Unit Frontal Area

Type of Engine	No. of Cylinders N	Frontal Areas per cent. of 9-cylinder A	Power Output per Unit Frontal Area $\frac{N}{A} \times 100$
Radial	5	90	5·55
Radial	7	92	7·61
Radial	9	100	9·00
Radial	11	120	9·17
Radial	14—Two-bank	92	15·22
Radial	18—Two-bank	100	18·00
Two-bank (opposed)	12	39	30·75
Two-bank Vee	12	39	30·75
Four-bank H-type	24	71	33·80
Four-bank X-type 60 degrees .	24	84	28·55
Four-bank X-type 90 degrees .	24	96	25·00

An examination of these results shows that the Vee, opposed, H-type and X-type engines have an appreciably lower frontal area per h.p. It must, however, be remembered that these comparisons do not take account of the radiator head resistances of liquid-cooled engines, so that the differences will be rather less between the radial and liquid-cooled types when this allowance is made.

Radial Engine Types. The more recent designs of air-cooled radial engines include those ranging from the small 5-cylinder ones of 80 to 100 h.p. used in light civil and training aircraft, to the powerful 14- and 18-cylinder ones of 1,500 to over 2,000 h.p., employed on the largest commercial and military bomber and other purpose aircraft.

The single-row radials include the 5-, 7- and 9-cylinder ones, whilst the double-row radials include the 14- and 18-cylinder units. It is, however, theoretically possible to employ 21- *and 27-cylinder three-bank* radials giving power outputs ranging from 2,100 to 3,000 h.p., although special problems in regard to the cooling of the middle and rear cylinder banks would have to be overcome.

Firing Order of Radial Engines. It may have been observed that the previous references to radial engines have included only the 5, 7, 9 and multiples of the two latter numbers of cylinders. The reason for this is that it is only possible in a single-row of cylinders to *obtain equal firing intervals if the number of cylinders is odd.* Thus, in the case of a four-cycle engine, there will be one firing stroke each

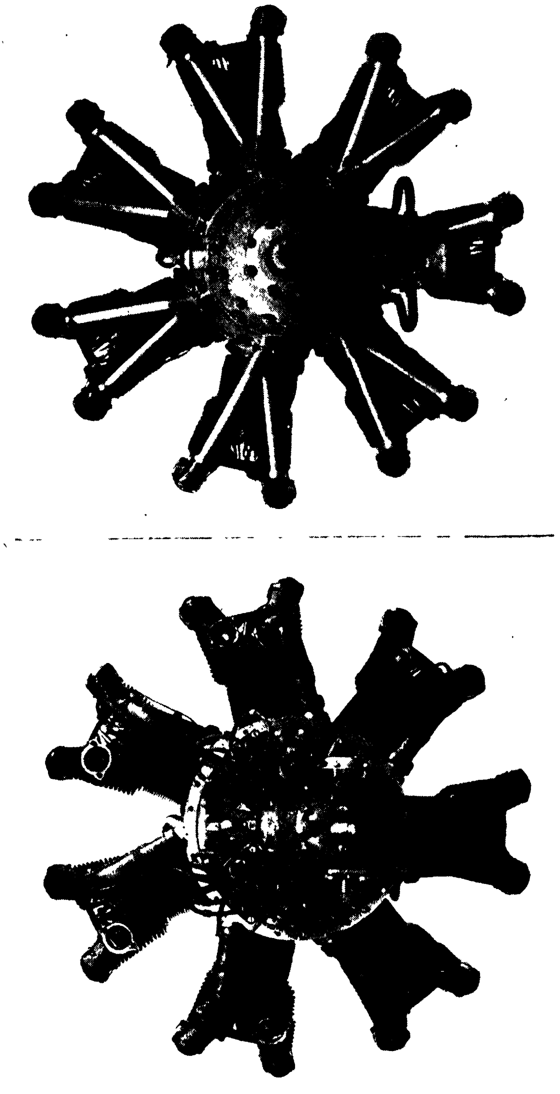

Fig. 133. The Armstrong-Siddeley "Genet Major IV" engine.

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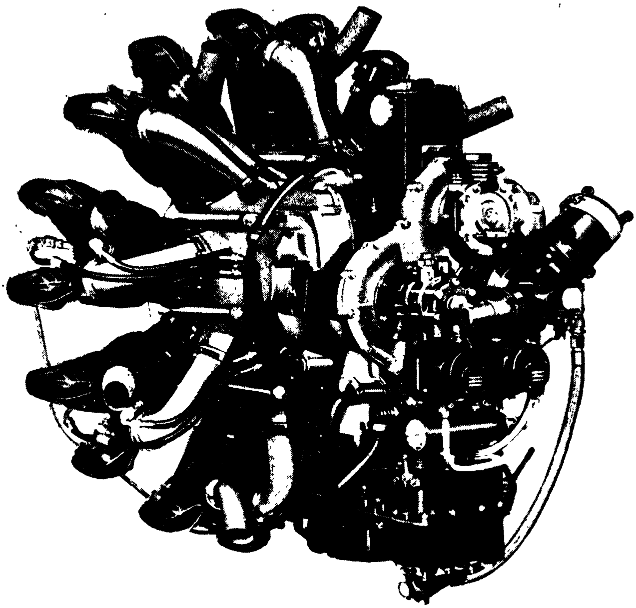

FIG. 134. The Alvis 9-cylinder radial "Leonides" engine (430 h.p.). Three-quarter rear view.

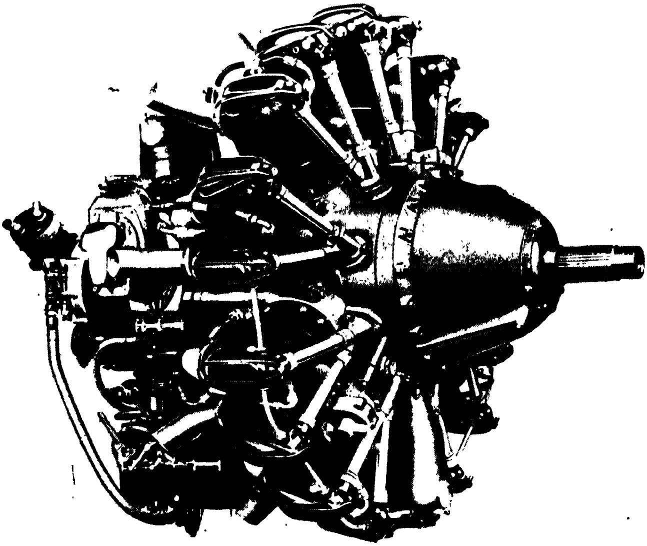

FIG. 135. The Alvis "Leonides" engine (430 h.p.). Three-quarter front view.

two revolutions, *i.e.*, 720° for each cylinder. If there are two cylinders, there will be 720/2 degree intervals between the firing strokes.

Consider, next, a radial engine having an even number of cylinders, *e.g.*, six, then a little consideration will show that the firing intervals will be 120, 120, 180, 120, 120 and 60 degrees; the firing order of the cylinders will be 1, 3, 5, 2, 4, 6. If any other case of a radial engine with an even number of cylinders be taken it will be found that the firing intervals are unequal. Unequal intervals mean greater variations of crankshaft (and airscrew) torque and should be avoided. If any example of an odd number of cylinders is considered, it will always be found that the firing intervals are equal. Thus, in the instance of the 9-*cylinder radial*, the firing order will be: 1, 3, 5, 7, 9, 2, 4, 6, 8, and all of the firing intervals will be 80°.

For a 7-*cylinder* radial, the firing order will be: 1, 3, 5, 7, 2, 4, 6, and the firing intervals, $720/7 = 102\frac{6}{7}°$.

For a 5-*cylinder* radial, the firing order will be: 1, 3, 5, 2, 4, and the firing intervals, $720/5 = 144°$.

The two row radials of 14- and 18-cylinders may be regarded as two separate 7- and 9-cylinder single-row radials coupled together, with cranks at 180°, for the purpose of considering their firing orders. The cylinders of the two rows *will fire alternatively* and in the above-mentioned order.

Engine Balance of Radials. The balance of all radial engines with five or more cylinders can be made practically perfect in the usual master connecting-rod type by suitable counterbalance weights.*

Typical Radial Engines. Statistical particulars of typical radial engines are given in Appendix II. As there is a general similarity in most single-row radials it will only be necessary to refer to two actual British examples, namely, of a low- and a high-powered engine for which purpose the Armstrong Siddeley Genet Major IV and the Bristol Mercury and Pegasus Series have been selected.

The Genet Major IV is a 7-cylinder radial with a cylinder bore of 4·25 in. (108 mm.) and stroke of 4·5 in. (114·5 mm.), giving a cylinder capacity of 446·9 cu. in. (7·32 litres). The compression ratio is 5·25 to 1 and the engine is rated at 160 h.p. at 2,400 r.p.m. at sea level. It is, however, capable of developing 180 b.h.p. at 2,700 r.p.m. on 77-octane fuel. The engine is not supercharged.

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* *Vide* "Aircraft Engines," Vol. II., A. W. Judge (Chapman and Hall Ltd.).

The airscrew has a gear-down ratio of 0·663 to 1. The dry weight is 367 lbs., *i.e.*, 2·04 lbs. per h.p. at maximum output.

The overhead valves are operated by push rods, enclosed within tubes, and rocker arms, the push rod units being arranged in Vee-pattern (Fig. 133) on the front of the engine. The rear cover carries the various accessories, including the two magnetos. The inlet pipes are arranged at the rear of the cylinders so as not to interfere with the flow of the cooling air. In other respects the constructional features of this engine follow standard radial engine practice.

The Bristol radial engines embody the results of research and development work over a long period of years, and they are now represented by both the mechanically-operated valve and the single sleeve-valve models; the latter are dealt with separately, later.

As a result of single-cylinder engine research work considerable improvement has been made in regard to the output per unit cylinder capacity. Thus, over a period of eighteen years, up to 1940, the output per litre has been increased by 150 per cent. and the gross B.M.E.P. has risen from 112 to 188 lbs. per sq. in. During this period the crankshaft speeds have increased from 1,625 r.p.m. (for the original Jupiter engine) to 2,925 r.p.m. for the more recent Pegasus engine. Despite the addition of gearing, supercharger, and a fairly extensive range of modern accessories the specific weight per h.p. has been reduced by 43 per cent. At the same time, a saving of fuel per B.H.P. hour amounting to no less than 25 per cent. has also been effected.

The improved power output per litre has been due primarily to more efficient cylinder finning, to the adoption of supercharging, higher engine speeds and employment of higher compression ratios, in consequence of improved cylinder head and valve design, and to the use of fuels of higher octane value.

Tabulated particulars concerning the dimensions, engine speeds, power, etc., are given in Appendix II.

The cooling of Bristol engines has received much research attention with the result that the most efficient arrangements and shape and pitch of cooling fins have been adopted. The total cooling area of these engines is relatively large, ranging from 150 to 180 sq. ft for the engines here mentioned.

In regard to the constructional features, some details of the cylinders, valves, crankshaft and crankcase are given in Chapter VI.

An interesting feature is the use of *a high initial oil-pressure system* which enables the engine to be opened up to full power soon after starting from the cold.

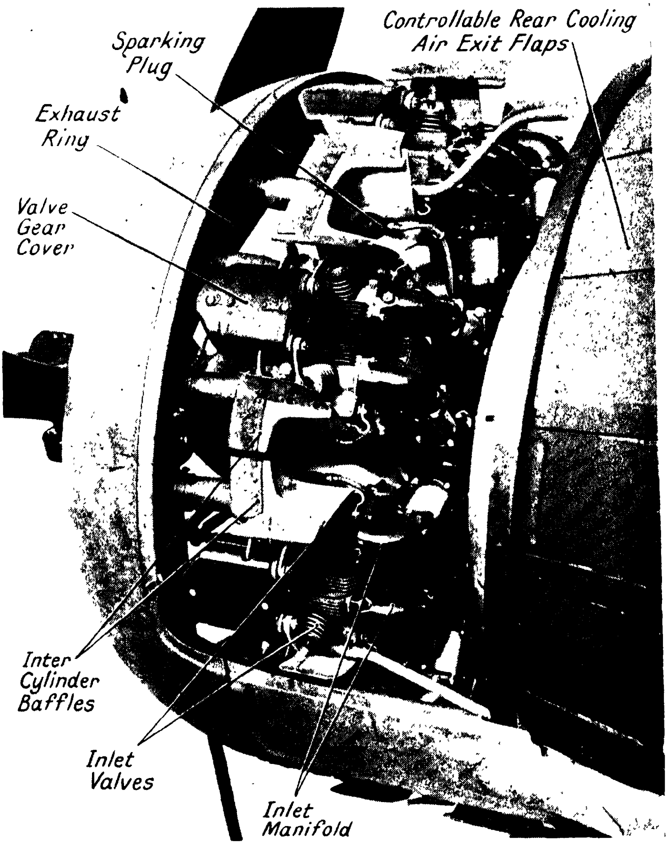


FIG. 136. Showing installation of Bristol "Mercury" engine in aircraft. The cylinder baffles and rear cooling air exit flaps can here be seen.

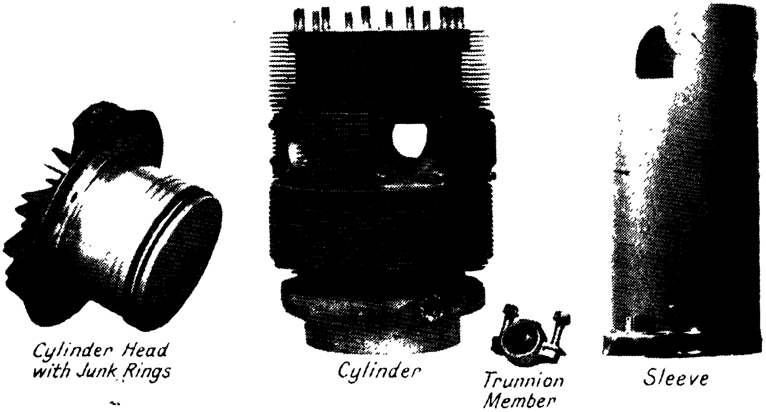


FIG. 137. Cylinder components of the Bristol sleeve-valve engines.

[*Facing p.* 157.

The two magnetos fitted at the rear of engine have automatic advance and retard mechanism, and the double-type contact breakers are interconnected with the throttle to provide an additional advance for maximum fuel economy during cruising flying.

The mixture, which is supplied by a Claudel Hobson carburettor, is delivered from the supercharger to the two inlet valves of each cylinder through nine pairs of large section induction pipes having tangentially arranged Y-branches from the supercharger.

The rear cover carries the various engine and auxiliary accessories.

In regard to the installation of the Bristol engines in aircraft, a special feature is *the inter-cylinder baffle system* for cooling purposes.

The exhaust manifold is mounted on the front of the engine by simple three-point attachments with flexible joints to allow for expansion. It has a large internal volume and a single outlet below and rearwards. The manifold forms part of the cowling system, being in the form of a ring (Figs. 113 and 136) which, as previously mentioned, is cooled by the reverse flow of air from the rear to the front of the exhaust ring, due to the fact that there is a greater air pressure immediately in front of the cylinders than at the nose of the cowling.

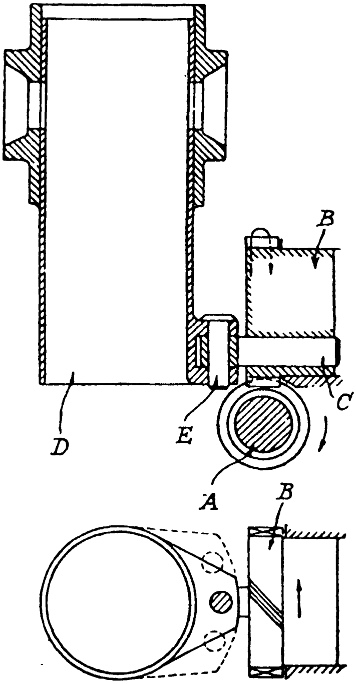


FIG. 138. The single sleeve valve engine principle.

The Bristol Sleeve-Valve Engine. In this more recent development of the radial engine the whole of the poppet valves and their operating push-rods, rocker arms and cam rings are dispensed with and their place taken by a simple ported-sleeve or liner arranged between the piston and cylinder wall. This sleeve receives an up-and-down and also a small amount of side movement by means of a crank mechanism operated at one-half engine speed in order to give the valve events.

The sleeve employed in Bristol engines is illustrated on the right in Fig. 137, which shows also the shape of one of the ports. Fig. 139 shows the operating mechanism, namely, a spherical joint with a central hole in the ball member in which a kind of crank pin, having a relatively small throw or travel, works making one complete rotation for every two-engine revolutions. The principle of the sleeve-valve engine is shown diagrammatically in Fig. 138, in which for simplicity reasons the piston and cylinder are omitted. The piston reciprocates within the sleeve and the sleeve within the cylinder proper, but with a very small movement as compared with that of the piston.

The method of driving the sleeve in this example differs from that of the Bristol engines, in using two trunnions instead of a trunnion and spherical joint. The gear shaft A, driven at one-half engine speed, engages with the sleeve-operating crank gear B through spiral gearing, the axes of A and B being at right angles. The gear B carries a tee-headed crank pin C, which is attached to the sleeve valve D by a pin E and held between suitable lugs on the sleeve. The crank pin C is free to rotate, and can also slide endwise in a bearing contained in the gear B; it can also swing sidewise about the pin E anchored in the sleeve lugs. This mechanism causes the sleeve to have the desired " elliptical " motion for the valve port events. The sleeve near its upper end is provided with ports of special shape, usually varying from four to six in number.

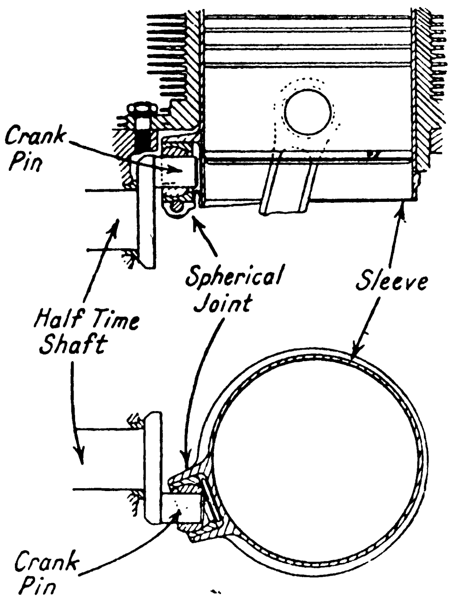


FIG. 139. Single sleeve valve operating mechanism.

The general arrangement of these valve ports is such that one-half of them form the inlet ports on one side, and the other half the exhaust ports on the other side of the sleeve. There are, however, several alternative arrangements for the ports.

The operation of the single sleeve-valve engine in regard to the valve port events is shown in detail in Fig. 140 for a five-port sleeve having two inlet ports on the right, a common inlet and exhaust port in the centre and two exhaust ports on the left. The cylinder unit has six ports arranged symmetrically, as shown. The movement of the sleeve ports is denoted by the dotted and arrowed ellipse; the black spot on the latter indicates the centre of the bottom edge of the middle common port. If the positions of this spot are traced it is not difficult to understand the cycle of sleeve movements. The six diagrams which are shown in Fig. 140, cover one complete cycle of operations, namely, as follows: (1) Induction ports opening; (2) Induction ports fully open; (3) All ports closed and compression proceeding; (4) Top of compression stroke, firing stroke about to begin; (5) Towards end of firing stroke exhaust ports about to open; and (6) Exhaust ports fully opened as piston ascends on its exhaust stroke. In the case of both inlet and exhaust ports the white spaces on the diagram indicate the port opening spaces.

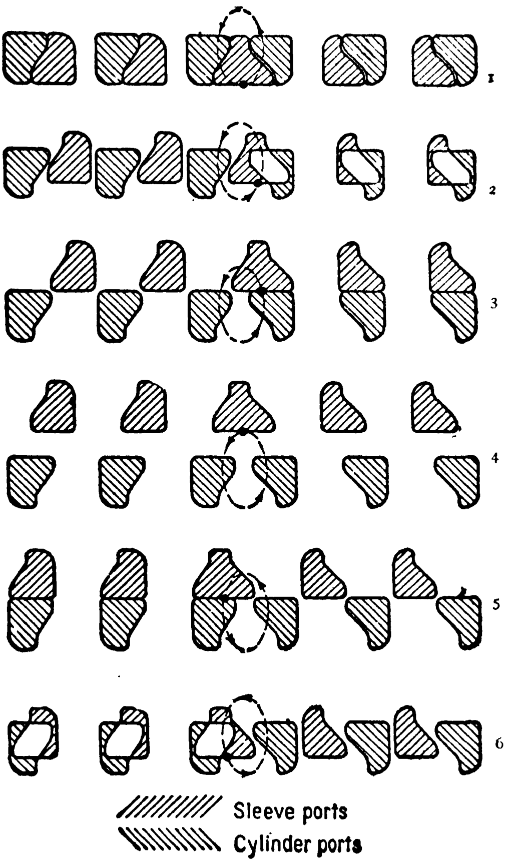


FIG. 140. Showing sequences of inlet and exhaust port openings in a five-port sleeve valve engine.

It will be observed that the timing of the inlet and exhaust events is done by the positions and shapes of the ports; also by the amount of movement of the sleeve.

One particular feature which is apparent from the diagrams is the relatively large area of valve port opening that can be given in each case; this enables a high volumetric or charge efficiency to be obtained.

The progress that has been made with the design and performance of the sleeve-valve engine is shown by the results of experimental work upon single-cylinder engines that has been carried out by the Bristol Aeroplane Company.

Thus, in 1931, tests made upon a single-cylinder engine of 5¾ in. bore gave the following results: b.h.p., 51; B.M.E.P., 120 lbs. per sq. in.; fuel consumption, 0·45 lb. per b.h.p. per hour.

In 1938, the results obtained from a single-cylinder engine of the same bore gave the following results: b.h.p., 131; B.M.E.P., 291 lb. per sq. in.; fuel consumption, 0·395 lb. per b.h.p. per hour; these values are better than for a poppet-valve engine of similar size.

The advantages of the sleeve valve engine can be summarised, briefly, as follows: (1) Owing to absence of exhaust valves—the heads of which are the hottest areas within the combustion chamber—a higher volumetric efficiency can be obtained and a greater compression ratio used before detonation occurs. (2) A more efficient shape of combustion chamber can be employed. (3) Much simple design of engine with considerable reduction in the number of components due to the elimination of valves, springs, collars, push-rods, rocker arms, lubricating devices, etc. (4) Engines are much quieter in operation owing to absence of the noisy valve mechanism. (5) Less maintenance attention required as there are no valves to regrind or clearances to adjust. (6) The outsides of the cylinders are of cleaner design, free from valve push rods and rocker arms, valve pockets, etc. (7) The cylinder heads are bolted to the cylinder barrel units and are therefore more accessible for inspection and decarbonising of the combustion chamber.

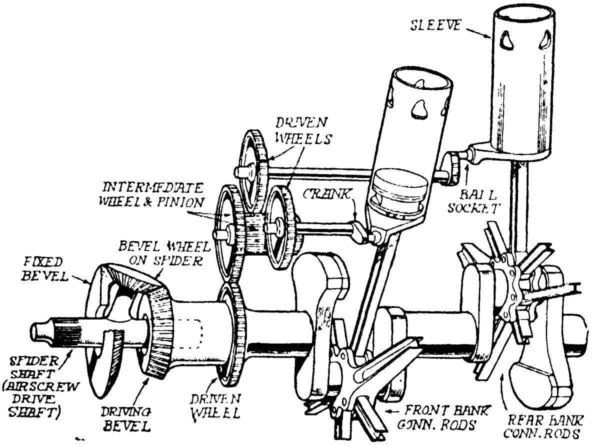
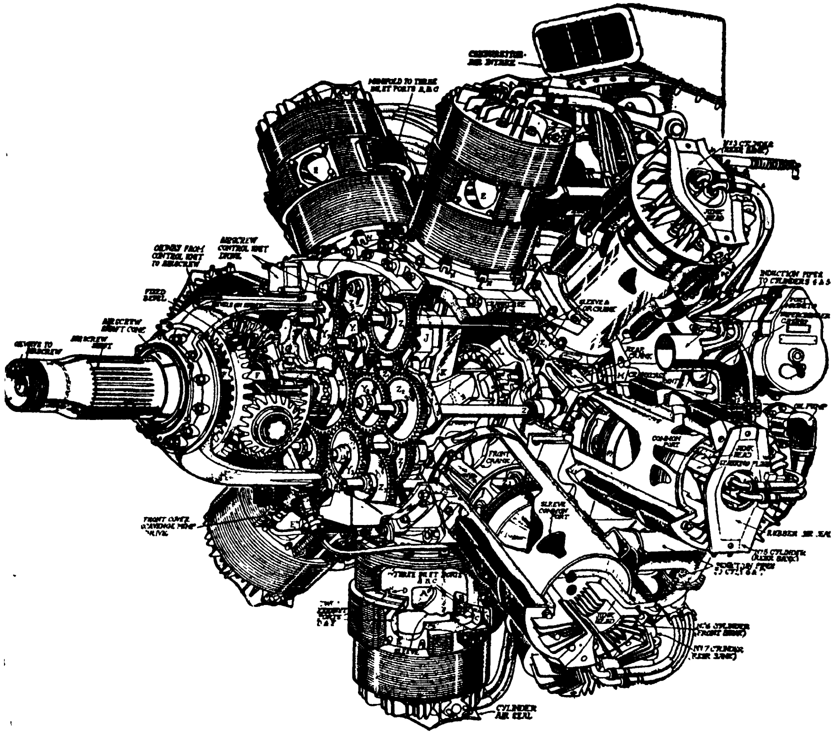


FIG. 141. Sleeve mechanism of Bristol 14-cylinder two-row Hercules engine.
[*Courtesy of "The Aeroplane"*

In general, the sleeve-valve engine gives a greater power output, an a poppet-valve engine of similar dimensions, in air-cooled signs. The results of tests made on a poppet-valve engine and a eve-valve one of similar size showed that about 30 per cent. more ower was obtained at the same engine speed and using the same



[*Courtesy of* " *The Aeroplane.*"

FIG. 142. The Bristol 9-cylinder sleeve-valve engine.

le of fuel; the fuel consumption per b.h.p. per hour was about per cent. less.

The previous disadvantages of the single sleeve-valve engine re as follows: (1) Greater oil consumption due to the necessity of nple lubrication of the sleeve. (2) More difficult to start from the cold owing to viscous oil film area between the sleeves. (3) Difficulty in obtaining suitable light metals for the sleeve and cylinder having similar expansion coefficients. (4) Excessive carbonising of the piston rings in the cylinder head.

These difficulties have now been overcome satisfactorily by reful design and the selection of suitable metals.

Constructional Features. The sleeve-valve radial air-cooled engine differs only from the poppet-valve one in respect of the mechanism for obtaining the inlet and exhaust operations ; in other design details it is practically identical. Thus, the pistons, connecting rods, crankshaft, crankcase and accessories are the same as for ordinary radial engines. A different design of cylinder and cylinder head are, however, employed, whilst the sliding sleeve and its operating mechanism replace the valve cam ring and poppet-valve mechanism.

The cylinder of the Bristol sleeve-valve engine is of symmetrical shape, as distinct from the unsymmetrical poppet valve design. The ports are arranged below the cylinder head joint and the cylinder barrel has circular cooling fins above and below the ports. The *cylinder head,* which is attached to the cylinder by means of twelve studs and nuts, has a special arrangement of cooling fins, as the cooling air has to be taken down inside the wall of the head to the crown. The cooling arrangement includes a baffle for deflecting the cooling air over the crown and causing a turbulent circulation around the sparking plugs. The cylinder head is provided with two piston-type of *junk rings* for sealing the upper portion of the sleeve against loss of pressure from within the cylinder ; it has also a number of oil retaining grooves. During the high cylinder pressure periods of the working cycle the sleeve is at the top of its path and its ports are well sealed by the junk rings. Two sparking plugs are fitted in the centre of the smooth and slightly convex face of the head which forms the top of the combustion chamber. The cylinder head is a die casting in Y-alloy and the cylinder of an aluminium alloy. The sleeve is machined from a special alloy steel, having the same coefficient of expansion as aluminium alloy ; it is surface hardened by the nitriding process.

The sleeve drive, as mentioned previously, employs a spherically seated bearing for the sleeve which can swivel so as to remain in line with the operating pin of the crank ; the latter is driven by a train of gears inside the front cover of the engine. The sleeve has an elliptical motion in which the vertical movement is about 50 per cent. greater than the horizontal one.

The Bristol sleeve-valve engines include the smaller Aquila (600 h.p.), the Perseus models (730 to 900 h.p.), the Taurus (1,010 h.p.), and the Hercules (1,300–1,600 h.p.) ; the powers given are the maximum take-off values. The two former types are 9-cylinder radials and the two latter 14-cylinder twin-row radials. The Hercules III engine has a bore of 5·75 in. and stroke of 6·5 in., with cubical capacity of 2,360 cu. in. (38·7 litres). It develops a ma

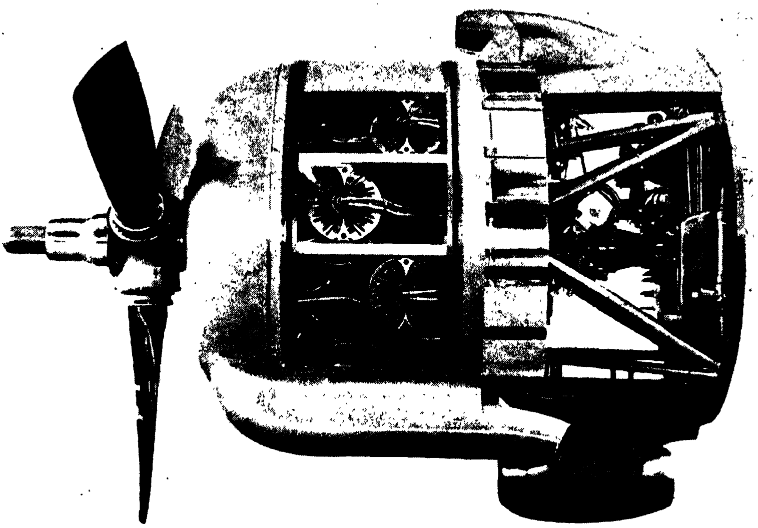


FIG. 143. The Bristol 14-cylinder sleeve-valve engine installed in aircraft. Showing cooling gills, cowling, exhaust manifold, engine mounting, etc.

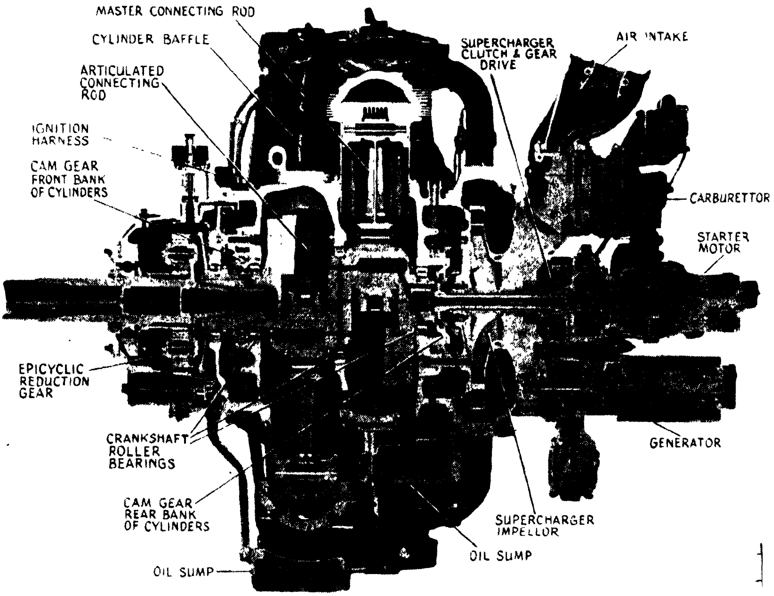


FIG. 144. The Pratt and Whitney "Twin Wasp" 14-cylinder engine (1,000 h.p.).

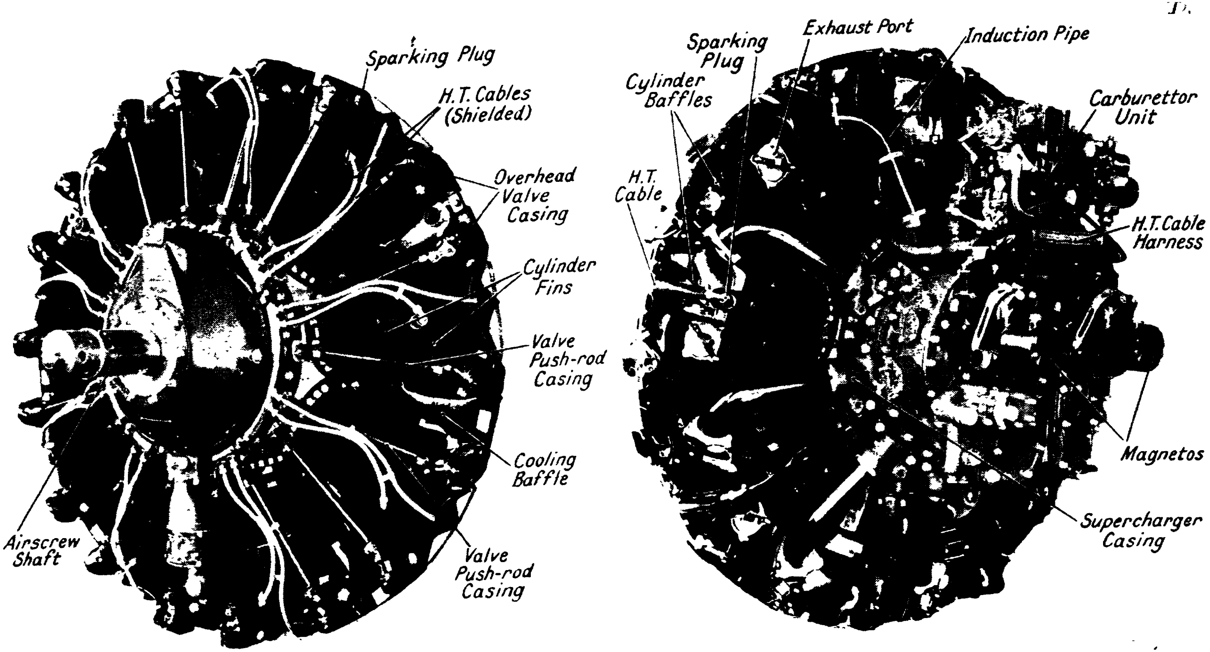


FIG. 145 The Wright "Cyclone" G.200 9-cylinder radial engine (1.200 h.p.).

mum take-off h.p. of 1,400 and weighs 1,850 lb. The maximum power for level flight is 1,425 b.h.p. at 1,500 ft. with the low-speed supercharger and 1,270 b.h.p. at 15,000 ft. with the high-speed supercharger in gear. A later model develops over 1,600 b.h.p. (take-off). The overall diameter of this compact engine is only 52 in.

The layout of the crankshaft, airscrew and sleeve-valve drive gears is shown in Fig. 141.

American Radial Engines. Two of the best known makes of radial air-cooled engines built in the United States are the Pratt and Whitney series and the Wright ones. The former include the various "Wasp" and "Hornet" engines. The original "Wasp" engine was a 400 h.p. 9-cylinder radial. Later, twin-row engines having two rows of seven cylinders each were produced ; these include the "Twin Wasp" and "Twin Hornet." Both the 9- and 14-cylinder engines are available in supercharged models with single- or two-speed superchargers.

The largest engine for which particulars are available is the "Twin Hornet" with single-speed supercharger. This has a bore of 5·75 in. (146 mm.) and stroke of 6·00 in. (152·4 mm.) with a cylinder capacity of 2,180 cu. in. (35·75 litres). The engine, designed for fuel of 100-octane value, has a compression ratio of 6·66 : 1 and centrifugal supercharger ratio of 7·56 : 1. Two alternative airscrew gear ratios, namely, 0·500 : 1 and 0·5625 : 1, are available. The engine has a normal rating of 1,100 b.h.p. at 2,550 r.p.m. to 6,200 ft. and 1,000 b.h.p. at 2,700 r.p.m. at 14,500 ft.

It has a maximum take-off output of 1,400 b.h.p. at 2,500 r.p.m. The dry weight is 1,635 lb. which is equivalent to 1·17 lb. per b.h.p. (maximum). Constructional features of these engines include Nitralloy cylinders with screwed and shrunk-on aluminium alloy cylinder heads ; hemispherical combustion chambers ; aluminium-bronze inlet valve inserts ; alloy steel exhaust valve inserts ; forged aluminium alloy pistons, ribbed underneath the crown, with finned inner skirts and having three compression rings, one single and one dual oil-control piston ring, each. Pressure baffles are provided for cooling purposes. These baffles serve not only to increase the cooling efficiency of the engine by directing the air to the front and rear bank cylinders in such a manner that uniform cooling is approximated to, but also to reduce the cooling drag. The baffle form on each cylinder is such that the air is directed through fins at the hottest places so as to avoid the formation of local hot spots. The baffles are of duralumin and are designed to facilitate engine maintenance; the sections between the rocker boxes may be left in position permanently.

The two-piece master connecting-rod for each cylinder bank has a detachable big-end cap with lead-silver lined bearings, the six I-section articulated rods for each bank are bronze-bushed for both gudgeon and knuckle pins. The crankshaft is of the two-throw, one-piece pattern and is supported by three roller bearings in the crank-case sections. The airscrew shaft is housed within the crankshaft by a bronze-lined bearing and in the nose section by a deep-groove ball thrust bearing. The counterbalance weights are riveted to the crank webs.

The engine is fitted with a double-barrel pattern down-draught self-priming Stromberg or Chandler-Evans non-icing and compensating carburettor; this is attached to the rear section of the crank-case unit.

The ignition is by means of two Scintilla magnetos, each operating its own independent set of sparking plugs through manifolds providing short leads.

The Wright radial engines include the smaller "Whirlwind" ones of 230 to 410 h.p., the "Cyclone" 9-cylinder radial (1,100 to 1,200 h.p.), the "Double-Row Cyclone" 14-cylinder, two-row radial (1,600 h.p.), and the Duplex Cyclone (2,000 h.p.); the latter is an 18-cylinder, two-row radial engine, and at the time of its introduction during the War of 1939 was the largest output radial engine in the world.

A considerable amount of research work that has been carried out on the Wright engines, particularly in regard to cylinder cooling and lubrication, has resulted in a marked improvement in the performance of these engines. Thus, during the period 1931 to 1939, the B.M.E.P. values, corresponding to maximum take-off power, have increased from 128 to 208 lb. per sq. in.; the engine speed has increased from 1,900 to 2,500 r.p.m. and the engine weight has been reduced from 2·2 to 1·1 lb. per h.p.

The G.100 (1,100 h.p.) engine has 9 cylinders and a two-speed supercharger and in its constructional features follows standard practice, but also has several original features. These include a special system of air-cooling baffles to direct the air around the exhaust and sparking plug regions in particular, in addition to the normal cylinder head and barrel portions.

The crankcase is made in five separate sections, namely, the *nose, power, mounting, supercharger* and *accessory units*. The power section is machined from alloy steel forgings; the other ones are aluminium alloy castings.

The crankshaft has highly polished main and crank-pin surfaces; a lead-bronze bearing is used for the master rod. The pendulum type of vibration damper is fitted to the rear crankshaft counterweight. The engine uses a planetary system of reduction gears for the air-screw drive shaft.

The G.200 engine is a later development and gives 1,200 b.h.p. at 2,500 r.p.m. It uses a higher compression ratio, namely, 6·7 to 1 instead of 6·3 to 1. The cooling area has also been increased to 220 sq. ft. Another improvement is the provision of streamlined valve guides and an increased valve port area of 20 per cent. The bore and stroke are the same as for the G.100 engine. In regard to the crankshaft this now has a double vibration damper.

The B.M.W. Radial Engine. This engine, which was developed for installation in German fighter aircraft, is a 14-cylinder two-row radial; one type is known as the 801D. It is of particularly neat and compact design and is enclosed within a low-resistance cowling unit of efficient performance. The bore and stroke are each 6·15 in. (156 mm.), giving a cylinder capacity of 42 litres. The engine has a take-off output of about 1,600 h.p. at 2,700 r.p.m. and is super-charged by means of a two-speed drive having step-up ratios of 7·46 and 5·07 to 1, respectively.

A special feature of this engine is the use of petrol injection equipment instead of the usual carburettor. The fuel is delivered by means of an injection pump having 14 plungers, direct to fuel injection nozzles in the cylinders.

Another interesting feature is the method of cooling the lubricating oil by means of two radiators of a shape built to conform to the form of the cowling nose portion. This is illustrated in Fig. 114. Air is taken in from the front of the nose by means of a special cooling fan driven from the front end of the crankshaft. Part of this air supply is employed for cooling the oil in the radiator units; the air flows forwards and then out from the front through a sliding nose unit which controls the rate of air flow. The cooling of the double bank of cylinders is carefully arranged so that a uniform flow is produced over the heads and barrels by means of a somewhat complicated system of baffles. It is possible, also, to regulate the air flow, an adjustable gill ring being provided for this purpose.

The two-throw crankshaft, having relatively short throws, due to the small piston stroke, is of built-up construction and uses a single-row ball-bearing for the centre main bearing between the cranks.

The engine is mounted on a tubular steel frame built up by the welding method. Between the engine and its mounting ten rubber-bushed mounting blocks are fitted.

The H-type Engine. A neat and compact engine is obtained by arranging a relatively large number of cylinders in four banks, as shown in Fig. 146. This system may be regarded as equivalent to two sets of opposed-cylinder engines, with their cylinders vertical, the two engines being geared so as to drive a common airscrew shaft. In this way it is possible to obtain a large power output per sq. ft. of frontal area.

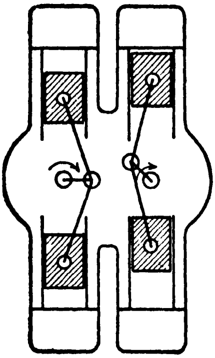


FIG. 146. The H-type engine.

A typical engine of this class is the Napier "Dagger" air-cooled 24-cylinder one which has four banks of six cylinders each, arranged with two banks inverted and the other two upright so as to form the four arms of the letter "H." It may also be regarded as consisting of two sets of 12-cylinder opposed engines geared together and with the cylinder axes vertical. The "Dagger" engine has relatively small cylinders and therefore operates at a higher speed than many other aircraft engines. Thus, the cylinder bore and stroke are 3·81 in. (97 mm.) and 3·75 in. (95 mm.) giving a cylinder capacity of 1,027 cu. in. (16·85 litres).

The compression ratio is 7·5 : 1 and on 87-octane fuel the engine has a maximum take-off power of 955 h.p. at 4,200 r.p.m. when supercharged to + 6 lb. per sq. in. The fuel consumption is 0·46 lb. per h.p. per hour. The engine weighs 1,390 lb. (dry), thus giving 1·4 lb. per h.p. The power output is 189 h.p. per sq. ft. of frontal area and 59·5 h.p. per litre of cylinder capacity. The crankshafts of each set of 12 cylinders (6 above and 6 below) are arranged so as to mesh with the airscrew reduction gear, which has a reduction ratio of 0·308 to 1 ; the airscrew shaft is above the centres of the two crankshafts. The well-finned steel cylinders have aluminium alloy heads, machined all over ; these contain the inlet and exhaust valves and their ports and passages. The cylinders are cooled by means of air-scoops mounted above and below the upper and lower groups of cylinders, the cooling air passing over the cylinder heads, down between the cylinder barrels and out through ports left in the sides of the cowling.

The engine is provided with a double-entry centrifugal supercharger driven by spur gears through layshafts which carry spring drives to relieve overloads and absorb shocks. A special S.U.

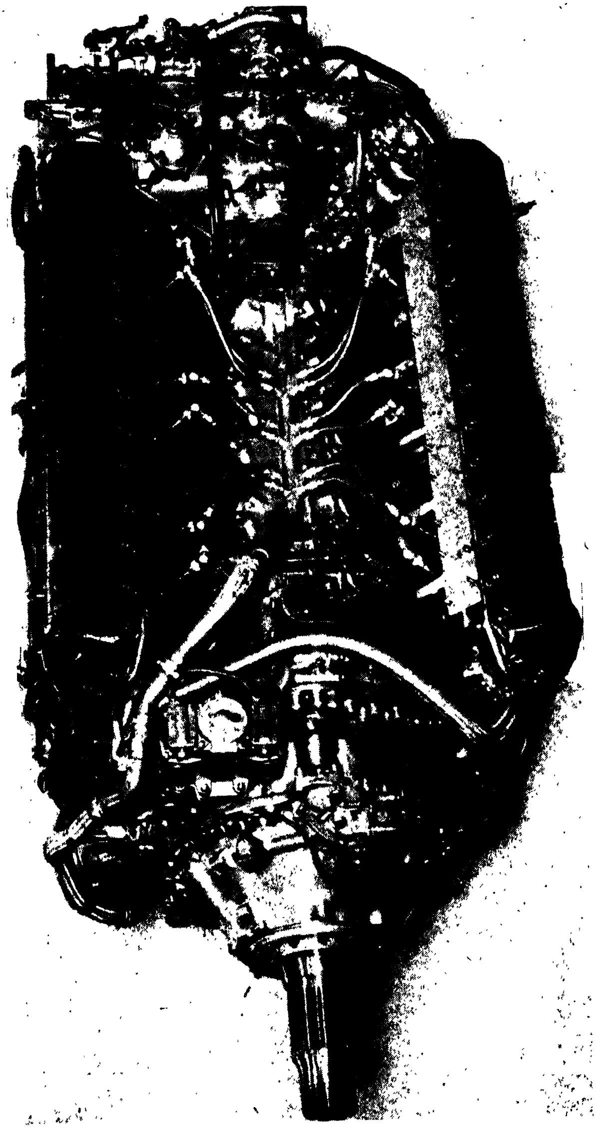


FIG. 148. The Rolls Royce "Vulture" 24-cylinder engine.

[*Facing p.* 166.

carburettor mounted below the supercharger has twin choke tubes, with fully automatic control, a two-position mixture control and four-stage boost control. Provision is made for warm and cold air intakes, a flame trap being fitted over the former intake; the choke and throttle are heated by the warm engine oil in order to prevent ice formation.

The crankshafts are each of the six-throw pattern, a pair of opposite connecting rods working on each crank pin. The connecting-rod assembly for each crank is made up of a forked rod in which a steel bearing-shell lined with lead-bronze is fixed and a plain rod which oscillates on the outside of the bearing shell. The hollow gudgeon pins rock in phosphor bronze bushes in the pistons, and the main crankshaft bearings are of the lead-bronze variety.

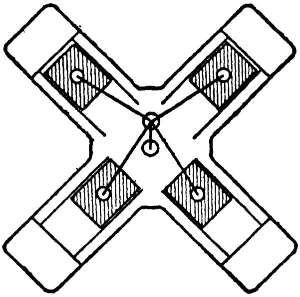


FIG. 147. The X-type engine.

The crankcase is of aluminium alloy and is made in halves joined along the horizontal centre line of the engine; it represents an excellent example of the use of a complex casting. A later development of the H-type engine is the Napier " Sabre," which is of much higher power output.

The X-type Engine. This essentially high-powered engine has four banks of cylinders arranged in the form of a cross, as shown in Fig. 147. A typical example of such an engine is the Rolls Royce " Vulture " (Fig. 148), which may be regarded as two " Peregrine " 12-cylinder engines arranged on opposite sides of the crankshaft. There are, therefore, four banks of 6-cylinders each, giving an X-type engine with the cylinder banks at 90°. The engine as developed in 1942 gave 1,845 b.h.p. at 3,000 r.p.m. at 5,000 ft. and 1,710 b.h.p. at 15,000 ft. with the high supercharger gear operating.

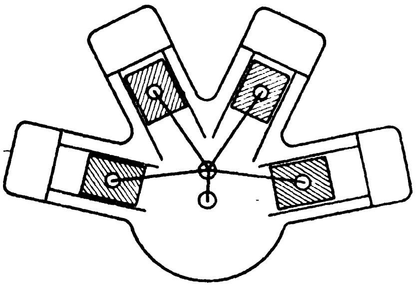


FIG. 149. The W-type engine.

9) **The W-type Engine.** In this alternative method of arranging four banks of cylinders in order to obtain a high-powered unit the cylinder blocks when seen in end view gave the " W " arrangement

indicated in Fig. 149. This method, however, results in a much wider engine than the X-type so that it gives a greater frontal area per h.p. when fitted into a suitable design of fuselage.

A typical example of such an engine is the Allison V–3421, 24-cylinder model, which may be regarded as the equivalent of two 12-cylinder V–1710 engines with a common crankcase and two crankshafts geared together. The engine in question belongs to the 2,000-h.p. class.

The Junkers Compression-Ignition Engine. This engine is one of the very few commercially successful C.I. aircraft class and it is relatively light for its power output, with a correspondingly low fuel consumption. Its chief drawback is the inconvenient shape, which makes it difficult to install in single fuselage units, although it would appear to be well suited for horizontal installation in deep-section wing, large aircraft.

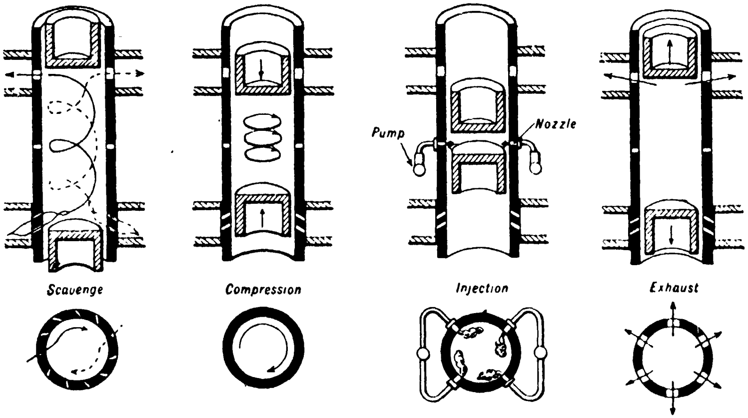


FIG. 150. Cycle of operations of the Junkers opposed cylinder compression-ignition engine.

The principle of this engine, which operates on the two-cycle sequence of operations, has been described in Chapter II, but it may be of interest to give an outline of the combustion and air scavenging processes for this engine.

Referring to Fig. 150, the left-hand diagram shows the pistons at the outer ends of their strokes. The upper piston has uncovered the exhaust ports, allowing the gases to escape through them. Immediately after this the lower piston uncovers the inclined ports in the cylinder walls and allows air under pressure to flow into the cylinder in a spiral path upwards, thus scavenging the cylinder clear of the exhaust gases in the manner indicated by the arrows.

The second diagram from the left shows the two pistons moving inwards, after the completion of the scavenging process—which leaves the cylinder filled with air under pressure—the air still retaining some of its spiral motion. In the third diagram from the left, the two pistons are seen in practically their nearest positions, the air charge being almost fully compressed and fuel injection occurring through four equally spaced injection nozzles ; this arrangement ensures a good distribution of the fuel particles in the air ; the latter is still in movement when injection occurs so that the combustion is further assisted. The expansion stroke follows, the two pistons being forced outwards by the high combustion pressure within until, as shown in the extreme right-hand diagram, the upper piston uncovers the exhaust ports, which are of ample area and equally disposed around the cylinder as indicated by the diagram in the lower right-hand corner. It will be observed that the air ports below are not yet uncovered so that no exhaust gases can escape through them ; moreover, when these ports eventually open the burnt gases are forced through the ports above by the scavenging air and do not therefore change their direction.

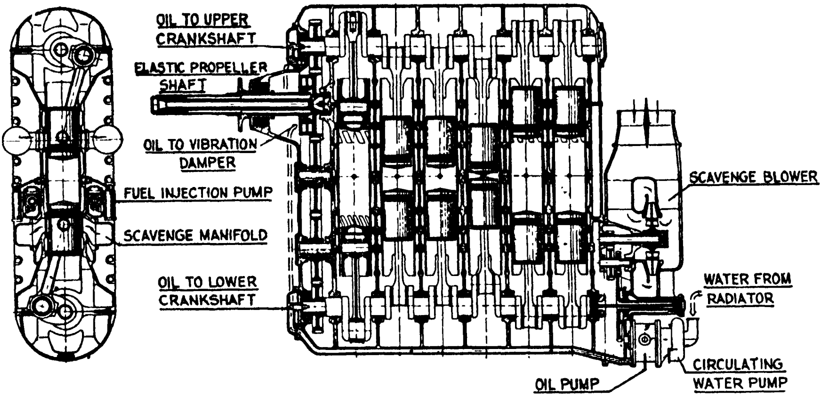


FIG. 151. Six-cylinder unit Junkers compression-ignition engine.

A typical double-six or equivalent 12-cylinder engine is shown in Fig. 151, the principal components being indicated. The engine is liquid-cooled. These engines, known under the general name of " Jumo," have been made in a range of models with maximum outputs varying from 550 to well over 1,000 b.h.p. in the double-six series.

The 750-h.p. Junkers Jumo-204 engine had a bore of 120 mm. and each piston had a stroke of 210 mm. The cylinder capacity was

28·6 litres and, as the engine gave 800 b.h.p. at 1,850 r.p.m., this was equivalent to about 28 h.p. per litre of cylinder capacity. The engine weighed 1,650 lb. complete; this is equivalent to 2·06 lb.

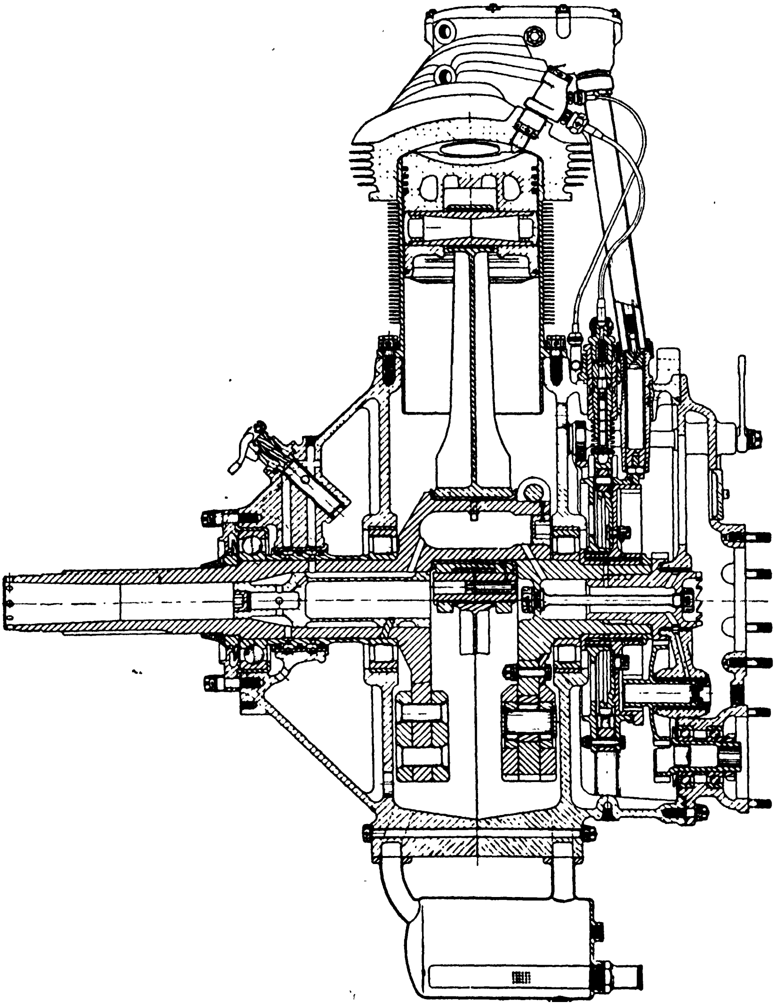


FIG. 152. The Guiberson compression-ignition air-cooled radial engine.

per h.p. on the maximum output. The frontal area was 8·3 sq. ft., *i.e.*, equivalent to about 96·5 h.p. per sq. ft. The engine length was 5 ft. 9½ in.

The compression ratio employed was 17 to 1 and the engine developed a B.M.E.P. of 96 lb. per sq. in.

The fuel consumption (minimum) was given as 0·34 lb. per b.h.p. per hour.

Comparison with Merlin Engine. A later engine, the Jumo 206, of 1,000 h.p. rating, had an output of 40 b.h.p. per litre and weighed 1·4 lb. per h.p.

Although very creditable for a C.I. engine of acknowledged " awkward " design, these results do not compare very favourably with those of the Rolls Royce Merlin engine RM2SM which, on 100-octane fuel and supercharged, gave 78·5 b.h.p. per litre and has a specific weight of 0·9 lb. per h.p. reckoned on the maximum potential ground power output.

The Guiberson Compression-Ignition Engine. There have been several different designs of radial C.I. engines of the air-cooled pattern, typical instances being the Packard 9-cylinder (240 h.p.), the Bristol " Phœnix " 9-cylinder (415 h.p.) and the Clerget 14-cylinder (650 h.p.) engine. A more recent commercial model, built in U.S.A., is the Guiberson 9-cylinder one operating on the 4-cycle principle and shown, sectionally, in Fig. 152.

The engine has a bore and stroke of 5·125 (130 mm.) and 5·50 (140 mm.), respectively, with a corresponding cylinder capacity of 1,021 cu. in. (16·7 litres). It employs a compression ratio of 15 : 1 and has a rated output of 320 b.h.p. at 2,200 r.p.m. with 340 b.h.p. at 2,250 r.p.m. for take-off purposes. The B.M.E.P. value is 113 lb. per sq. in. at the rated h.p. The fuel consumption is quite low for such an engine, being 0·38 lb. per b.h.p. hour at the full rated power. When at the cruising power, namely, 190 b.h.p., the fuel consumption drops to 0·34 lb. per b.h.p. hour.

The engine has a diameter, overall, of 47 in. and weighs 620 lb., *i.e.*, 1·94 lb. per rated h.p.

Constructional features of this engine include aluminium alloy pistons ; steel cylinders with aluminium alloy heads having valve seating rings of Silchrome steel for the overhead valves ; a two-piece aluminium alloy crank case ; two-part crankshaft with roller-type main bearings ; valve cam ring of the four lobe " monorail " type running at one-eighth engine speed in opposite direction to the crankshaft—the inlet and exhaust valve cams are unified in one lobe for the valve action ; fuel injection system comprising nine individual fuel pumps and spring-loaded fuel injection nozzles with triple orifices. The engine is started by means of the explosive starting cartridge method.

Some Other Compression-Ignition Engines.* Apart from the

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* Illustrated and described in " High Speed Diesel Engines," A. W. Judge. (Chapman and Hall Ltd.).

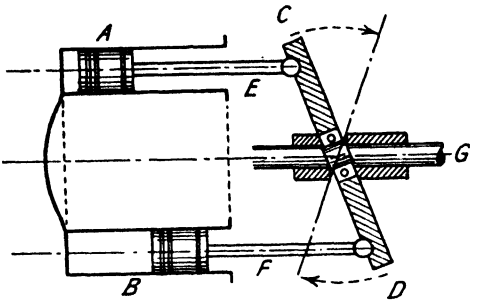

FIG. 153. Principle of wobble-plate or axial engine.

engines previously mentioned there have been others of Continental design, most notable amongst which are the Maybach 12-cylinder Vee-type (410 h.p. at 1,400 r.p.m.); the Mercedes Benz 12-cylinder V33-types (700–750 h.p. and 900–1,200 h.p.); the larger engines were used on the ill-fated Zeppelin LZ129 "Hindenburg" airship. In the U.S.A. a 12-cylinder inverted Vee-type engine, known as the "Deschamp," and operating upon the 2-cycle principle has been built and tested. It developed 1,200 b.h.p. at 1,600 r.p.m. for a weight of about 2 lb. per h.p. In France, the 12-cylinder Coatalen Vee-type engine of 150 mm. bore and 170 mm. stroke (36 litres) gave 550 b.h.p. at 2,000 r.p.m. for a weight of 1,200 lb., *i.e.*, about 2·2 lb. per h.p.; the engine was supercharged and had a fuel consumption of 0·35 lb. per b.h.p. per hour.

Axial or Barrel-type Engines. This design has several attractive features and it has therefore been a favourite type for the inventor, but has not yet reached the commercial stage. The principle is that of a number of cylinders arranged with their axes parallel to the main shaft (which is the equivalent of the petrol engine crankshaft). The drive to the latter is by means of ball-ended piston rods and socket-bearings for these, mounted on an inclined disc or plate. The latter is known as a "wobble" or "swash plate," according to whether the engine cylinder unit is fixed and the main shaft rotates or the shaft is fixed and the cylinder unit with its pistons, etc., revolve bodily around the shaft and inclined disc attached to it.

The principle of the

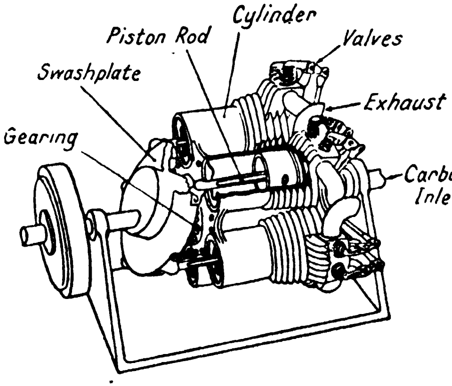

FIG. 154. Swash plate engine.

former type engine is illustrated diagrammatically in Fig. 153, which shows only two of the cylinders, A and B, with their unit pistons and rods E and F respectively. The latter have ball and socket joints in the inclined plate CD mounted on ball bearings on the inclined portion of the main driving shaft G.

As the pistons reciprocate within their cylinders on the 2- or 4-cycle principle of operations the inclined plate is forced to rotate the main shaft, whilst it wobbles to and fro as indicated by the dotted lines near C and D in Fig. 153. It will be observed that any convenient number of cylinders may be arranged around the shaft axis. If the shaft is fixed the cylinder unit will rotate bodily about it.

Various designs of engines, including the Macomber, Helm, Bristol and the Michell swash plate type with Michell thrust-socket bearings have been made to operate on this principle. More recently the American Herrmann and Hall barrel engines have been put forward as suitable for aircraft. The advantages claimed for the barrel-type engine are that it gives a smaller frontal area per h.p. than other engine and can be made lighter per horse power. Further, since the pistons can be given a true harmonic motion, the engine's speed can be increased by about 12 per cent. without increasing the maximum inertia forces. The principal disadvantage of the barrel-type engine lies in the relatively high frictional losses between the piston rod and inclined plate bearings owing to the heavy thrust pressures ; attempts to reduce these losses usually result in appreciable increase in the weight of the engine.

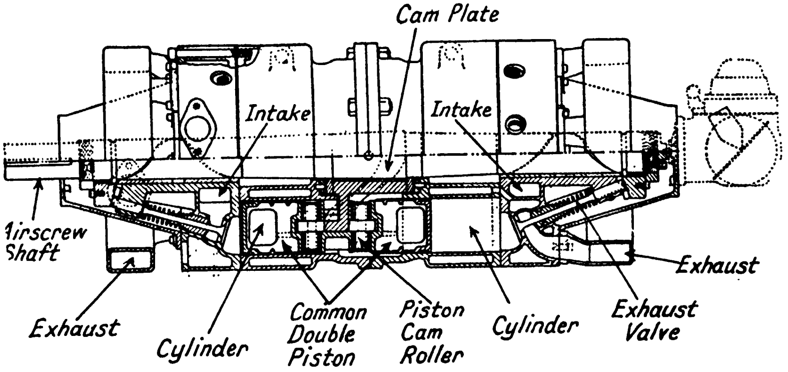

FIG. 155. The Herrmann barrel-type engine.

It has been computed that an 18-cylinder barrel engine of the Herrmann type would develop 2,000 h.p. for a frontal area of 6 sq. ft., *i.e.*, 333 h.p. per sq. ft. An experimental engine with 12 cylinders arranged in six opposing pairs of 5·4 litre capacity gave 140 to 150 b.h.p. at 1,900 r.p.m., *i.e.*, about 26 to 28 h.p. per litre for a dry weight of 1·5 lb. per h.p.

At present barrel-type engines are still in the experimental state.

The Internal Combustion Turbine. The simplest type of turbine with which aircraft engineers are familiar is the exhaust gas-driven single wheel Rateau turbine which utilises the difference of pressure between the exhaust gases released from the engine and the outside atmospheric pressure to drive a turbine wheel having a relatively large number of curved blades around its periphery through which the exhaust gases at high velocity pass and then escape to the atmosphere. The gases thereby give up some of their energy to the turbine wheel. An appreciable percentage of the engine's output can be recuperated in this manner and utilised for driving a centrifugal air compressor for supercharging the engine. As this type of turbine operates at a speed of 20,000 to 30,000 r.p.m. it could not be utilised for aerial propulsion purposes without a large ratio step-down gear; such gears are, however, used in marine turbines for obtaining the relatively low propeller shaft speeds required for maximum efficiency.

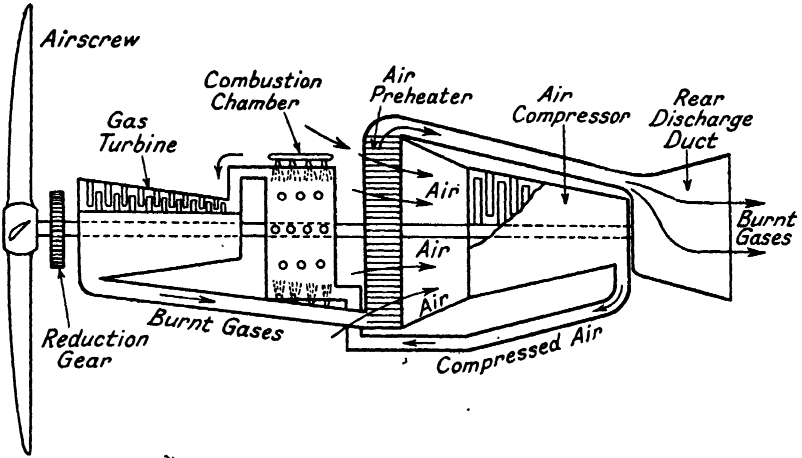

FIG. 156. Schematic layout of aircraft gas-driven turbine plant.

The more recent development of the gas turbine locomotive on the Continent, namely, the Brown Boveri one ordered by the Swiss Federal Railways, has awakened fresh interest in the possibilities of this type of prime mover for aircraft purposes.

The chief difficulty in connection with gas turbines is that of the high working temperatures necessary in order to give sufficiently good thermal efficiencies to justify their competition with the petrol type engine. These high temperatures introduce special practical problems in regard to the ability of the metals employed to withstand such temperatures without losing too much of their strength values and also to resist the corrosive effects of the hot combustion products ; in recent years, however, a good deal of progress has been made with heat and corrosion-resistant steels and other alloys.

It may here be mentioned that for a thermal efficiency of the order of 15 to 18 per cent. the gas temperature in the turbine would be about 1,000° F., for efficiencies of 24 per cent. a temperature of 1,200° F. would be necessary. In this connection it is understood that already such efficiencies have been attained in stationary installations, so that these values are equal to those of modern steam turbine plant although not so good as those for modern high compression petrol and C.I. engines.

Fig. 156 illustrates, schematically, the lay-out of a gas turbine installation combined with an exhaust ejector unit for an aircraft.

In order to obtain the highest efficiency it is necessary to preheat the air before it is taken into the air compressor. For this purpose the burnt gases leaving the propulsion gas turbine are lead through a heater of the same pattern as a steam engine condenser or a radiator ; the hot gases flow around a series of thin tubes through which the air supply to the centrifugal multi-stage air compressor, shown on the right, is drawn. After compression in the various stages of the latter the pressure increases to about 25 to 40 lb. per sq. in. and air at this pressure is discharged into the combustion chamber which is heat-insulated and provided with a number of spraying nozzles resembling those used in high speed compression-ignition engines. The combustion of the oil used as fuel causes the generation of gaseous products at a high pressure and temperature. These are led to the intake end of the gas turbine at a temperature of about 600° C. (1,112° F.) whence in passing through the blades of the rotor unit they do useful work. The speed of the rotor is usually of the order of 20,000 to 25,000 r.p.m., so that it is necessary to reduce this speed, by means of a reduction gear system of the epicyclic or direct helical pattern in order to drive the airscrew. It may be noted that the gases after leaving the turbine pass wholly or partially through the air preheater and are then ejected rearwards in order to give a forward propulsive effect on the aircraft.*

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* For fuller information vide *Gas Turbines and Jet Propulsion for Aircraft.* (G. G. Smith. Flight Publishing Co., Ltd.)

CHAPTER VIII

THE LUBRICATION SYSTEM

THE modern aircraft engine contains a relatively large number of components that rotate in bearings or slide in suitable guides. In every case it is necessary to provide ample lubrication for these moving members in order to reduce the coefficient of friction to a minimum and thus ensure that the power lost by friction is as small as possible.

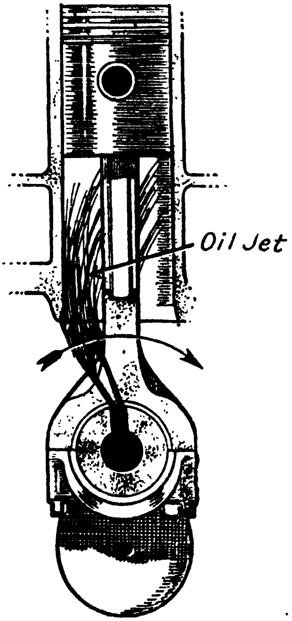


FIG. 157. Oil-jet method of lubricating the cylinder walls.

When two metallic surfaces slide together the introduction of oil between the surfaces results in the formation of an oil film between the surfaces so that they are not in metallic contact; the frictional coefficient is then reduced considerably. It is necessary to employ a suitable grade of oil in order to prevent the pressure between the surfaces from forcing it out, thus allowing metallic contact to take place.

In the case of aircraft engine bearings, such as those of the crankshaft and camshaft, a high-grade lubricating oil is supplied under a pressure of 50 to 80 lb. per sq. in., in order to preserve the oil film between the bearing surfaces and at the same time to carry off the surplus heat; for this purpose the oil is kept in constant circulation through the engine.

It is not necessary, however, to use this high-pressure oil for the purpose of lubricating all of the rubbing parts, so that a low-pressure oil supply of a 4 to 8 lb. per sq. in. pressure is provided for certain of the components; the latter include the various gears and their bearings, the overhead valve rocker arms, airscrew reduction gear, supercharger drive gear, etc.

The pistons and cylinder walls are generally lubricated by the oil that leaves the connecting rod big-end bearing and, passing through a hole drilled in the rod side of the bearing, emerges as a fine jet which is directed on to the cylinder walls (Fig. 157). The piston picks up this oil and distributes it evenly over the cylinder walls. In addition to lubricating the piston and cylinder, some of the oil is splashed up into the inside of the piston and helps to lubricate the gudgeon pin bearing; a suitable oil hole is provided in the small end of the connecting rod for this purpose. Alternatively, the oil may flow in from the cylinder walls through a hole in the hollow gudgeon pin and thence to the small end bearing.

In some instances a more positive method of lubricating the small-end bearing is employed. This consists in the provision of a hole through the web of the connecting rod from the upper half of the big-end bearing to the small-end one; oil can thus pass from the former to the latter.

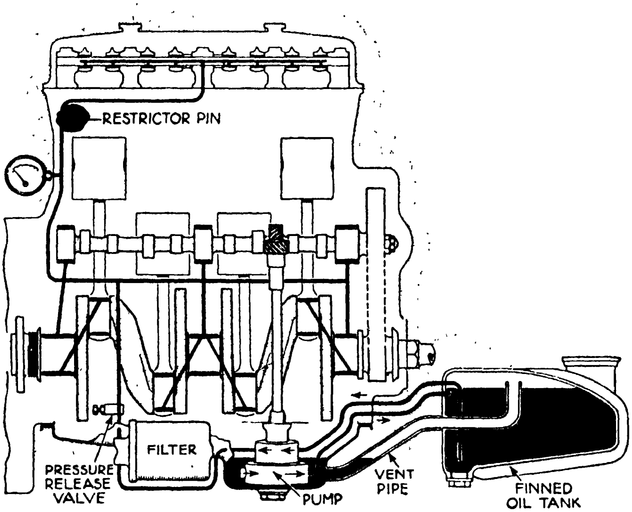
The method of lubricating the *crankshaft main and big-end bearings* is to make the crankshaft hollow, by drilling suitable holes so as to form a continuous passage from one end to the other. Oil under high pressure is then supplied to the outside of the main bearings whence it flows through holes drilled in the main journals to the interior oil passages. From the latter it emerges by holes drilled through the crank pins and thus lubricates the big-end bearings. As mentioned previously, it escapes from the latter and lubricates the pistons and cylinders.

In all lubricating systems employed on aircraft (and automobile) engines the oil that has been used for lubricating the interior working parts is collected, filtered and re-circulated. For aircraft engine purposes the used oil is filtered carefully and then cooled before it is returned to the main oil reservoir or tank; from the latter it is delivered to the engine again and is thus in constant circulation around the lubrication system.

The Dry Sump System. The high-pressure method of lubricating automobile engines employs a relatively large oil reservoir, or sump, at the base of the crank case. From this the oil pressure pump draws its supply and delivers it to the hollow crankshaft feed system, the camshaft bearings, timing gears and, if fitted, to the overhead valve mechanism. After lubricating the working surfaces the oil drains down the sides of the crankcase and into the sump, whence it is mixed with the remaining oil, filtered and re-circulated.

Whilst this method is very satisfactory and economical for automobile engines, it is unsuited to aircraft ones, for in the latter type, owing to the various inclinations of the machine, during climbs and manœuvres, the oil in the sump would flow into the crankcase and find its way on to the cylinder walls in large amounts. The result would be excessive oil consumption and possible leakage of the oil past the piston rings to cause a smoky exhaust.

To obviate these drawbacks the *dry sump method* has been adopted. The principle employed is to draw the used oil that drains into the bottom of the crankcase, by means of an oil pump known as the *scavenge pump*, and deliver it first to an oil cooler and thence to a separate oil reservoir or tank. The pressure pump, of smaller capacity than the scavenge pump, draws its supply of oil from the oil reservoir through a filter and circulates it in the engine, whence it drains into the bottom of the crankcase. The latter is therefore prevented from accumulating oil, whilst the oil taken from the engine is cooled down for use again ; otherwise it would become too hot and tend to lose its lubricating qualities.



[*Courtesy of " The Autocar."*

FIG. 158. Dry sump lubrication method.

The arrangement of the dry sump system on an automobile engine of the overhead valve pattern is shown in Fig. 158. The oil pump unit consists of two separate pumps, namely, a smaller pressure one above and a larger scavenge one below. The upper pump draws oil from the finned oil tank on the right and delivers it to a common pressure feed line, through the *pressure release valve*, shown on the left. From the common feed line (indicated by the black line above and parallel with the crankshaft), the oil is fed to the main bearings below and thence through the drilled crankshaft to the big-end connecting-rod bearings. The oil that escapes from the latter is directed on to the cylinder walls for their lubrication.

The common pressure feed line also supplies the camshaft bearings above and the oil escaping from these bearings lubricates the cams and valve tappets. Another supply of high-pressure oil is taken upwards, on the left, through a restricted passage, which limits the quantity of oil that can pass, to the overhead valve rocker bearings. The used oil from the overhead valve gear drains into a trough below the rocker shaft, and thence down a vertical passage into the bottom of the crankcase. The lower, or scavenge pump, draws the " drained " oil from the crankcase and returns it to the oil tank. The oil is filtered on the suction side of the pressure pump.

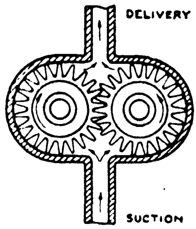


FIG. 159. Gear wheel type of oil pressure pump.

The gear-wheel type of pump is widely used on both automobile and aircraft engines. It consists of a pair of gear wheels in mesh, within a casing, as shown in Fig. 159. The gear teeth have a very small clearance within the casing. One of the gears is driven from the engine and as the gears rotate, in reverse direction, oil is carried round in the teeth spaces from below and delivered above. It is possible to obtain relatively high oil pressures with this type of oil pump, namely, 80 to 100 lb. per sq. in.

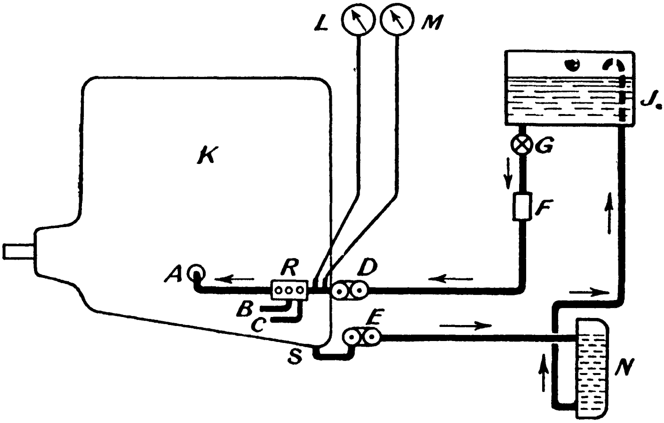


FIG. 160. Schematic layout of aircraft engine lubrication system.

Fig. 160 illustrates, schematically, the lay-out of an aircraft engine dry sump system, in which K denotes the engine, S the crankcase sump, N the oil cooler, J the oil reservoir, D the pressure and E the scavenge pump. The arrows indicate the directions of flow of the oil. From the tank J, oil flows through a cock G and oil cleaning filter F to the suction side of the pressure pump D, whence oil is delivered under high pressure to a triple oil pressure release valve unit R. This unit has three spring-loaded valves which provide three different oil pressure supplies, viz., high, intermediate and low pressure supplies (shown at A, B and C, respectively) for lubricating different parts of the engine. In practice the high pressure supply is used for operating the variable pitch airscrew, whilst the intermediate pressure feed is for the main crankshaft and big-end bearings and the low pressure feed for the camshaft, rockers, reduction and other gears, etc.

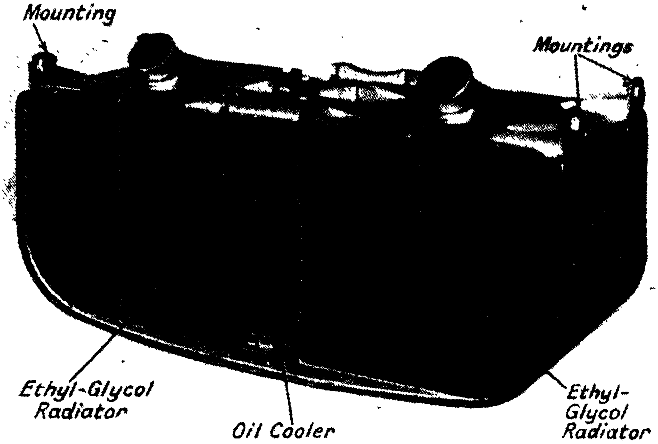


FIG. 161. Combined liquid and oil-cooling radiator used on aircraft.

The pressure and temperature of the oil delivered by the pressure pump are measured by the gauges shown at L and M; these are arranged on the pilot's instrument panel and afford a reliable indication of the operation of the engine lubrication system.

The oil cooler consists of a relatively small radiator unit similar in construction to the main liquid-cooling radiator. The oil circulates around the air-cooled honeycomb spaces. The oil cooler is sometimes combined with the main cooling liquid radiator to form a single unit as shown in Fig. 161.

Modern oil coolers are made in dual stage units consisting of a first stage of larger tube spaces through which the oil can circulate continuously; and a second stage through which the heated air from the first stage passes. In this way there is no risk of the second stage becoming over-cooled as during a long dive or gliding operations at high altitudes. Immediately the oil temperature rises both stages are in operation.

After the engine is started from the cold it is necessary to warm up the oil as quickly as possible. This cannot be done if the oil cooler is in operation, so that the latter is temporarily put out of operation by means of a by-pass pipe with a thermostatic device which diverts the oil flow through the cooler as soon as a certain temperature is reached.

Typical Dry Sump System. Fig. 162 shows the lay-out of a typical aircraft engine dry sump lubrication system. The arrangement is practically the same as that given in Fig. 160, but with certain additions, including the hot oil supply for heating the carburettor in order to prevent icing. The positions of the oil temperature pressure and connections are indicated at A and B, respectively, but the oil pressure release valve unit has been omitted for the sake of clarity.

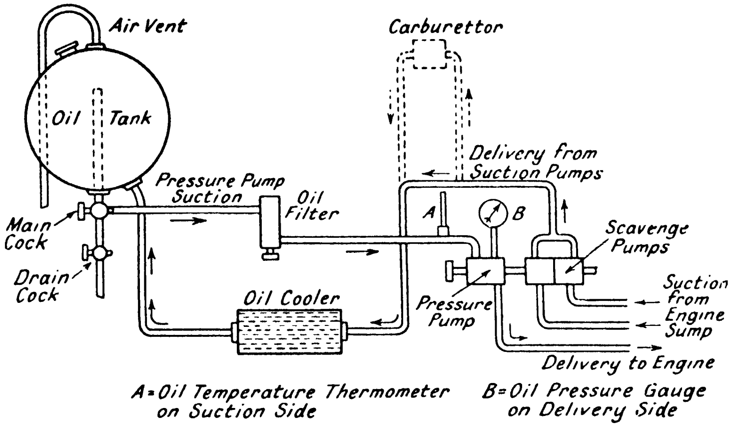


FIG. 162. Layout of aircraft engine lubrication system.

The Rolls-Royce Merlin Lubrication System. The " Merlin " engine dry sump lubrication system illustrated in Figs. 163 and 164 employs one pressure and two scavenging pumps, the latter working in parallel arrangement to drain, independently, the front and rear ends, or sumps, of the crankcase. All of the pumps are of the gear-wheel pattern and are actuated from the wheelcase through an idler gear from the lower vertical drive shaft to the water pump. The pressure pump delivers oil to a triple relief valve unit (Fig. 165) on the right-hand side of the upper half crankcase, which regulates the oil pressures, firstly for operation of the variable pitch airscrew

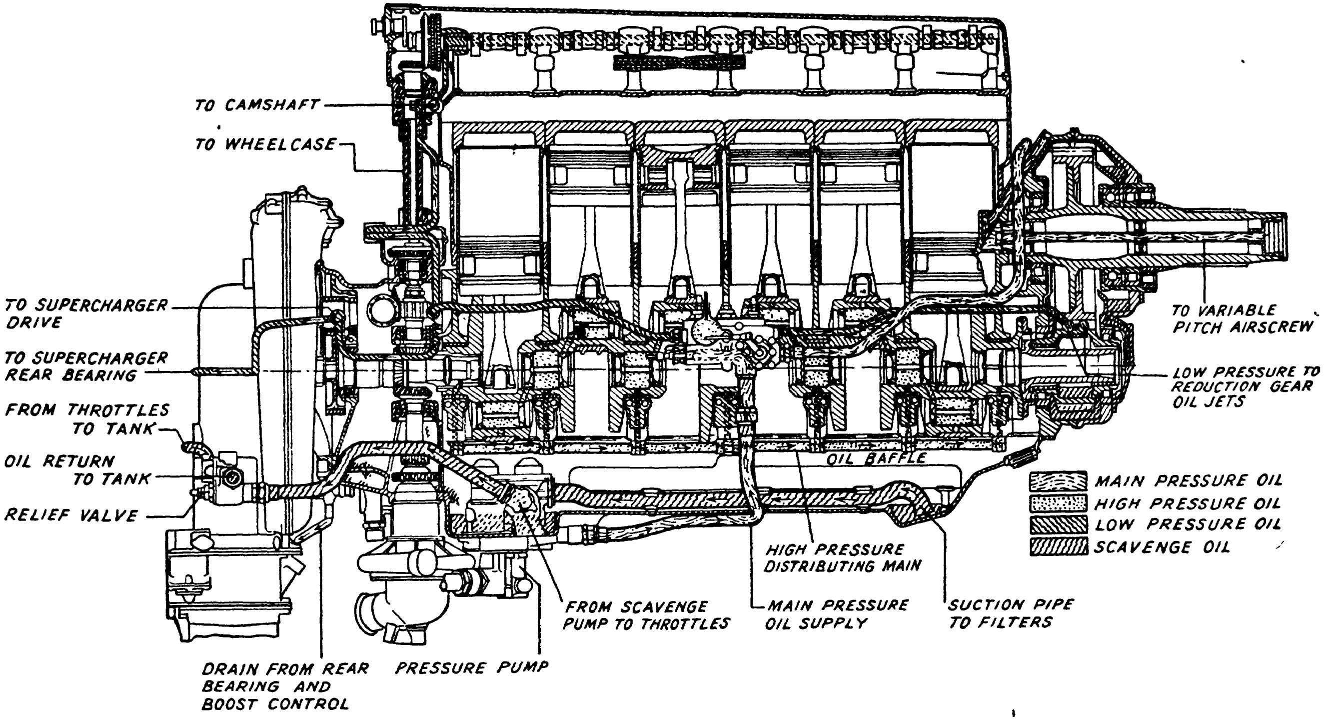


FIG. 163. Rolls Royce " Merlin " engine lubrication system (side view).

(150 lb./sq. in.) and fuel pump bushes, secondly for the main high pressure feed (70 lb./sq. in.) to the crankshaft and bearings, and finally, for low pressure feed, to the auxiliaries. The relief valve body contains also a pressure gauge connection, a thermometer pocket for measurement of the oil inlet temperature and a change-over valve, for airscrew pitch control, which allows the high pressure

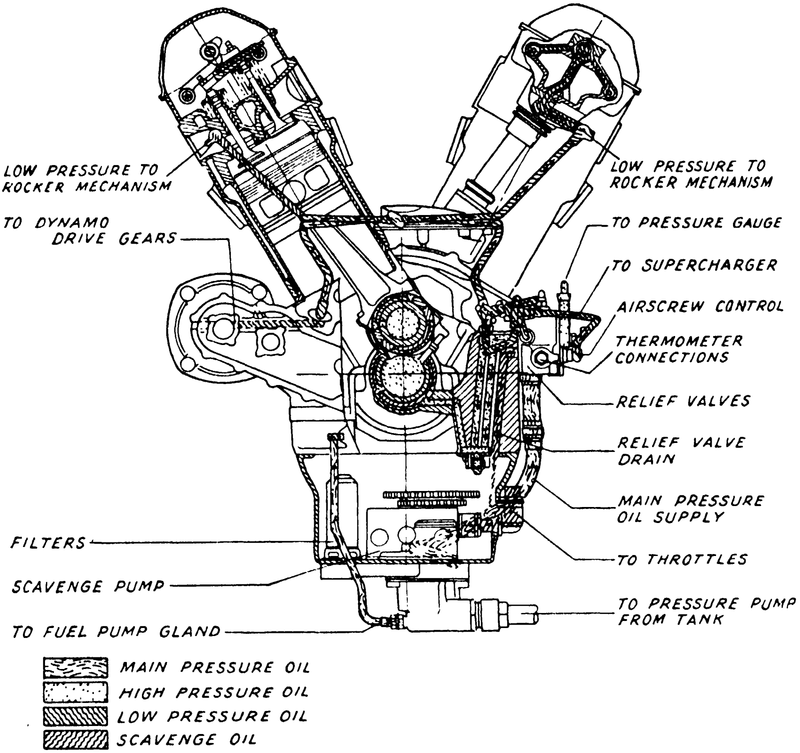


FIG. 164. Rolls Royce " Merlin " engine lubrication system (end view).

stage to be connected with or shut off from the airscrew hub by movement of a control lever operated from the pilot's compartment.

The oil from the second stage (engine main oil pressure) is fed into drilled passages in the crankcase, and thence to a main gallery pipe supplying each of the seven main bearings. The big-end bearings are fed *viâ* oil passages in the crank webs and holes drilled in the crank-pins.

The pistons, gudgeon pins and connecting rod small-ends are lubricated by splash, a baffle being provided in the crankcase lower half to prevent an excess of oil being thrown into the cylinders.

The third stage is regulated between 4 and 8 lb./sq. in. and supplies the various auxiliaries such as camshaft, rockers, reduction gear, generator and supercharger drive gears and tail bearing. Oil draining back to the crankcase through the camshaft drive housings is used for the lubrication of the inclined camshaft drives and the wheelcase gears.

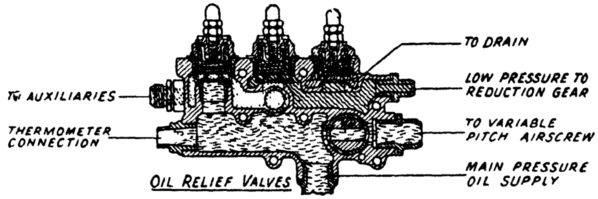


FIG. 165. Triple relief valve unit of the "Merlin" lubrication system.

The scavenge pumps drain the front and rear of the crankcase independently, one drawing oil through a pipe along the bottom of the crankcase from the forward end and the other from the rear sump, both delivering into a common duct leading to the oil tank return. Separate gauze filters are arranged on the suction side of each scavenge pump, both filters being easily detachable downwards for cleaning.

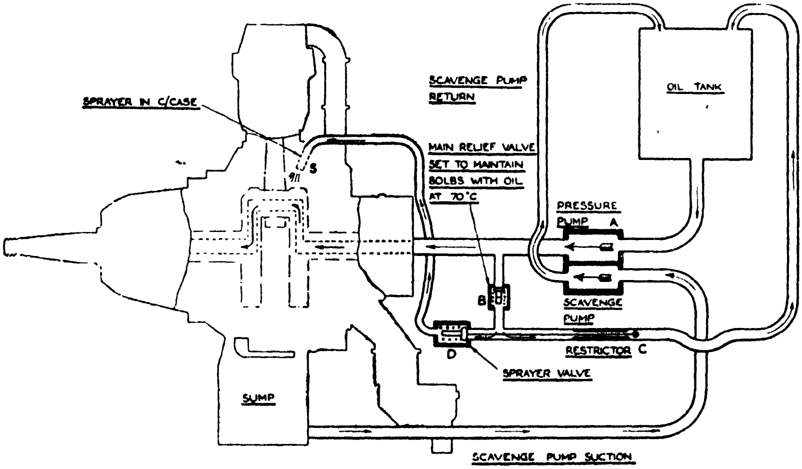


FIG. 166. The Bristol high initial oil pressure system.

Bristol High Initial Pressure System. The more recent Bristol radial engines employ a special lubrication system known as the *high initial oil pressure* one. Whilst air-cooled engines require less time for the oil to warm up, the Bristol system still further reduces the warming up period. Referring to Fig. 166, under normal conditions the oil enters the engine from the pressure pump (A) through the rear end of the crankshaft. The main pressure relief valve (B) is set to maintain the oil pressure at 80 lb./sq. in. with the oil at 70° C. The by-passed oil from this valve is returned under its own pressure to the oil tank, together with the oil from the scavenge pump.

A restrictor (C) of suitable size is fitted between the main relief valve (B) and the return pipe line to the oil tank. This restrictor is so constructed that it will allow normal circulation of by-passed oil at a reasonable pressure. When the oil is cold, however, the increased viscosity and quantity of the oil by-passed by the relief valve cause the restrictor to create a higher pressure. The resulting high oil pressure in the tail end of the crankshaft ensures an adequate supply of oil to all bearings, especially the big-end bearing, which under normal pressure and high viscosity would not receive a sufficient flow. The increased pressure created by the restrictor also opens valve (D) which is connected to a sprayer (S) fitted in the top of the crankcase. This sprayer supplies splash oil abundantly to the pistons as long as the flow of cold oil from the big-end is insufficient to lubricate them under full power conditions.

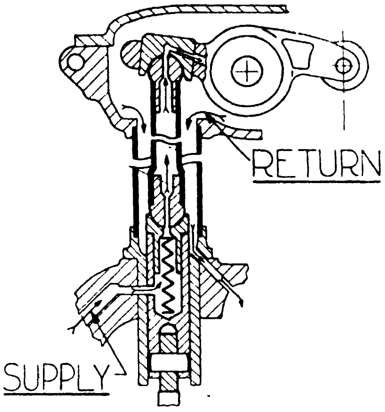


FIG. 167. Overhead valve mechanism lubrication method.

Immediately the oil becomes warm and its viscosity decreases, the pressure created by the restrictor is automatically reduced, the sprayer valve shuts and the auxiliary supply is cut off.

Lubrication of Overhead Valve Gear. The moving parts of the push-rod and rocker arm valve-actuating mechanism that require positive lubrication include the ball-and-socket member at the top of the push-rod and the rocker arm bearing. Sufficient oil, in the form of mist, is present in the valve casing to lubricate the other end of the rocker arm and the valve guide. The usual method employed (Fig. 167) is to enclose the hollow push-rod in a tubular casing made with an oil-tight joint at the tappet end; the upper part of the casing is also made with an oil-tight joint in the valve casing. Oil from the low pressure supply enters through a hole drilled in the hollow tappet and flows through the hollow push-rod to the ball joint, whence it is led through a hole drilled in the rocker arm to the rocker arm bearing. The oil from the latter drains back through a passage formed between the outside of the push-rod and the inside of the tubular casing to the sump of the crankcase. In *radial engines* this sump is located between the bottom cylinders, *i.e.*, at the lowest part of the engine.

Lubricating Oils. High-grade mineral oils, derived from petroleum by a process of distillation are used for aircraft engines. In some instances *compound oils*, *i.e.*, mixtures of mineral and vegetable oils (of which castor oil is an example), are employed.

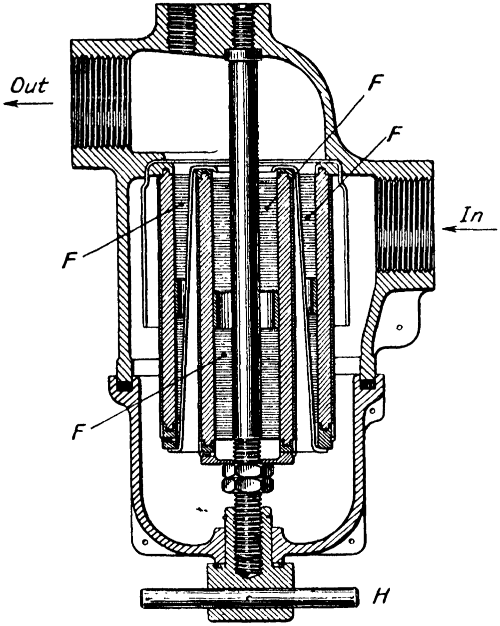


FIG. 168. The Auto-Klean oil filter.

Castor oil or compound oil with castor oil as one constituent are often used for running in new engines, as these oils have excellent lubricating properties and the bearing surfaces retain some of the oil for relatively long periods after the change over to mineral oil is made, when the running-in period has been completed. Castor oil is not satisfactory for regular use, however, on account of its tendency to gum-up the piston rings, increase the cold starting friction of the bearings and cylinder walls and produce a greater degree of carbonisation in the combustion chamber.

Lubricating oils made by newer processes, including doped, hydrogenated and volatised oils, have excellent chemical and physical properties. They give the desired degree of lubrication at engine-working temperatures without volatising, oxidising or losing too much viscosity ; at the same time they are not too viscous or " gummy " at low temperatures.

The more recent mineral oils, obtained by the special processes mentioned previously, have been shown to be equal or superior to both the compound and castor oils in their wear-resisting and lubrication properties.

Oil Filters. The used oil that drains back into the crankcase often contains minute carbon particles and occasionally small metal particles due to wear. It is necessary, therefore, to clean this oil before it is circulated again through the engine. The oil is cleaned by forcing it through a filter of felt or fine wire gauze, or by rotating the oil at a high speed in order to throw out, or to *centrifuge*, the solid matter to the outside of the cleaner casing where it can be collected and drained away.

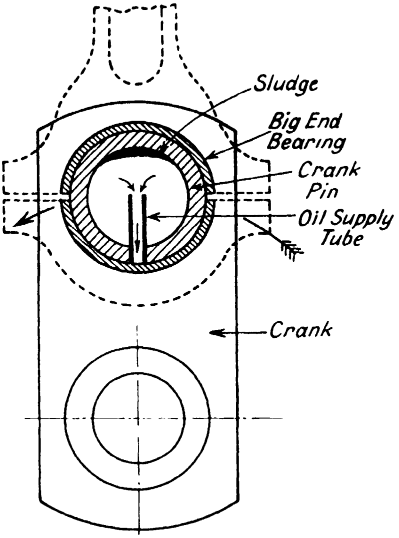


FIG. 169. Oil sludge trap in crankpin of radial engine.

One efficient type of oil filter, known as the Auto-Klean (Fig. 168), contains a Monel metal fine mesh gauze cloth cylinder through which the used oil passes to the inside chamber. This cylinder removes the larger particles. The oil then passes between a series of thin metal discs (F) arranged axially one above the other. The clearances or spaces between the discs are exceedingly small, so that the finer solid particles in the oil are prevented from passing through, leaving only the cleaned oil to flow into the interior of the filter, for returning to the engine. In order to clean this type of filter it is necessary only to rotate the plates by means of a handle (H) provided for this purpose, when the solid matter falls to the bottom of the filter, whence it can be drained off at regular intervals.

An improved aircraft engine filter of this type contains a small oil-pressure operated motor which rotates one set of cleaner discs slowly and continuously, thus obviating the need for periodical hand operation.

In some instances, notably in the case of radial engines, use is made of the centrifugal effect of the oil within the hollow crank-pin to centrifuge any solid matter in the oil to the inside surface of the crank-pin, whence it is removed when the engine is overhauled. The oil required to lubricate the big-end bearing is taken from a central tube (Fig. 169) to the opposite side of the bearing. This arrangement is known as a *sludge trap*.

CHAPTER IX

THE IGNITION SYSTEM

Some General Considerations. The purpose of the ignition system is to provide a regular series of high voltage sparks at the correct moments to the sparking plugs in the combustion chamber so as to fire the charges in their correct sequence.

As in automobile engine practice, there are two principal methods of providing these high voltage sparks, namely, the *magneto* and the *battery and coil* ignition systems. Whereas in automobile engines coil ignition has almost entirely supplanted magneto ignition in aircraft engines of present design the magneto reigns supreme, although a good deal of experimental work has been carried out with the coil ignition system.

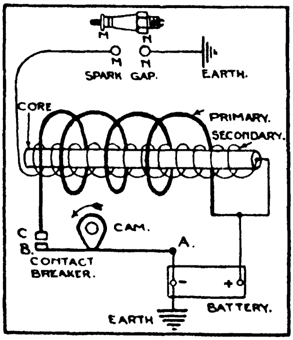


FIG. 170. The coil ignition system.

The Coil Ignition System. The principle of this system is that of using an electrical transformer having a small number of turns of relatively thick wire for its primary circuit and a large number of turns of very small diameter insulated wire for its secondary circuit. A low voltage (6 to 12 volts) current, provided from a battery, is arranged to circulate around the primary circuit. Periodically this current flow is interrupted by means of a mechanically-operated contact breaker. The effect of this is to cause a high voltage (5,000 to 10,000 volts) current to flow momentarily in the secondary circuit containing the sparking plug ; this high voltage is sufficient to provide the spark across the plug points for ignition purposes. Fig. 170 illustrates the application of the principle in question, which, incidentally, is very similar to that employed in the case of the medical or " shocking " coil, except that a cam-operated contact breaker is used in the former instance and an automatic solenoid type in the latter. Referring to Fig. 170 the primary windings are indicated by the thick spiral lines and the secondary ones by the thin lines. The primary circuit contains a pair of contacts, B and C, which are forced open by the cam, once every two revolutions of the engine (for the 4-cycle engine). The current from the battery positive flows through the primary and contacts, B, C to A and thence to the metal frame of the engine, to which the negative battery pole* is connected. The high tension current flows along the secondary winding across the spark gap MN (or sparking plug points) to the metal frame of engine, *i.e.*, to " earth." It will be seen that by using an " earth " return for the primary and secondary circuits the wiring is simplified.

In the coil ignition system the H.T. coil and contact breaker units are usually made as separate members, and being of small bulk are easily mounted on the engine ; the battery and wiring, however, are a drawback.

The coil ignition system gives a stronger spark at low engine speeds than a magneto and a better spark over a wider range of ignition advance and retard.

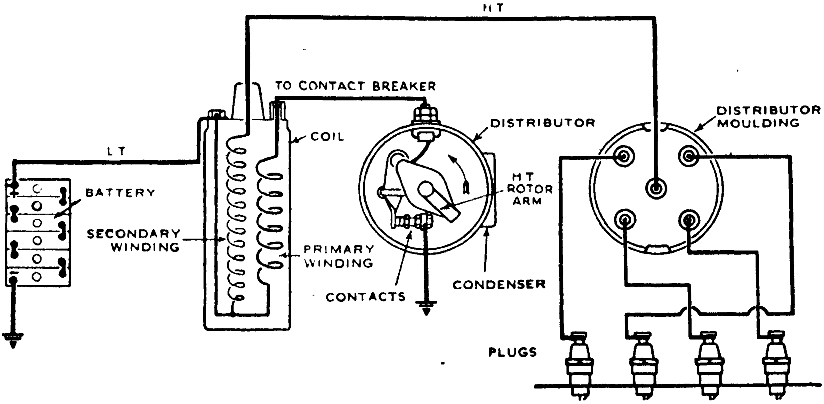


FIG. 171. Coil ignition arrangement for 4-cylinder engine, showing contact-breaker unit and distributor. The rotor arm shown, actually revolves within the distributor moulding as the contact-breaker and distributor units are co-axial.

The H.T. current is passed through a distributor unit which supplies each cylinder in turn with a spark at exactly the correct moment, in the cycle of operations (Fig. 171).

The *disadvantages* of the coil ignition method for aircraft purposes may be summed up, briefly, as follows :—

(1) A separate low-tension battery is required and should the battery be run down it would be impossible to operate the engine. Thus, in the case of an aircraft used occasionally in certain of the less frequented countries, it may not always be possible to keep the battery charged. The magneto, on the other hand, is a self-contained ignition unit with its own current generator, driven from the engine.

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* In modern car systems the positive pole is earthed.

(2) Increased weight and bulk.

(3) With the magneto higher sparking rates can be attained than with the coil system.

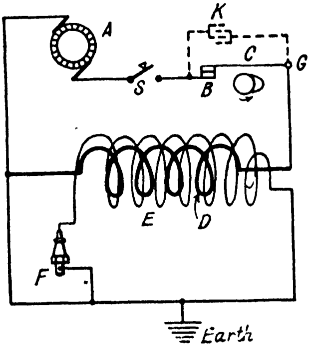

FIG. 172. Principle of the magneto.

(4) There is a greater risk of fuel ignition, in a crash with coil ignition, owing to the possibility of the low-tension cables from the battery becoming fractured and thus causing sparks.

(5) Where the low-tension current supply is taken from the aircraft electrical system's battery, a serious source of electrical interference with the radio receiver occurs and is more difficult to eliminate than in the case of the magneto.

The Magneto. This ignition device operates upon the same principle as that used for coil ignition, but, as mentioned previously, it contains its own low-tension current generator and does not therefore require a battery or outside low-tension cables ; it is, in fact, an entirely self-contained unit requiring only an engine drive.

The principle of the magneto is shown, schematically, in Fig. 172 for the type known as the *rotary armature* one. The latter member, A, has the primary D and secondary winding E on its rotating shaft, in a somewhat similar manner to dynamo armature windings. The primary circuit includes a contact-breaker unit BC with a rotating cam C. There is also a switch *S* for cutting-out the ignition when required. The secondary circuit consists of the winding E and sparking plug F, the outer metal shell of which is " earthed."

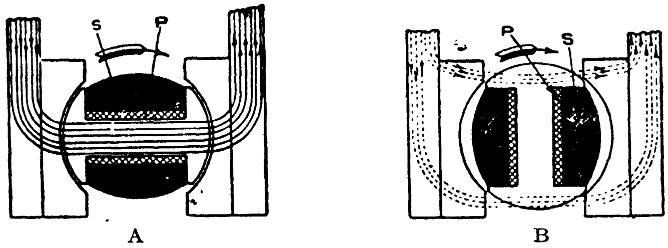

FIG. 173. (A) Position of maximum magnetic flux. (B) Position of minimum flux in magneto. P—Primary. S—Secondary.

When the armature, which has a soft iron core, rotates between the poles of a permanent horse-shoe magnet the magnetic core flux changes according to the position of the armature in relation to the magnet poles. The flux increases to a maximum when the armature is across the poles and decreases to a minimum when it is parallel with the poles; it is in the latter position (Fig. 173, *B*) that the maximum voltage is generated and the contact breaker points are opened by the cam. Fig. 174 illustrates the lay-out of a 4-cylinder engine magneto, the sparking plugs and their connections to the H.T. distributor unit being denoted by the numbers 1, 2, 3 and 4.

The cam F for operating the contact breaker is of the annular type, there being two such cams. The primary coil is inside the secondary coil; the latter at *a*, *b* has one end "earthed" and the other taken through light spring-loaded brushes E and C to a rotating conductor B having a carbon brush which makes contact, in turn, with each of the four numbered metal segments similar to S, so that the high tension current is led in turn through the H.T. cables to the sparking plugs.

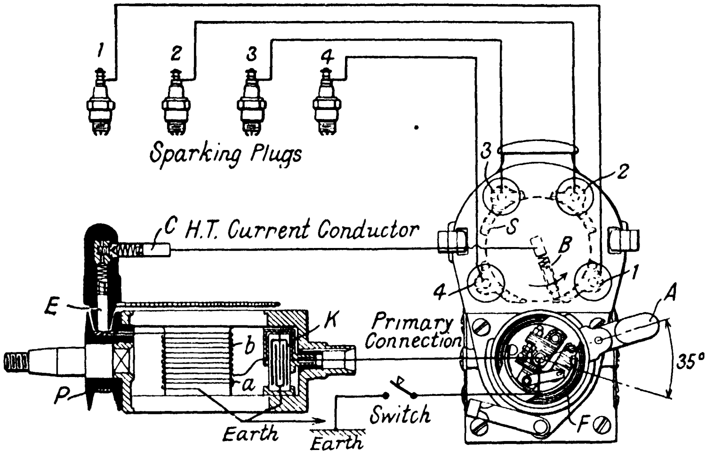

FIG. 174. Four-cylinder rotary armature type magneto layout.

In order to alter the timing of the sparks in relation to the piston position, *i.e.*, to *advance or retard the ignition*, the ring containing the two fixed cams is arranged to rotate through a small angle by means of the manually-operated lever shown at A; usually an angle of 30 to 35 degrees is provided. To prevent arcing across the contact-breaker points when the latter break the primary circuit *a fixed condenser* is connected in shunt with the two contacts. This condenser, which is of 0·1 to 0·3 microfarad capacity, becomes charged during the "break" and discharged when the contacts close together again. By this means the contacts are prevented from becoming pitted. Further, by suppressing the discharge across the contacts at the " break " and sending a reverse current through the closed contacts the condenser causes a more rapid and complete suppression of the magnetic flux and therefore produces a higher and more regular voltage in the secondary circuit.

The distributor on modern magnetos is not of the wipe contact type shown at B in Fig. 174 but of the *jump-spark* or *fixed gap* pattern indicated in Fig. 175. The metal-tipped rotor A does not actually touch the fixed contact metal inserts in the moulded insulator casing, but makes a gap of the order of 0·01 to 0·015 in., across which the spark jumps to the distributor contacts.

The *contact breaker unit* in the later magneto models has a rotating cam and a fixed contact member (Fig. 176) consisting of one fixed contact and another mounted on one end of a lever which can rock on a pivot pin at its other end ; it is held against the fixed contact by means of a flat section spring. *The cam has as many lobes as the engine has cylinders* for magnetos driven at one-half engine speed, *i.e.*, six in the example shown in Fig. 176.

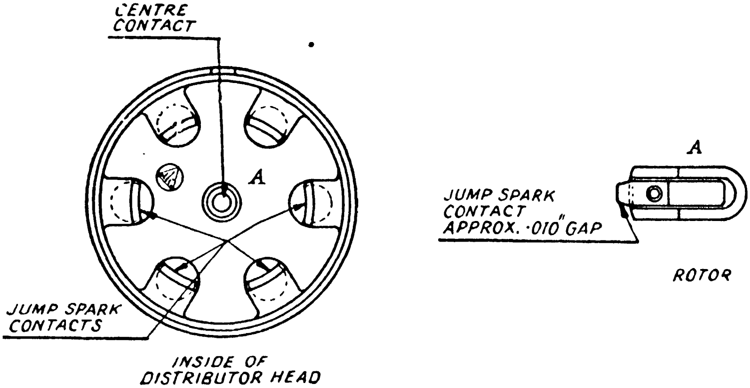

FIG. 175. Distributor and rotor arm (jump spark type).

In the case of 8-cylinder engines, however, it is usual to have a four-lobed revolving cam and two contact breakers.

For radial engines the cam is often given the same number of lobes as the engine has cylinders and it is made integral with the distributor spindle. In order to provide for compensation on *account of the link rod angles with the master rod,* the cam profile is to give *corresponding unequal angular intervals* between the made consecutive sparks.

The contacts of magneto and coil ignition system contact breakers were formerly made of an alloy of platinum and iridium for automobile ignition units. Later the contacts were made of, or tipped with, tungsten in order to obtain greater resistance to wear and impact effects. It is necessary, however, to limit the maximum current at " break " to a value below 3·5 amperes and the maximum voltage to 300 in order to avoid appreciable " pitting " of the contact surfaces ; if unchecked, this will cause misfiring.

An alloy consisting of 3 parts platinum and 1 part iridium is now often used for aircraft magneto contacts, and with these the limiting current at " break " is about 5 amperes.

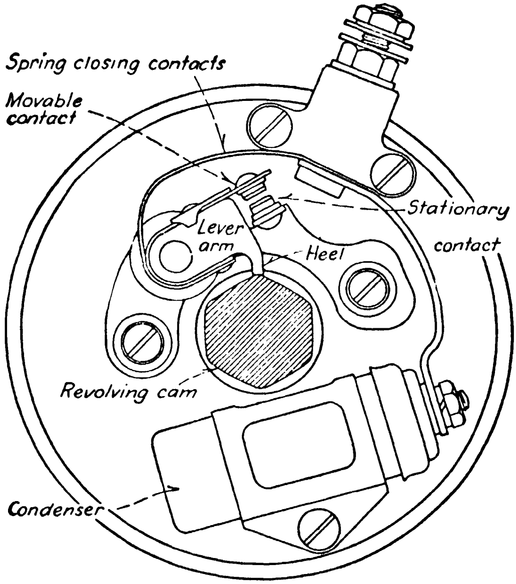

FIG. 176. Six-lobe cam contact breaker unit.

The permanent magnets of earlier magnetos were made of hardened cast steel and later of tungsten steels with 5 to 6 per cent. of tungsten, as these had better magnetic properties. Later, the more efficient cobalt steels, with about 35 per cent. cobalt were employed. More recently a special nickel-aluminium-iron alloy, of which Alnico and Alni are examples, has largely replaced the other materials, since it has better permanent magnetic qualities and enables much lighter magnets to be used.

Other Types of Magneto. The rotating armature magneto has certain disadvantages for aircraft engine purposes. Thus, its armature enables only two sparks per revolution to be obtained so that as the number of cylinders increases so must the magneto armature speed.* For example, *a 12-cylinder magneto* would need to be driven at *three times engine* speed ; a 6-cylinder one at one-and-a-half times engine speed and a 4-cylinder one at engine speed.

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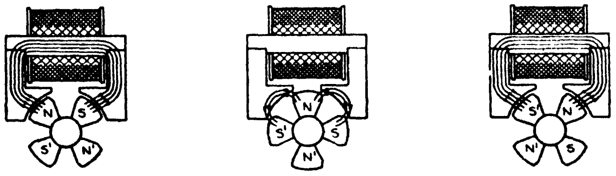
* In general the speed of magneto $= \frac{N \times n}{2S}$ where N = number of cylinders, n = number of engine revolutions per minute and S = number of sparks produced per revolution of armature.

Another disadvantage is due to the fact that the more delicate parts of the magneto, namely, the primary, secondary coils and the condenser form the revolving members and are therefore liable to breakdown, more particularly under high speed and vibration effects. The disadvantage of having a revolving contact breaker has already been referred to.



POSITION 1.
FLUX THROUGH WINDINGS
A MAXIMUM.

POSITION 2.
FLUX THROUGH WINDINGS
ZERO.

POSITION 3.
FLUX THROUGH WINDINGS
A MAXIMUM (reversed)

FIG. 177. Principle of polar inductor magneto.

For these reasons this type of magneto, although used on certain light aircraft engines, has more recently been replaced by the *polar inductor* and *rotating magnet* types of magneto.

The principle of the polar inductor magneto is illustrated in Fig. 177. In this, both the magnets and coils are fixed and the changes of magnetic flux are obtained by rotating soft-iron inductors between the magnet poles. Four small air gaps are arranged in the magnetic circuit, one being between the annular end of each inductor and the ring magnet pole which surrounds it, and also a gap between the end of the inductor finger and its corresponding armature pole. During each revolution of the rotor shaft there are four complete reversals of flux, so that for the type illustrated there

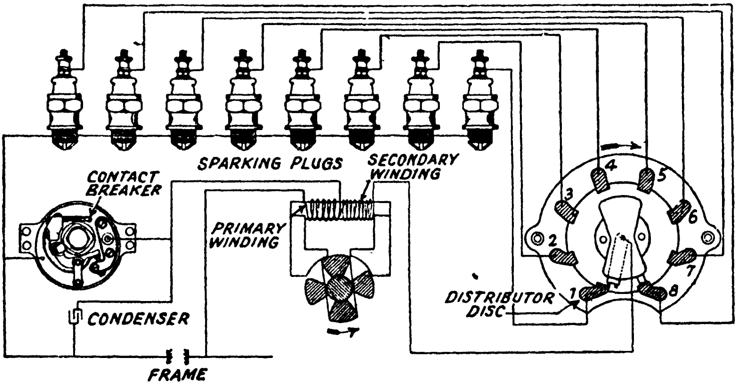


FIG. 178. Layout of 8-cylinder polar inductor magneto.

are four sparks per revolution. When the inductor rotates an alternating current is generated which reaches a maximum four times per revolution. The inductor fingers, which move past the poles of the laminated circuit carrying the armature windings, become alternately N and S poles, and as each pair of fingers is followed by a second pair the flux in the laminated circuit is reversed. The primary winding is broken at the correct moment by means of a contact breaker, thus causing a high voltage spark to occur in the secondary circuit, in a similar manner to the rotating armature magneto previously described.

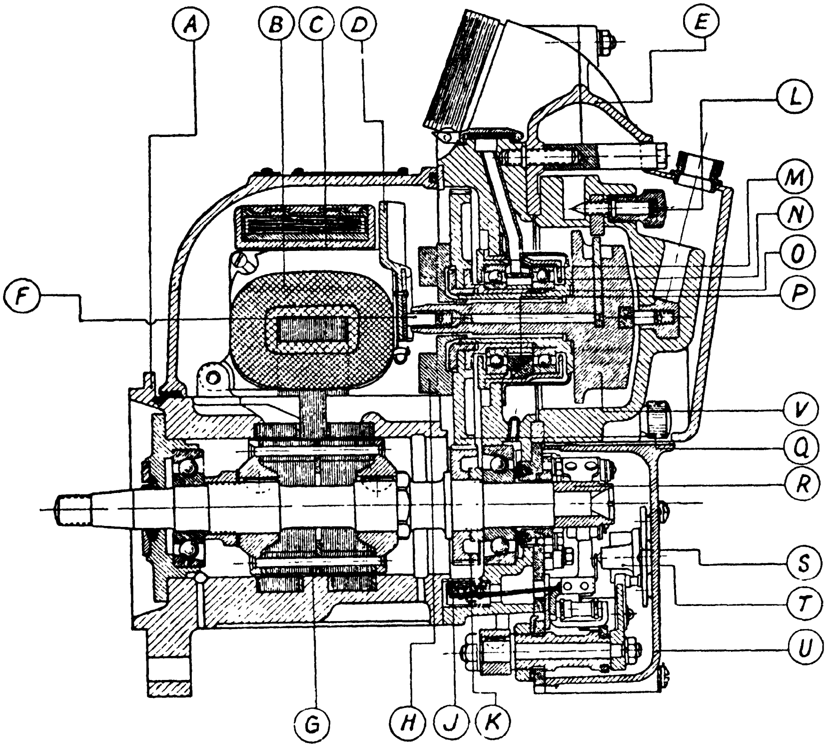


FIG. 179. Section view of Rotax " Watford " 9-cylinder magneto.

A—Poles shoes tunnel. B—Coil. C—Condenser. D—H.T. pick-up plate. E—Screen. F—Distributor arm carbon to pick-up. G—Rotor unit. H—Fan. J—L.T. spring and block. K—Pinion wheel. L—Terminal knob. M—Lubrication feeder. N—Distributor bearing housing. O—Distributor bearing sleeve. P—Distributor bearing gas excluder. Q—Distributor wheel. R—Contact breaker operating cam. S—Earthing block insulator. T—Earthing block insulator. U—Contact breaker cover. V—Distributor rotor arm.

The lay-out of the B.T.H. 8-cylinder pattern polar indicator magneto is shown in Fig. 178. In this design the beginning of the primary winding is connected to the armature core or earth, and the end is connected to the beginning of the secondary winding and to the contact breaker. The cam operates the rocker arm separating the contacts four times per revolution of the shaft. The end of the secondary winding is connected to a small brass insert in the armature coil moulding. This insert makes contact with the collector brush which is in turn connected to the rotating metal brush. The spark leaps from the rotating brush to the various segments as the brush rotates, and thus the ignition sparks are distributed to the various plugs on the engine.

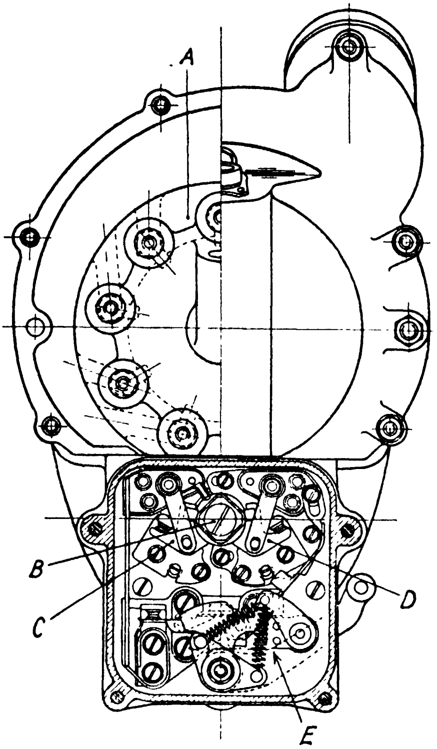


FIG. 180. End View of Rotax "Watford."

Nine-cylinder magneto, showing nine contact distributor at A; four-lobe cam at B; fixed contact breaker at C and moveable contact breaker at D. The quick-action switch mechanism is shown at E.

In regard to the contact breaker, it is necessary to close and open the primary circuit four times during each revolution of the rotor shaft, and this is effected by means of a four-point cam which is mounted on the end of the shaft. This cam operates a bell-crank lever, the end of which carries the movable contact. When the lever is deflected by the cam the distance between the platinum points is 0·012 in. The usual fibre bush is replaced by a bronze one which is lubricated by means of a small oil wick.

A sectional view is given in Fig. 179 of the Rotax Watford 9-cylinder radial engine magneto giving four sparks per revolution of the inductor spindle. This magneto will operate satisfactorily at 8,000 r.p.m., and it does not interfere with radio reception, as the darts concerned are effectively "screened." It has a double contact breaker mechanism which provides a means of increasing the ignition advance on the engine at predetermined positions of the throttle, *i.e.*, coinciding with normal cruising position, in excess of that normally obtained through the action of the automatic timing device. The mechanism is actuated by a lever interconnected with the carburettor throttle.

In regard to *the speed of rotation of polar inductor magnetos*, as this type gives four sparks per revolution, a 4-cylinder magneto will have to rotate at one-half engine speed ; a 6-cylinder one at three-quarters engine speed, and a 12-cylinder one at one-and-a-half times engine speed. For an engine having a number of cylinders denoted by *n* the correct magneto speed will be *n*/8 times engine speed.

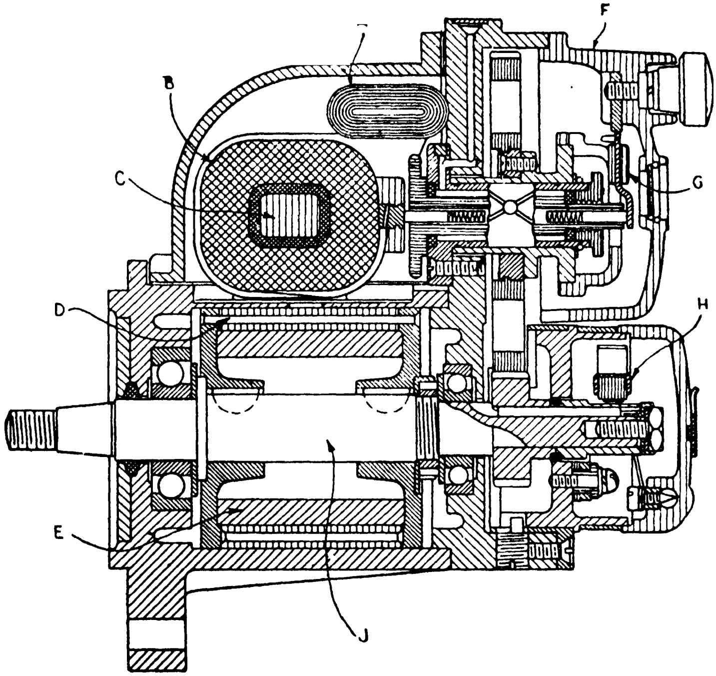


FIG. 181. Six-cylinder rotating magnet type magneto.

A—Condenser. B—Windings. C—Laminated armature core. D—Laminated magnet pole. E—Ring magnet. F—Distributor. G—Distributing brush holder. H—Contact-breaker. J—Straight through shaft.

The Rotating Magnet Magneto. In this design the coil, contact-breaker unit and condenser are stationary and the magnet, which is of special shape, rotates. The primary and secondary coils are wound around a laminated iron core of the form shown in

Fig. 181. The two-pole magnet during one complete revolution gives two complete flux reversals and therefore two sparks per revolution. The four-pole magnet, for similar reasons, gives four sparks per revolution. It is possible, within certain limits, to employ a larger number of poles so that if these are equal to the number of cylinders of the engine the magnet shaft can be rotated at the same speed as the engine's camshaft ; this type of magneto is termed a *camshaft-speed* one.

In this design of magneto the contact-breaker unit is stationary ; it is operated by a cam on the camshaft, having the same number of lobes as the number of sparks per revolution, *i.e.*, as the number of magnet poles. If, however, two contact breakers are provided in the same unit the magneto camshaft can be made with one-half the number of lobes.

Notes on Aircraft Magnetos. In order to ignite the weaker mixtures used in aircraft engines it is necessary for the ignition system to provide a voltage of at least 5,000. The usual sparking voltages lie between 5,000 and 8,000 ; the higher values are generally used for aircraft engine purposes in order to take into account the possibility of increased gaps of the sparking plugs due to their electrodes burning away in service.

It is usual practice to *duplicate the ignition system*, including the magneto, high-tension cables and sparking plugs, in order to obviate any risk of ignition failure. The two ignition systems are quite independent of one another, but the mechanical drive to the magnetos is generally a common one. The ignition systems are synchronised so that the sparks occur simultaneously in each cylinder. Should one system fail to operate, the engine will perform equally well on the other one.

Effect of Altitude. The effect of altitude increase is to produce more severe conditions than those experienced with automobile engines. As mentioned previously, the air density decreases with increase in altitude. As the air density decreases so does the voltage necessary to break down the air gaps between the metal conductor members of the magneto. There is, therefore, an increased tendency for the high tension current to leak to the " earthed " metal parts. Unless the aircraft magneto is carefully designed to safeguard against this tendency misfiring will occur at high altitudes.

All British aircraft magnetos are required to operate satisfactorily under air density conditions equivalent to an altitude of 45,000 ft., *i.e.*, about one-fifth of the ground value of the air density.

Effect of Temperature. Aircraft magnetos must also function at higher temperatures than the outside atmosphere ones, since they are enclosed within the engine cowlings and are usually shielded from the cooling air streams. For this reason, all of the parts of the magneto are required to work satisfactorily at appreciably higher temperatures than automobile ones. The chief detrimental effect of the higher temperature is upon the moulded insulation parts and the armature windings. Special insulating materials have been developed for aircraft magnetos to enable them to operate at temperatures up to 85° C. The standard test for British aircraft magnetos requires them to be placed in a closed box, having dry air at 65° C., with the base or flange of the magneto raised to 85° C.; the magneto must function satisfactorily in a twenty-four hour endurance test under these temperature conditions.

Radio Interference and Screening. It is a well-known fact that when electric sparks occur between two conductors wireless waves are transmitted and these give rise to crackles or noises in radio receivers in the vicinity. The contact-breaker and the sparking plugs are sources of such radio transmissions, and in order not to interfere with the reception of radio on aircraft it is necessary to prevent these waves from reaching the receiver. This is effected by enclosing the items in question in metal casings and "earthing" these to the machine's common earth. Not only the sparking plugs themselves, but their high tension cables must be screened.

The effect of this screening is to reduce the voltage output of the magneto in a similar manner to that of placing a condenser of a certain value across each sparking plug gap. Aircraft magnetos are therefore required to undergo acceptance tests with condensers of 250 m.mfd. capacity and also a shunt resistance of 200,000 ohms across each spark gap.

The Safety Gap. The safety gap in magnetos is an air gap arranged between a selected point in the high-tension supply from the secondary coil to the distributor rotor and the "earthed" metal part of the magneto to afford a leakage path should the output voltage exceed a certain prearranged maximum value; in this way excessive voltage effects on the coil windings are avoided. The safety gap therefore determines the altitude voltage performance of a magneto, since the reduced air density gives a lower breakdown voltage across this gap.

When safety gaps are fitted these are about 8 mm. to 10 mm. across, and to avoid corona effects the spark gap is often arranged to rotate; in one such method the earthed electrode member is the larger gear wheel for driving the distributor rotor arm.

Sparking Plugs. Aircraft pattern sparking plugs have to operate under more severe conditions than aircraft ones. Not only are the temperatures of the plugs higher, but the compression pressures are also greater so that a rather higher sparking voltage, with its disadvantageous effects, is needed. A further drawback is the use of leaded fuels which have an erosive effect upon the electrodes and a chemical action on certain types of insulation. The sparking plugs must be both gas- and water-tight and completely screened, to prevent radio interference. It is necessary also that the plugs should be designed so as to permit of easy dismantling for cleaning purposes.

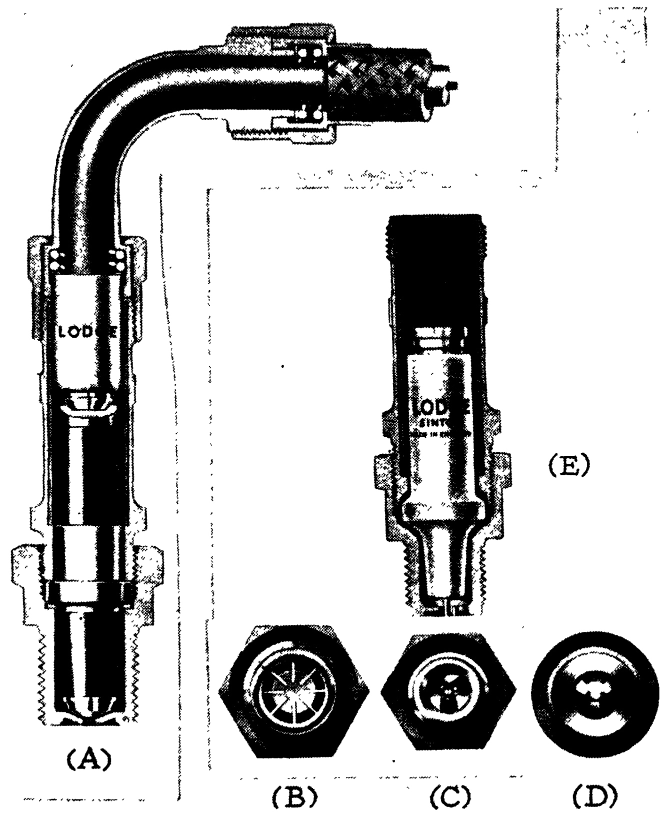


FIG. 182. Lodge aircraft engine sparking plugs.

A—Complete screened mica-type plug. B—7-point platinum-iridium electrode plug. C and D—Two other alternative electrode arrangements. E—Sintox sintered aluminium-oxide insulator plug.

The insulating materials used include *mica* (of the clear ruby or muscovite grades) ; ceramic materials such as *porcelains, steatite,* and the more recent one known as Sillimanite ; and *sintered aluminium oxide, e.g.,* Sintox. The latter material is much stronger than the others, has a better heat conductivity and is not attacked by the leaded fuel products.

The metals used for the electrodes include tungsten, high nickel-iron, pure nickel, nickel-platinum and the harder platinum-iridium alloy, with 20 per cent. iridium. The nickel and platinum alloys appear to give the best results.

Fig. 182 illustrates the Lodge sparking plug with its electrical shield, which is used in conjunction with metal-braided encased high-tension cables on aircraft engines ; mica insulation is used in this particular example, with a ceramic-type insulated connecting member to the cable conductor. It embodies a special spring ferrule providing a coupling with a butted metal joint which is weatherproof.

Another well-known plug has three square-sectioned platinum electrodes around the central platinum-iridium electrode which is insulated from the outer steel shell by Sintox. The platinum wires are brazed to the outer steel shell.

The sparking plug gap for magneto ignition is from 0·012 to 0·015 in. *The contact breaker gap* for a magneto is from 0·012 to 0·014 in.

CHAPTER X

ENGINE STARTING, TESTING AND MAINTENANCE

Engine Starting Methods. The principal methods available for starting aircraft engines include (1) Hand starting; (2) Cartridge starters; (3) Compressed air systems; (4) Inertia starters, hand- or electric motor-actuated; (5) Electric motor starters.

(1) *Hand Starting.* The earlier method of starting engines of relatively low powers, namely, up to about 350 h.p., was as follows: The ignition was switched off, the carburettor controls set to give a rich mixture and the throttle partly opened. The engine crankshaft was then given a few revolutions by swinging the airscrew, finally leaving one blade of the latter in a convenient position for obtaining a good pull. The ignition was switched on and the airscrew was given a sharp pull by hand, over the compression of one or more cylinders to start the engine.

Larger engines usually required either a hand starting reduction gear built into the engine itself—as with the Rolls Royce Eagle engines of the 1916–20 period—or the assistance of two or more mechanics who would link hands and give a united pull to the airscrew blades. In addition, whilst the engine crankshaft was being turned a special magneto, known as a *hand starter* one, was operated by another mechanic so as to give a shower of ignition sparks to the sparking plug of whichever cylinder was under compression.

(2) *Cartridge Starters.* These devices, of which the Coffman (U.S.A.) and the Farman (French) are examples, utilise the pressure of gases generated by the explosion of a special cartridge to give the required turning effort. The cylinders are primed with fuel beforehand and the crankshaft is first set by hand so that the piston of the particular cylinder exposed to the gas pressure is some 10° to 20° down its firing stroke.

The cartridge is fired by a special pistol device fitted either to the cylinder head or connected by metal tubing to the cylinder head or to an engine-driven gas-distributor as in the compressed-air starting system; the distributor method is not so good as the direct-cylinder connection one, as the gas is cooled in transit and the cartridge explosion pressure much reduced.

The Coffman starter, which has been used on Bristol engines (Fig. 183), utilises the high-pressure gases, at 2,000 to 2,500 lb. per sq. in., from a cartridge weighing about 1 oz., ignited by a small dry battery, to operate a piston in the starter cylinder unit. The piston unit operates a worm screw which transmits the power necessary to turn the engine crankshaft at a maximum speed up to 200 r.p.m. for a period of five or six revolutions. This starter, complete with its connections, weighs about 25 lb. for a 500-h.p. engine ; it does not require a booster magneto.

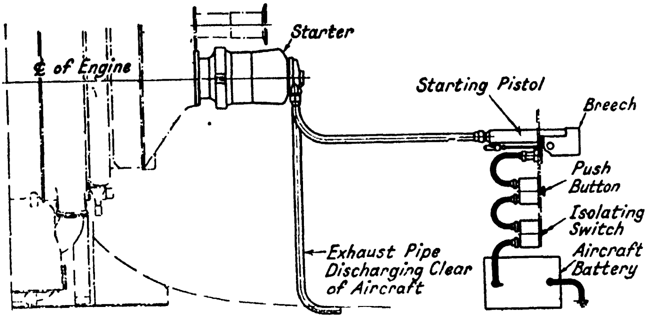


FIG. 183. The Bristol " Coffman " cartridge starting system.

(3) *Compressed Air Systems.* In this method compressed air from an air bottle is admitted to a distributing valve unit operated by one of the half-engine-speed shafts of the engine, so that the air is admitted into the appropriate cylinders at the proper moment, namely, at the beginning of the expansion stroke of the cycle (Fig. 184). After the engine has been set into rotation the cylinders become charged with mixture and, with the aid of a hand-starter magneto, the engine can then be started. A later improvement on this method is the use of carburetted air obtained by passing the compressed air through an auxiliary carburettor so that it picks up a certain amount of fuel ; in this way the engine will commence to " fire " earlier than if compressed air alone is used.

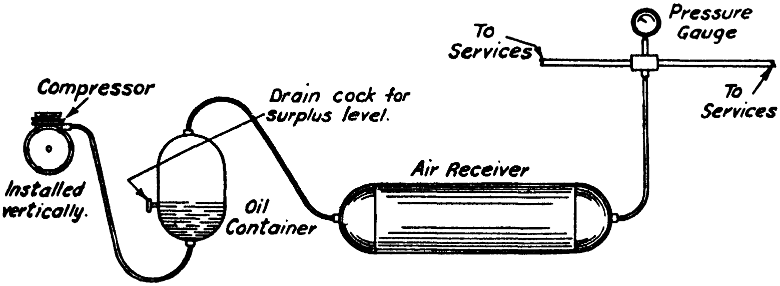


FIG. 184. Compressed air engine starting system.

The compressed air system includes a starting button for the pilot, pressure gauge, air-compressor and reservoir, master cock for controlling the air supply to the starter button and non-return valves in the cylinder heads to prevent the cylinder explosion-pressure effects from being communicated to the compressed air system.

(4) *Inertia Starters.* The principle of these starters is that of utilising the energy stored up in a relatively small flywheel which is made to rotate at a very high speed to supply the starting effort. The flywheel can be speeded up beforehand, either by a geared-up starting handle or an electric motor. When the flywheel unit is running at a sufficiently high speed, the engine having been primed beforehand, the flywheel starting jaw is slid along to engage with a similar jaw on the engine crankshaft, so as to rotate the latter. It is necessary to use a torque-overload device of the spring-loaded clutch pattern in the starter drive to the crankshaft. It is also necessary to use a hand-starter magneto or an electric booster coil for starting.

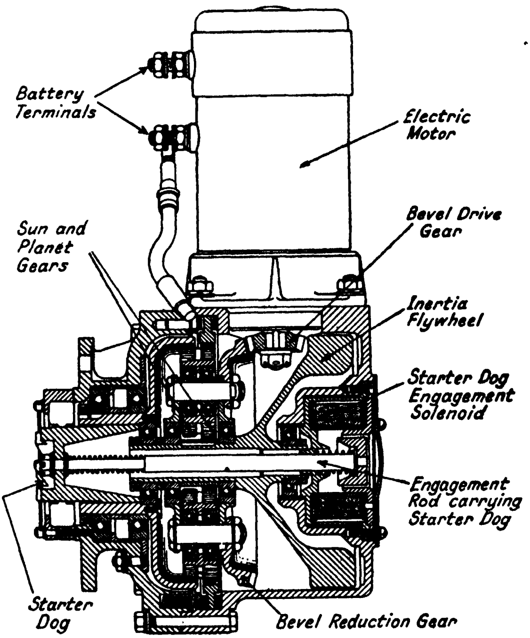


FIG. 185. The B.T.H. electric inertia starter with vertical motor.

For engines above about 300 h.p. the inertia starter flywheels are energised by electric motors (Fig. 185). A typical installation is a combination motor with the flywheel and armature as a single unit, rotating at 15,000 r.p.m. There is a bevel- or epicyclic-reduction gear train in one end of the motor casing, to reduce the armature speed down to about 75 r.p.m. at the starter dog end; the teeth on the latter are brought into engagement with corresponding ones on one of the engine shafts by means of a solenoid mounted on the starter unit. The starter motor requires from ten to thirty seconds to speed up to the full armature revolutions. The starter unit in question is provided with a slipping clutch to prevent overloading of the gears, etc., and a spring device to facilitate engagement of the dog clutch.

(5) *Electric Motor Starters.* These are of the direct cranking pattern and operate in a similar manner to those of automobile engines. They derive their starting current from accumulator sets brought to the aircraft on a suitable truck at the aerodrome. A flexible cable and plug-in connection are used for transmitting the current to the engine electric motor starting system. In emergency, the engine may be started from the aircraft low-tension battery system.

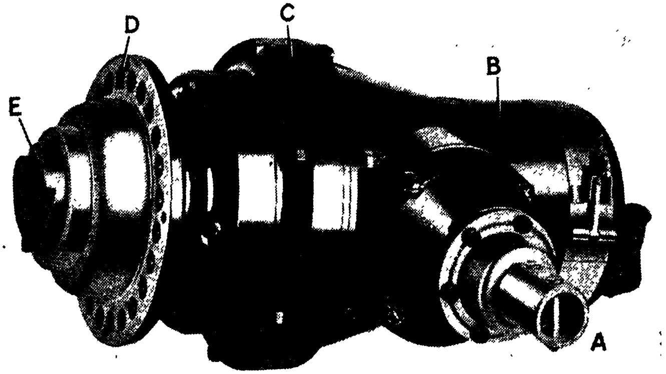


FIG. 186. The Rotax-Eclipse combined direct cranking and electric starter.
A—Hand-starting shaft connection. B—Electric motor. C—Gear-wheel housing. D—Mounting flange. E—Engine shaft engagement dogs.

More recent electric motor starters embody also ***a hand-cranking gear,*** such that in the event of there being no electrical supply available a starting handle can be attached to a shaft (shown at A in Fig. 186) of the unit. This shaft drives the engine through an automatic meshing and un-meshing gear, provided with an adjustable torque overload release, through an 18 to 1 reduction gear ; the electric motor reduction gear is 90 to 1. The starting unit in question weighs 36 lb. for the 800-h.p. engine model and operates from a 24-volt battery.

An improved starting unit used in the U.S.A., known as the " Eclipse," consists of a combination hand and electric motor inertia starter, but provided with a device for continuing the cranking over of the engine by means of the electric motor after the kinetic energy of the flywheel has been used up; it is applicable to engines up to 2,000 h.p. rating.

Cold Weather Starting. When aircraft engines have to be started in cold weather it is generally necessary to heat them and also their lubricating oil to a certain minimum temperature; otherwise the starting effort, or torque, required may be outside the maximum range of the starting device. With liquid-cooled engines the coolant is warmed beforehand and maintained in this condition ready for quick starting.

In the case of air-cooled engines the use of a heater cover, consisting of a lined canvas hood to enclose all of the engine, and a heater of the Davy lamp or catalytic type—using petrol or paraffin—is satisfactory for the purpose. The hot combustion products from the lamp below are guided upwards by a suitable canvas funnel so as to circulate around the engine. Heater lamps of the previously mentioned types are quite safe even in the presence of petrol vapour, and a lamp of about 1 gallon capacity will maintain an engine at a sufficiently warm temperature for easy starting purposes for about a day and a half. The advantage of the oil lamp heating system is that for normal air temperatures it will also heat the lubricating oil if the tank is under the engine heater cover. Where external electric power is available a more convenient method is to use the engine heater cover and to employ electric resistance heaters for the coolant and oil systems. In the case of the coolant system an immersion heater or a separate coolant tank with its immersed heater may be employed; in the latter method the auxiliary coolant tank is connected by two water-cock fittings to the bottom part of the radiator, so that a natural circulation of the heated coolant occurs. Alternatively, a small electric motor-driven circulating pump may be used to ensure effective distribution of the heated coolant.

The Testing of Aircraft Engines. Production models of aircraft engines are required to undergo a number of somewhat exacting official tests before they are installed in aircraft. Re-conditioned engines are also given a searching test in order to discover any latent defects.

New engines are tested at the manufacturers' works in special test houses, provided with sound-absorption devices such that there are no high intensity or objectionable exhaust noises heard in the vicinity of the works. So satisfactory is the design of the modern test house that it is possible to carry on a conversation in the control room adjoining, whilst two 1,000-h.p. engines are working within a pair of such test houses between which the control room is situated. All of the instruments and measuring devices are grouped within the control room, the engine under test being visible through an armoured glass observation window; the engine room itself is illuminated by powerful electric lamps.

The test installation is somewhat elaborate and includes apparatus for carrying out: (1) Brake-horse-power tests at various speeds; (2) Fuel consumption tests at various outputs; (3) Supercharged engine tests with various "boosts"; (4) Endurance, acceleration and slow-speed tests.

The engine under test is bolted down to a special test bed and is connected by means of a flexible coupling to a power-measuring plant, known as a *power brake or dynamometer.* Suitable arrangements are provided for cooling the engine, whether liquid- or air-cooled, and maintaining the correct working temperatures of the cylinders and also the lubricating oil.

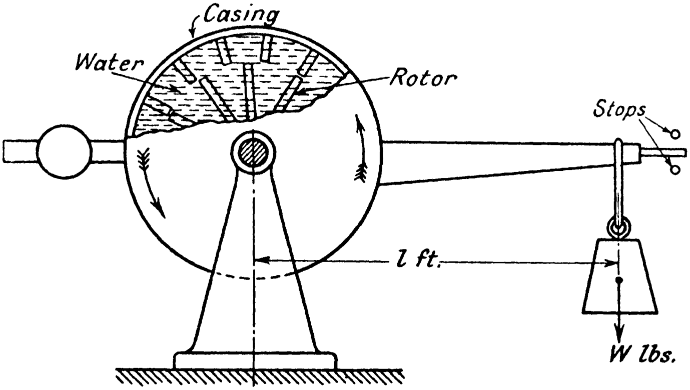


FIG. 187. Principle of Hydraulic Brake.

The full endurance test * for a new engine type is one of 100 hours' duration at 90 per cent. full power and normal speed, made up of ten non-stop runs of ten hours each. Fifty hours of this test are made upon the engine fitted with an airscrew for absorbing the power of the engine. The last ten hours of the test are made with a dynamometer and the last one hour of the test is carried out at full power and normal engine speed. Supercharged engines require a special series of tests as specified by the Air Ministry.

The dynamometers used for the power output tests are either (1) *hydraulic* or (2) *electrical;* both types operate upon the same torque-

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* Full particulars are given in "Testing of High Speed Internal Combustion Engines," A. W. Judge. (Chapman and Hall Ltd.)

arm principle illustrated in Fig. 187, which refers to the hydraulic method in which the whole of the engine power transmitted to the dynamometer is absorbed in the churning and consequent heating up of the water in the casing.

In the electric dynamometer the engine drives a generator the current from which can be utilised for electrical energy supply purposes in the works, so that the power is not wasted as with the hydraulic type. This is an important matter when appreciable numbers of high-power production engines have to be tested.

Referring to the hydraulic dynamometer shown diagrammatically in Fig. 187, this illustration shows the rotor member, connected to the engine shaft, rotating inside a casing filled with water. The casing has a number of projections to assist in increasing the resistance to rotation of the rotor and it is mounted on anti-friction bearings concentric with the rotor shaft axis so that if there were no constraint upon it, it would be free to rotate about the rotor shaft. When the latter is rotating, the effect of the rotor is to churn up the water, thus causing it to exert a drag or torque effect upon the casing, equal to the torque transmitted by the rotor from the engine. The casing is prevented from rotating, *i.e.*, is balanced, by means of weights at the end of the casing arm ; the product of the total weight by the length of the arm is equal to the torque of the engine shaft, assuming the arm itself is balanced.

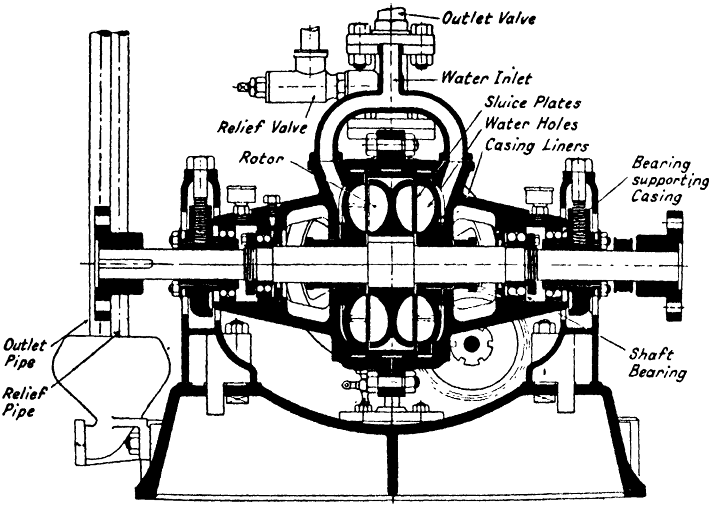

FIG. 188. The Heenan and Froude hydraulic dynamometer, with controlling sluice gates.

The horse power of the engine can then be estimated from the following simple relation

$$\text{b.h.p.} = \frac{2\pi . W . l . N}{33{,}000}$$

where W = weight in lbs. on torque arm, l = length of torque arm in ft., N = r.p.m.

$$\text{b.h.p.} = k . W . N.$$

where $k = \dfrac{2\pi l}{33{,}000}$.

By making the length of the casing arm, l, a certain value the formula can be simplified. Thus in the Heenan and Froude dynamometer (Fig. 188) the length $l = 5$ ft. $3\frac{1}{40}$ in., so that $k = \dfrac{1}{1{,}000}$.

In the dynamometer shown in Fig. 188 the paddle and vane arrangement of Fig. 187 is replaced by cups of semi-elliptic cross-section on both the rotor and the inside of the casing, a design which enables relatively high powers to be absorbed with small diameter rotors. The dynamometer has a constant flow of water through it, so that it is kept cool. When operating, water is supplied to the pockets by holes drilled in the vanes and the water is discharged by the revolution of the rotor in the casing pockets, so that a kind of vortex action is set up. The resistance offered by the water to the action of the rotor reacts upon the casing, which tries to turn in its anti-friction roller supports, but is prevented from doing so by the load on the torque arm and a spring balance device which enables the torque arm loads to be read off. The larger hydraulic dynamometers are arranged with sluice plates between contiguous flat surfaces of the rotor and casing in order to provide a convenient method of varying the load on the engine. By means of an external handwheel the sluice plates can be advanced or withdrawn so as to cut off communication between the rotor cavities and the casing cups or to accentuate this in order to increase the resistance of the dynamometer.

In addition to the test house power-measurement tests aircraft engines are usually required to undergo *thrust tests* similar to those imposed upon the engine's thrust bearings by the airscrew under flight conditions; for this purpose an end thrust of 6 lb. per b.h.p. is usually applied. It is often more convenient, however, to fit an airscrew of appropriate design and test the engine with this.

Another test is the *tilting one*, in which the engine, fitted with its airscrew, is mounted on a test stand provided with trunnion bearings housed in another and larger test stand, so that the engine unit, with its fuel and oil tanks, can be run at different inclinations to the horizontal in order to simulate climbing, diving and manœuvring conditions ; the maximum tilting angle is generally about 70°.

For high-powered engines of 1,500 to 2,500 h.p. it is often necessary to use a combination of hydraulic and electric dynamometers, as shown in Fig. 189. In this case the two dynamometers are connected together so that both act on the torque arm principle to absorb the power of the engine under test.

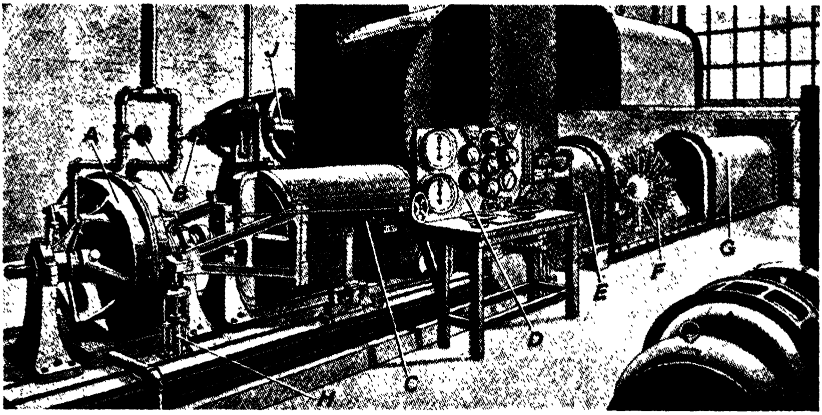

FIG. 189. Combined hydraulic and electric dynamometers coupled together for testing high output aircraft engines.

A—Hydraulic dynamometer. B—Water control cocks. C—Electric dynamometer. D—Test control panel. E—Cooling air duct. F—Radial engine under test. G—Cooling air exit duct. H—Torque arm dash pot. J—main cooling air fan.

Engine Maintenance. The high standard of performance and reliability of the modern aircraft engine, after it leaves the manufacturers' works, must be maintained by the aircraft engineer staff by a careful system of regular inspection and attention to engine details requiring periodical adjustment, cleaning, lubrication, etc.

In the case of civil aircraft it is usual to inspect the engines thoroughly after each routine or day's flight ; this does not apply, of course, to short training flights. The items chiefly needing attention include inspection of the switches (to ensure these are " off ") ; engine controls and their locking devices ; fuel and oil pipes and unions (for leakages) ; valve-operating gear for valve clearances and sound springs ; high tension leads (for chafing or cracks) and sparking plug points (for correct gap clearances and freedom from oil); contact breaker for correct gap and freedom of rocker arm; exhaust manifold, pipe joints and fastenings; carburettor control-gear, lubricating joints where necessary and checking the throttle and mixture controls, etc., for freedom of movement; checking tightness of main nuts and bolts, especially engine bearer nuts; airscrew hub variable pitch unit for hub tightness and oil leaks; radiator and oil cooler joints (for leaks).

In addition oiling and greasing instructions for the particular engine unit should be carried out and when the inspection is completed the engine should be started and run up, checking the reachings of the oil pressure, fuel pressure, tachometer, boost pressure, etc. Each magneto should be tested in turn by cutting out the other.

If the flight has been a long one, as on military operations, it is necessary also to clean the oil and fuel filters. The fuel and oil tanks should be refilled.

After twenty-five to fifty hours (in addition to the daily inspection) the oil sump should be emptied, removed and examined for metal particles; fuel and oil filters removed and cleaned and then refilled with clean oil; valve clearances checked and re-set; sparking plugs removed, cleaned and tested on special ignition machine; magneto distributors cleaned and the contact breakers checked for condition of contacts and gap clearances; a spot of oil given to each contact-breaker pivot; fuel pipes to carburettor disconnected and fuel system flushed out; cylinders tested individually for compression by removing all the sparking plugs but the one in the cylinder under test; all controls examined for wear; carburettor float chamber cleaned; cooling liquid drained out and examined for deposits, engine-mounting securing nuts and bolts checked; all working joints, etc., requiring lubrication to be replenished with lubricant; all external nuts checked for tightness and locking device examined, etc.

The cylinders, or cylinder blocks, crankcase and sump should be inspected for cracks; also the engine bearer arms. The airscrew is inspected for tightness on the hub and the blades for cracks or distortion; the track of the blades is checked for this in the latter case.

Every twenty-five to fifty hours, according to the type of engine and nature of its duties, this procedure should be repeated, and if any major fault occur, such as excessive vibration or harsh running, the cause of which is not ascertainable by exterior inspection and adjustment of carburettor or magneto, the engine should be removed for overhaul.

After 250 *to* 300 *hours of running* it is usual to remove and dismantle the engines of military aircraft, although those of civil aircraft operate for much longer periods owing to the less strenuous nature of their duties. In some instances the latter types of engine will run satisfactorily for 800 to 1,000 hours before requiring a complete overhaul, but it is necessary to carry out the daily and twenty-five to fifty hour maintenance instructions during this total period.

Usually, the limiting factor for aircraft engine overhaul periods is the accumulation of solid matter centrifuged inside the hollow crankpin (see Fig. 169, page 187), which limits the overhaul period to about 1,000 hours. This deposit not only tends to upset the balance of the crankshaft but if not removed it will reach the level of the oil tube and may eventually block the oil outlet to the big-end bearing. This sludging tendency can, however, be reduced by using special lubricating oils and oil filters ; and by more frequent oil changing.

The top or *general overhaul,* as the case may be, involves a thorough inspection of the dismantled parts after the latter have been degreased, and precision check measurements of diameters of such members as the cylinders, pistons, gudgeon pins and small-end bushes, connecting rod big-end bearings, main bearings, crankshaft pins and main journals, camshaft cams and bearings, valve gear, valve stems and guides, valve seatings, etc. All tanks should be flushed out before refilling and all working components should be lubricated before reassembly. Worn parts should be replaced with new ones, and if the mating part has worn, oversize components should be used. Thus, if the cylinder is slightly worn, oversize pistons and rings are indicated. Many worn parts can satisfactorily be reconditioned by electro-deposition with nickel or chromium.

In general, aircraft engine manufacturers issue comprehensive maintenance, overhaul and testing manuals, giving detailed instructions for each different model of engine ; these should therefore be consulted in individual cases.

APPENDIX I

USEFUL ENGINE FORMULÆ

THE following selection of the more important formulæ relating to petrol-type engines is included for the benefit of those concerned with elementary design, performance and test calculations :—

(A) **Efficiency**

The Ideal Air Standard Efficiency $E = 1 - \left(\frac{1}{r}\right)^{0.404}$ where r is the compression ratio.

The *Petrol Engine Efficiency* $E_1 = 1 - \left(\frac{1}{r}\right)^{0.296}$.

This expression, due to Tizard and Pye, gives the maximum efficiency attainable when a 20 per cent. weak mixture is used.

Values of the efficiency E_1, for compression radios of 4, 5, 6, 7 and 8 to 1 are 33·66, 37·90, 41·16, 43·76 and 45·96 per cent., respectively.

The *Thermal Efficiency* of an engine is ratio of the useful work (or power) obtained from the engine, to the equivalent heat energy of the fuel used by the engine. If the power is expressed in terms of *Indicated Horse Power* (I.H.P.) the efficiency is termed the *Indicated Thermal Efficiency* (I.T.E.). If the *Brake Horse Power* (B.H.P.) it is called the *Brake Thermal Efficiency* (B.T.E.).

If w lb. of fuel of calorific value C (British Thermal Units per lb.) be consumed in t minutes by an engine giving an indicated horse-power denoted by I.H.P.

Then *Indicated Thermal Efficiency* $= \dfrac{\text{I.H.P.} \times 33{,}000 \times t}{778wc}$

or I.T.E. $= 2540 \cdot \dfrac{\text{I.H.P.}}{Wc}$ where W = lb. of fuel used per hour.

Volumetric Efficiency $= \dfrac{V}{30CN}$ where V = volume of air used per hour in cu. in ; C = total cylinder displacement in cu. in. and N = R.P.M.

Mechanical Efficiency $= \dfrac{\text{B.H.P.}}{\text{I.H.P.}} = \dfrac{\text{B.H.P.}}{\text{B.H.P.} + \text{F.H.P.}}$

where F.H.P. = total H.P. lost by friction and gas pumping.

(B) Horse Power

(1) $$\text{I.H.P.} = 9{\cdot}91664 \times 10^{-7} \,.\, p_m \,.\, d^2 \,.\, l \,.\, \text{N} \,.\, n,$$

where p_m = indicated m.e.p., d = bore (ins.), l = stroke (ins.)
N, = R.P.M., and n = number of cylinders.

(2) also $$\text{I.H.P.} = \frac{p_m \,.\, \text{V} \,.\, \text{N}}{792{,}000},$$

where V = displacement volume of cylinders in cubic inches.

(3) *Brake Mean Effective Pressure* (B.M.E.P.) $= \dfrac{792{,}000\,\text{B.H.P.}}{\text{V.N.}}$ lb. per sq. in.

(C) Engine Torque

$$\textit{Mean torque}\ \text{T} = \frac{5252\ \text{B.H.P.}}{\text{N}}\ \text{lb. ft.}$$

$$\text{or B.H.P.} = \frac{\text{T.N.}}{5252}\ \text{lb. per sq. in.}$$

$$\text{and B.M.E.P.} = \frac{150{\cdot}8\ \text{T}}{\text{D}} = \frac{192\ \text{T}}{d^2 \,.\, \text{s}}\ \text{lb. per sq. in.}$$

where T is the flywheel mean torque per cylinder in lb.-ft., corresponding to brake horse-power at n revolutions per minute. d and s are the bore and stroke, respectively, in inches; and D = total cylinder displacement in cubic inches.

Thus b.m.e.p. and torque are mutually proportional, and a simple change of scale enables torque to be read off directly from the b.m.e.p.—revolution curve.

(D) Gas Velocity and Valve Diameter

$$\text{Gas velocity V} = \frac{\text{D}^2 \,.\, \text{L} \,.\, \text{N}}{360\, d^2},$$

where

D = diameter of cylinder in inches, d = diameter of valve in inches,
L = length of stroke in inches,
N = revolutions per minute,
V = gas velocity in feet per sec. (200 to 240 f.s. are the maximum values in practice).

Example.—For a gas velocity V = 240 f.s.

$$d^2 = \frac{\text{D}^2 \,.\, \text{L} \,.\, \text{N}}{86{,}400}.$$

USEFUL INFORMATION

Atmospheric Pressure

Standard Atmospheric Pressure = 14·496 lb. per sq. in.
= 29·5306 inches of mercury at 0° C.
= 760 millimetres of mercury at 0° C.

1 pound per square inch = 2·035 inches of mercury at 0° C.
= 51·7 millimetres of mercury at 0° C.
= 2·31 feet of water at 17° C.

1 cubic foot of air at 14·7 lb. per square inch, and at 0° C. weighs 0·080728 pound (1·29 ounces). 1 litre weighs 1·2928 grammes.

WORK AND POWER

1 foot-pound = 1·356 joules.
1 joule = 0·7373 foot-pound.
1 English horse-power = 33,000 foot-pounds per minute.
= 1·014 metric horse-power.
= 746 watts.
1 kilogrammetre = 7·233 foot-pounds.
1 metric horse-power = 75 kilogrammetres per second.
= 0·986 English horse-power.

HEAT

1 British thermal unit = heat required to raise 1 lb. of water from 60° F. to 61° F.

$$\text{Heat equivalent of 1 h.p.} = \frac{33{,}000}{778} = 42{\cdot}4 \text{ B.T.U. per minute.}$$

Joules' equivalent = 778 foot-pounds.

VELOCITY

1 mile per hour = 1·467 feet per second.
= 44·70 centimetres per second.

METRIC EQUIVALENTS

1 inch = 25·40 millimetres.
1 millimetre = 0·03937 inch.
1 square inch = 645·16 square millimetres.
= 6.4516 square centimetres.
1 cubic inch = 16·387 cubic centimetres.
1 cubic centimetre = 0·0610 cubic inch.

Temperatures

If F = degrees Fahrenheit, and C = degrees Centigrade, then

$$\frac{F - 32}{9} = \frac{C}{5}.$$

APPENDIX II. BRITISH AIRCRAFT ENGINES

Maker's Name and Engine Type	No. and Arrangements of Cyls.	Cooling	Bore and Stroke	Capacity	Reduction Gear Ratio	Compression Ratio	International Rating			Maximum Altitude Rating			Take-off Power	Dry Weight
							Altitude (Supercharging)	Engine Speed	Power	Altitude	Engine Speed	Power		
			mm.	Litres			ft.	R.P.M.	B.H.P.	ft.	R.P.M.	B.H.P.	B.H.P.	lb.
AERO ENGINES														
Pixie	4 I.L.	A.	80·77 × 100	2·048	D.	5·58	S.L.	2,350	45	S.L.	2,624	50	—	129½
ALVIS														
Leonides	9 R.	A.	122 × 112	11·78	0·5 : 1 0·63 : 1	6·3	8,250	3,000	435	9,000	3,100	440	450	708
Pelides	14 R.	A.	146 × 165	38·67	—	6	5,000	2,150	1,065	7,500	2,150	975	1,060	1,475
ARMSTRONG SIDDELEY														
Genet Major IA	7 R.	A.	108 × 114·35	7·32	D.	5	S.L.	2,200	150	S.L.	2,425	165	—	327
Genet Major IV	7 R.	A.	108 × 114·5	7·32	0·663 : 1	5·25	S.L.	2,400	160	S.L.	2,700	180	—	367
Lynx IVC	7 R.	A.	127 × 139·7	12·4	D.	5	S.L.	1,900	215	S.L.	2,090	240	—	515
Cheetah VA	7 R.	A.	133·3 × 139·7	13·65	D.	5·2	S.L.	2,100	285	S.L.	2,400	326	—	596
Cheetah IX	7 R.	A.	133·3 × 139·7	13·65	D.	6·35	6,000	2,100	310	7,300	2,425	350	340	635
Cheetah X	7 R.	A.	133·3 × 139·7	13·65	D.	6·35	6,750	2,300	325/340	7,000	2,425	355	360/375	694
Tiger VIII	14 2-R.	A.	139·7 × 152·4	32·7	0·594 : 1	6·2	6,200 12,800 2-S.	2,375 2,200	840 756	6,600 15,000	2,450 2,450	862 782	918	1,290
Tiger IX	14 2-R	A.	139·7 × 152·4	32·7	0·594 : 1	6·2	6,250	2,375	775/805	6,500	2,450	810	845/880	1,260
BRISTOL														
Mercury VIII, IX	9 R.	A.	146 × 165	24·8	0·572 : 1 0·50 : 1	—	13,000	2,400	795/825	14,000	2,650	840	725	1,005 (+5)
Mercury XI, XII	9 R.	A.	146 × 165	24·8	0·50 : 1	—	3,500	2,400	780/820	6,000	2,750	890	830	1,005 (+5
Pegasus XC	9 R.	A.	146 × 190·5	28·7	0·50 : 1	—	3,500	2,475	710/740	5,250	2,600	830	920	1,030
Pegasus XXII, XXIII	9 R.	A.	146 × 190·5	28·7	0·50 : 1 0·572 : 1	—	4,000	2,250	800/840	6,500	2,600	890	1,010	1,030 (+5)
Pegasus XVII, XVIII	9 R.	A.	146 × 190·5	28·7	0·572 : 1 0·50 : 1	—	4,750 14,750 2-S.	2,250	780/815 720/750	3,000 15,500	2,600	1,000 885	965	1,130 (+5)
Pegasus XIX, XX	9 R.	A.	146 × 190·5	28·7	0·572 : 1 0·50 : 1	—	8,500	2,250	800/835	10,000	2,600	925	835	1,130 (+5)
Pegasus XXV, XXVII	9 R.	A.	146 × 190·5	28·7	0·50 : 1 0·572 : 1	—	11,000	—	795/830	9,500	—	915	830	1,035 (+5)

Hercules II	14 R.	A.	146×165	38·7	0·444: 1	—	5,000	2,400	1,100/1,150	4,000	2,750	1 375	1,300	1,680
Hercules IV	14 R.	A.	146×165	38·7	0·444 : 1	—	4,500	—	1,010/1,050	5,500	—	1,220	1,380	1,680
Taurus II	14 R.	A.	127×137	25·4	0·444 : 1	—	5,000	—	860/900	5,000	—	1,065	1,010	1,300
Perseus X	9 R.	A.	146×165	24·9	0·50 : 1	—	14,500	2,400	700/730	15,500	2,750	880	750	1,110
Perseus XI, XII	9 R.	A.	146×165	24·9	0·572 : 1 0·50 : 1	—	6,500	2,400	715/745	6,500	2,750	905	830	1,105 (+5)
Perseus XIIC, XIVC	9 R.	A.	146×165	24·9	0·50 : 1 0·666 : 1	—	4,000	2,250	680/710	6,000	2,600	815	890	1,100(+10)
Aquila IV	9 R.	A.	127×137	15·6	0·50 : 1	—	4,500	2,600	450/470	6,000	3,000	540	600	830
Cirrus (Blackburn)														
Minor	4 I.L.	A.	95×127	3·605	D.	5·8	S.L.	2,300	82	S.L.	2,600	90	82	227
Major 150	4 I.L.	A.	120×140	6·33	D.	5·8	S.L.	2,000	138	S.L.	2,450	150	132	325
De Havilland														
Gipsy Minor	4 I.L.	A.	102×115	3·759	D.	6	S.L.	2,250	80	S.L.	2,600	90	80	210 (±5)
Gipsy Major I	4 I.L.	A.	118×140	6·124	D.	5·25	S.L.	2,100	120	S.L.	2,350	130	130	300
Gipsy Major II	4 I.L.	A.	118×140	6·124	D.	5·25	S.L.	2,400	140	S.L.	2,400	140	—	310 (±5)
Gipsy Six I	6 I.L.	A.	118×140	9·186	D.	5·25	S.L.	2,100	185	S.L.	2,350	200	200	450 (±7½)
Gipsy Six II	6 I.L.	A.	118×140	9·186	D.	6	S.L.	2,400	205	S.L.	2,400	205	205	469 (±7½)
Gipsy Twelve	12 I.V.	A.	118×140	18·372	0·667 : 1	6	7,500	2,400	405/420	7,750	2,450	410/425	525	1,058
Napier														
Rapier VI	16 H.	A.	89×89	8·830	0·390 : 1	7	4,750	3,650	355/370	6,000	4,000	380/395	365	713
Dagger III	24 H.	A.	97×95	16·8	1 : 2·69	7·75	3,500	3,500	700/725	5,000	4,000	780/805	760	1,305
Dagger VIII	24 H.	A.	97×95	16·8	0·308 : 1	7·5	9,000	4,000	925	8,750	4,200	1,000	955	1,390
Pobjoy														
Niagara III	7 R.	A.	77×87	2·835	0·468 : 1	6	S.L.	3,300	88	S.L.	3,650	95	95	156
Niagara V	7 R.	A.	81×87	3·130	0·4375 : 1	—	S.L.	4,000	125	S.L.	4,600	137	119	185
Rolls-Royce														
Kestrel XIV, XV, XVI	12 V.	C.W.	127×140	21·3	0·632 : 1	6	11,000	2,600	690	14,500	3,000	745	670	955
Kestrel XIV, XV, XVI (v.p.)	12 V.	C.W.	127×140	21·3	0·477 : 1	6	12,250	2,750	715	14,500	3,000	745	745	985
Kestrel XXX	12 V.	W.	127×140	21·3	—	—	11,750	2,400	550	14,250	2,750	600	720	967
Merlin II, III	12 V.	E.G.	137·2×152·4	27	0·477 : 1	6	12,250	2,600	900	16,250	3,000	1,030	890	1,335
Merlin X	12 V.	E.G.	137·2×152·4	27	0·477 : 1	—	2,500 13,250 2-S.	2,600	1,400 965	5,250 17 750	3,000	1,145 1,025	1,065	1,394

A. = Air. W. = Water. C.W. = Composite water. E.G. = Ethylene Glycol. R. = Radial. 2-R. = Two-row Radial. H. = "H" formation. V = "V" formation. L. = In Line. I. = Inverted. H.O. = Horizontally opposed. D. = Direct Drive. S.L. = Sea Level. 2-S. = Two-speed Supercharger.

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