THE DEVELOPMENT OF THE MONO-SLEEVE VALVE FOR AERO ENGINES.*

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INTRODUCTION.

THE shortcomings of poppet valves have been so frequently stated that to enumerate them again almost seems to necessitate an apology. It may, nevertheless, be useful to repeat some of the drawbacks, because it was the recognition that they might be abolished by the use of a different type of valve that led to the development of the sleeve valve.

(1) Cam and spring mechanisms are objectionable when high operational speeds and absolute reliability are required.
(2) The poppet valve is continually and violently hammered; it is alternately exposed to corrosive gases and cool mixtures, and its temperature distribution is uneven and fluctuates rapidly.
(3) The inserted seat is submitted to similar treatment, yet it must remain tight both on the closed valve and in the cylinder head.
(4) The valves introduce hot spots and occupy valuable space in the combustion chamber. They prevent the use of the best form of combustion space, and restrict the freedom of location of the plugs.
(5) The valve-operating mechanism introduces awkward external shapes which are objectionable, especially in baffled air-cooled engines.

* The author recently presented a paper on this subject to the Society of Automotive Engineers, U.S.A., entitled " The Single Sleeve as a Valve Mechanism for the Aircraft Engine "—see *S.A.E. Journal*, September, 1938, p. 349. Certain passages and illustrations included in this paper are taken from the S.A.E. paper, for which acknowledgement is made to The Society of Automotive Engineers.

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In spite of its drawbacks the poppet valve has had a remarkably long innings, and continues to thrive owing to lavish expenditure and considerable development in the form of a series of opportune discoveries and improvements. Further progress depends on new development, but, at the present time, no outstanding improvements appear to be on the horizon.

In view of its obvious advantages it may seem astonishing that the regular motion of the positively controlled sleeve valve has not been employed sooner. Conservatism and lack of initiative and financial backing are believed to be the main reasons, but it must also be recognised that a number of problems of some difficulty are involved, and in solving them the most modern material and machining technique have had to be employed.

This paper reviews the somewhat chequered history of the sleeve valve, is in the main a *précis* of the mono-sleeve development of the Bristol Co. over the last decade, and will, it is hoped, prove of some interest in showing how the various problems have been overcome.

Historical Review.

To Charles Y. Knight, of Chicago, must be given the honour of developing the first sleeve-valve engine. It was produced towards 1905, but did not greatly impress American designers. Great Britain can claim to be the first country to have taken the design up seriously.

In 1909 the Daimler Co. produced a remarkable double-sleeve valve engine which successfully completed a difficult endurance bench test of over a hundred hours, followed by a 2,000 miles' trial at Brooklands. Three standard models of this engine were presented the same year at the London Motor Show. Subsequently, a number of Continental manufacturers followed the lead given by the Daimler Co.

The Knight engines used only reciprocating motions for their sleeves, and as two sets of ports must be exposed in sequence it is necessary to employ two movements, each performed by a separate sleeve. This greatly complicates the problem, and makes the design sensitive to distortion, faulty lubrication, and adverse operating conditions. It is a great credit to the Daimler Co. that these difficulties were overcome, but no design on the same principle could stand up to modern aero-engine conditions.

It was, therefore, an important step forward when the discovery was made that the two movements could be performed on one sleeve simply by combining a translatory and a rotary motion. The resulting twisting movement can easily be produced by a crank drive. Not only is the design simpler, but the twisting motion is invaluable in wiping the oil outside the sleeve so as to maintain an even layer over the whole surface. The two designs are, therefore, fundamentally different, and the shortcomings of the Knight type are no indication of weaknesses in the mono-sleeve valve type.

The discovery of the new valve was made simultaneously and quite independently by two inventors in 1909—the Scottish engineer, Peter Burt, of the Argyll Co., and the Canadian engineer, James McCollum.

An agreement was made between McCollum and the Argyll Co., and the mono-sleeve valve engine has since been generally referred to as the Burt-McCollum type.

The first sleeve-valve aero engine was of this type, and it was produced in 1913/14 by the Argyll Co. for the Naval and Military Aeroplane Engine Competition organised by the British Government in 1914. It was an in-line water-cooled 6-cyl. engine of 785 cu. in. capacity, and produced a maximum power of about 130 b.h.p. It created an excellent impression despite continual trouble due to the crankshaft. Unfortunately, the World War caused the development work to be shelved, and the only research work on sleeve valves during the War period was an experimental adaptation of a 12-cyl. 140 b.h.p. vee engine produced by the Royal Aircraft Establishment, then known as the Royal Aircraft Factory.

A widespread interest in sleeve-valve engines of both types developed in the motor car industry immediately after the War. A particularly promising design was the mono-sleeve valve engine produced by the Barr and Stroud Co., of Glasgow, for motor cycles. This engine was the first air-cooled sleeve-valve engine, and it was unfortunate that lack of funds caused the production to be dropped.

Aero-engine manufacturers again turned their attention to sleeve valves, but they were at first interested only in the Knight type. Panhard, in France, and Minerva, in Belgium, both produced engines to this design. Interest in the mono-sleeve valve engine returned only in 1925, when the Continental Motors Corp. of Detroit, U.S.A., acquired the Burt-McCollum patents. This company exhibited a mono-sleeve valve engine in 1927. It was of the nine-cyl. type, and developed 220 b.h.p. from 787 cu. in. capacity.

The interest of the British aero engine industry in the mono-sleeve valve engine was stimulated by a report issued in 1925–26 by the Aeronautical Research Committee. The experimental work carried out by Mr. H. R. Ricardo was referred to in warm terms, and attention was drawn to the advantages offered by the mono-sleeve valve.

The Bristol Aeroplane Co. entered the picture in 1926 and has so far performed the feat of staying there.

The present position is that the nine-cyl. single bank Perseus sleeve-valve engine has been in steady production for some months, and the double row, fourteen-cyl. Taurus and Hercules engines are about to go into large-scale production at Bristol; other engines of the same type are being developed by the same firm, and reports are frequently made that sleeve valves are being actively investigated by a number of aero-engine firms and research institutions at home and abroad.

Initiation of the Bristol Research.

In 1926 the Bristol Co. anticipated that a single-row radial engine producing 1,000 b.h.p., would shortly be required, and it was considered that the optimum cylinder size for such an engine would be over 5 in. dia. It was felt that a two-valve engine could not be run at a sufficiently high speed to obtain the desired power with the fuel then available. A 4-valve air-cooled cylinder with enclosed rocker mechanism was considered to be impracticable for a reasonable weight. The only suitable scheme of poppet valves was, therefore, to retain the 4-valve cylinder with open rocker gear and compensated push rod mechanism.

Since that date the poppet has, of course, been considerably improved. Hollow valves with sodium cooling and stellited seats are now usual, and credit must be given to American designers for the marked improvement in the technique of the 2-valve cylinder with completely enclosed and lubricated rocker gear, thus considerably enhancing the performance of the 2-valve cylinder. However, the duty of the poppet valve continues to become more strenuous in spite of these improvements in technique, necessitating additions in cost and complexity of the valve mechanism, and it may be said that although these developments have given the poppet valve an extended lease of life, the position has become even more critical as speeds have increased.

A determined effort was, therefore, made by the Bristol Co. in 1926 to find an alternative mechanism. The cuff type, rotary, and the double and mono-sleeve valves were all carefully considered. The rotary valve was excluded because of its operating mechanism and its difficult lubrication. The cuff valve suffered from the latter drawback and from limitations of port area and combustion chamber design.

The limitations of the double-sleeve valve were recognised, and it was considered that the type had no future. The much simpler mono-sleeve valve was, however, very attractive, even though no serious work on air-cooled sleeve valve engines, particularly of large bore, had been undertaken. The only data available were some results of preliminary tests undertaken by Mr. H. R. Ricardo, and the promising Barr and Stroud motor cycle engine.

The conclusion was reached, after several months of preliminary investigation, that the Burt-McCollum valve gear presented the greatest possibilities, and it was decided to commence an extensive programme of research. The risk of such work was considerable, and it was fully realized that several years would be lost if the promises of the original investigations were not fulfilled.

The development was, however, greatly assisted by the technical encouragement and financial assistance given by the Air Ministry. Without this help it is somewhat problematical whether the real difficulties encountered and the varied early setbacks could have been overcome. Another encouraging aspect was the continued faith and enthusiasm of the participating Bristol staff.

Bristol Single-cylinder Research.

The first Bristol mono-sleeve research unit is shown in Fig. 1, Plate XXI. It was constructed and run towards the end of 1927, during one of the recurring periods when the inline air-cooled engine came into the picture. The proposal was to design an inverted 12-cyl. engine, and the unit took the form of a vee-twin, so as to simulate a cylinder pair of this engine. The bore and stroke were 5¾ in. by 6 in.

Considerable experience was obtained with this unit during 1928, and the then relatively high brake mean effective pressure of 135 lb. per sq. in. at 2,000 r.p.m. was obtained.

The nickel cast iron sleeves were, however, unable to withstand the high pressure to which they were exposed when masking the ports during the explosion stroke. Cracks and even punctures were liable to occur. Attempts to use steel cylinder barrels with semi-steel sleeves were unsuccessful, due to high local temperatures.

The preliminary running, nevertheless, made clear that the major problems were the cylinder head cooling and the sleeve valve material.

On the basis of the experience gained, the unit was rebuilt in 1930 with forged KE 965 steel sleeves, aluminium alloy barrels and heads, and generally increased finning. One of the sleeves was run in the soft condition, the other was nitrided.

Tests soon showed that the soft sleeve was unsatisfactory, but extremely promising results were obtained with the nitrided component. The design modifications had considerably improved the cooling, some 50 deg. C. reduction in head temperature being realized. A brake mean effective pressure of 145 lb. per sq. in. at 2,000 r.p.m. was finally obtained, but trouble was experienced with the crankcase, and the unit was again rebuilt.

In 1931 a number of single-cylinder units, incorporating the latest improvements, were added to the Research Dept., and in March the modified design enabled a hundred hours' endurance test, without stripping down or adjustment, to be completed satisfactorily at 2,000 r.p.m. and 120 lb. per sq. in. brake mean effective pressure. The success of this test was the real turning point in sleeve-valve development. It proved that the mono-sleeve valve could be made satisfactorily in air-cooled form, and since then continuous research has proceeded at Bristol on high priority.

Fig. 2 shows the advances in power output, brake mean effective pressure, and fuel consumption made from year to year with Bristol 5¾ in. bore single-cylinder units. The values plotted on this curve were all maintained during one hundred hours, the tests being run without adjustment or breakdown.

Considerable research has been accomplished on cylinders of bores other than 5¾ in. In 1931 the development of a high-speed vee-12 or a cross engine was considered, and an experimental in-line engine having six 4½ in. × 4½ in. cylinders was built (see Fig. 3, Plate XXI). Research work proceeded on this experimental unit for two years, but was eventually dropped in favour of a return to the high-power radial engine, for which a larger bore cylinder was considered necessary.

Work was commenced in 1933 on a 5 in. × 5⅝ in. cylinder intended for a 350 b.h.p. civil engine. The powers obtained early on this cylinder were, however, so promising that when the 9-cyl. engine—

subsequently known as Aquila I—was type tested in 1934 it was for a maximum power of 500 b.h.p.

Fig. 4 shows power curves of the Aquila size cylinder, naturally aspirated, with 87 and 100 octane fuels.

The sleeve valve has not been adopted without extensively exploring the possibilities of the poppet valve, and simultaneously

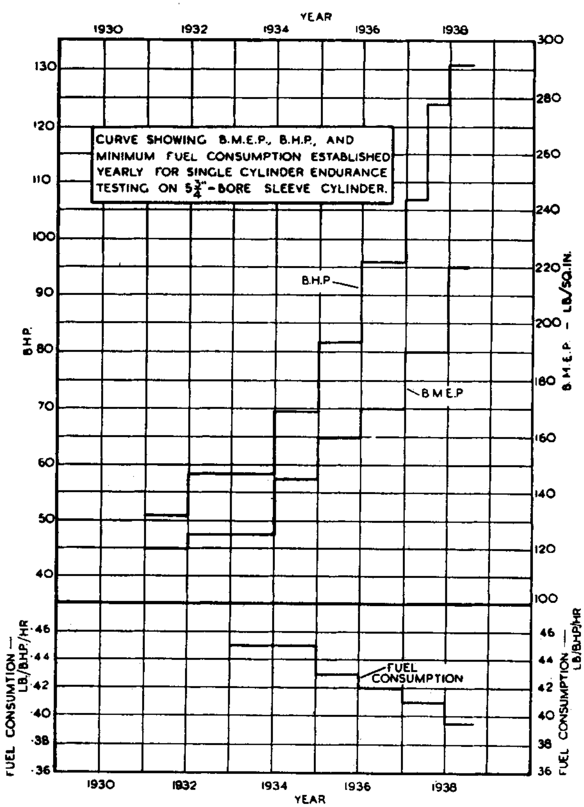

Fig. 2.

with the research on sleeve valves, poppet valve units were being investigated. For instance, a year or two previous to the development of the Aquila cylinder, research work was commenced on a cylinder of the same bore, but with two poppet valves and overhead camshafts. Data were obtained enabling a particularly valuable comparison of the two types of valve to be made, and for this reason a few details of the design may be of interest.

The cylinder size (98·2 cu. in.) was carefully selected to allow the maximum efficiency for two valves at high speed, and modern technique was incorporated in regard to valve-operating mechanism and sodium-cooled valves. Exhaustive single-cylinder tests were carried out with cylinders having single and double camshafts

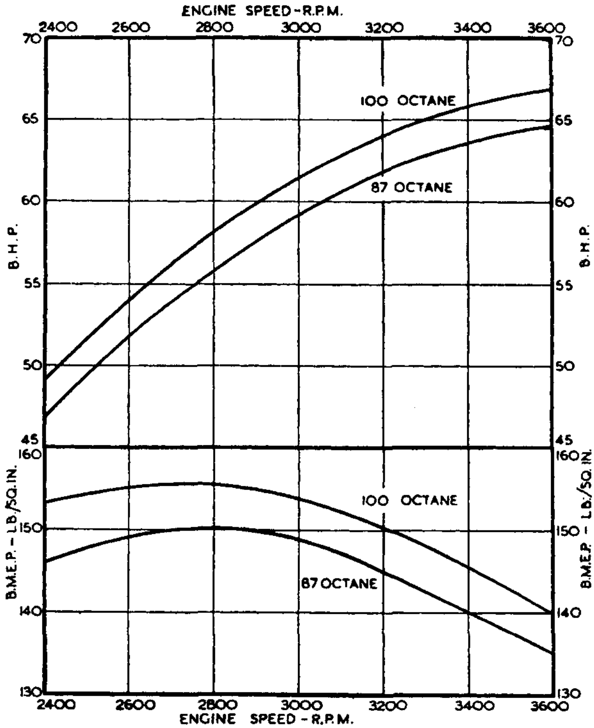

Fig. 4.—Power curves for Aquila unit—natural aspiration with 87 octane and 100 octane fuels. Compression-ratio adjusted to give similar detonation characteristics for main engine operating conditions at appropriate ratings.

(Fig. 5, Plate XXII), and a complete double-row engine was even built and tested.

The design was, however, not proceeded with because it was rendered obsolete by the development of the sleeve valve.

Performance of Sleeve-Valve Units.

Up to date some 35,000 hours have been run on single-cylinder mono-sleeve valve research.

The performance of the Perseus size of cylinder can best be gauged by comparing it with that of the Bristol Mercury, a four-valve poppet-type engine of the same bore and stroke.

Data for single-cylinder units of these engines are given in Table I.

TABLE I.

COMPARATIVE DATA OF BRISTOL CYLINDERS.

		Perseus	Mercury.
Cylinder type		Perseus	Mercury.
Valving		Sleeve	4 poppet push rod
Bore and stroke ... in.		$5\frac{3}{4} \times 6\frac{1}{2}$	$5\frac{3}{4} \times 6\frac{1}{2}$
Displacement ... cu. in.		168·8	168·8
Cylinder assembly weight ... lb.		42·1	46
Cooling fin area ... sq. in.		2,970	2,364
Peak power naturally aspirated	B.m.e.p. ... lb./sq. in.	138	130
	R.p.m.	3,200	3,000
	B.h.p. per sq. in. piston area	3·62	3·20
	Mean piston speed ft./min.	3,460	3,250
Sustained power for 100 hours 87 octane fuel	B.m.e.p. ... lb./sq. in.	190	165
	R.p.m.	2,800	2,650
	B.h.p. per sq. in. piston area	4·37	3·59
	Mean piston speed... ft./min.	3,040	2,870
Sustained power for 100 hours 100 octane fuel	B.m.e.p. ... lb./sq. in.	220	185
	R.p.m.	2,800	2,750
	B.h.p. per sq. in. piston area	5·05	4·18
	Mean piston speed ft./min.	3,040	2,980

The power quoted can be maintained during 100 hours without distress.

Fig. 6 shows comparative power curves of the Mercury and Perseus units at full throttle under naturally aspirated conditions at various r.p.m. The graph illustrates the good breathing efficiency of the sleeve-valve unit, as does also Fig. 7, comparing a modern 2-valve American poppet valve, the Bristol Mercury 4-valve, and the Perseus sleeve valve. A comparison of weights is given on Fig. 8, Plate XXIII.

A feature of all the sleeve valve units and engines tested has been the remarkably stable shape of the fuel consumption loops. An example is shown in Fig. 9 for the Perseus unit. The smoothness of running under extreme economy conditions is just as satisfactory with the main engine.

The comparison between a sleeve-valve unit and a two-valve poppet type unit can best be made by referring to the Aquila and the 5 in. bore poppet valve cylinder previously mentioned. The

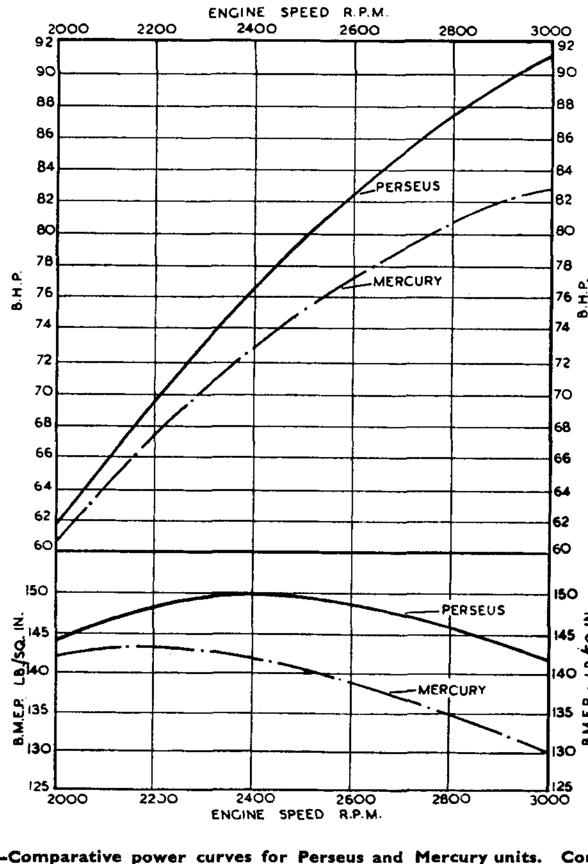

Fig. 6.—Comparative power curves for Perseus and Mercury units. Compression-ratio adjusted to give similar detonation characteristics. 87 octane fuel. Full throttle. Normal aspiration.

bores of the two cylinders are the same, but the strokes are slightly different ($5\frac{3}{8}$ in. for Aquila, 5 in. for the poppet valve type).

Fig. 10 gives comparative power curves for naturally aspirated units of these cylinders with the compression ratios adjusted to give similar detonation characteristics, while Fig. 11 gives comparative power curves at the same compression-ratio. Comparative data between the same two types of cylinder are given in Table II.

TABLE II.

COMPARATIVE DATA OF SLEEVE AND POPPET VALVE CYLINDERS.

Cylinder type and valving	Sleeve	2 poppet overhead camshaft
Bore and stroke, in.	5 × 5⅜	5 × 5
Displacement, cu. in.	105·6	98·2
Cylinder assembly weight, lb.	31·5	42·8 with double camshaft 44·2 with single camshaft
Cooling fin area, sq. in.	1,920	1,660
Peak power naturally aspirated 87 octane fuel:		
B.m.e.p., lb. per sq. in.	138	121
R.p.m.	3,600	3,300
B.h.p. per sq. in. piston area	3·37	2·525
Mean piston speed, ft. per min.	3,220	2,750
Sustained power for 100 hours 100 octane fuel:		
B.m.e.p., lb. per sq. in.	240	No development on 100 octane fuel
R.p.m.	3,300	
B.h.p. per sq. in. piston area	5·36	
Mean piston speed, ft. per min.	2,960	

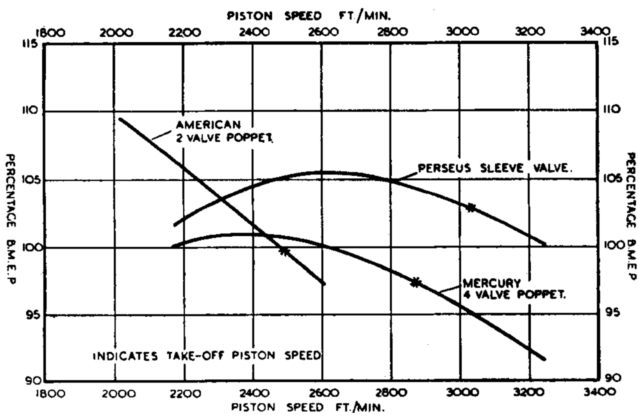

Fig. 7.—Comparative breathing efficiencies of 2-valve, 4-valve, and sleeve-valve cylinders.

It is wished to emphasize again that the last two columns are not snatch readings.

A point to be remembered when analysing the above performance figures is that the sleeve valve is still a relatively new device. Its

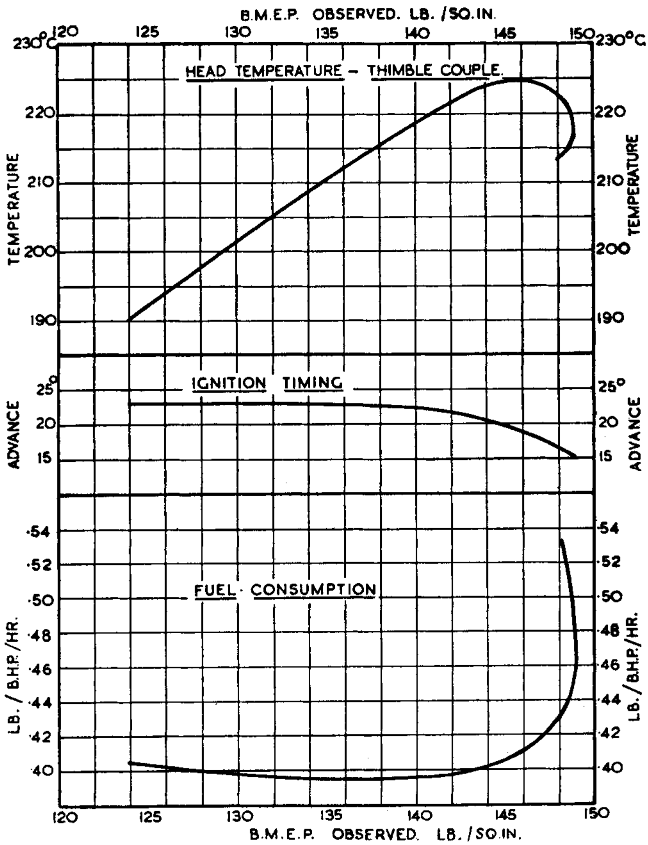

Fig. 9.—Perseus unit—fuel consumption loop—normal aspiration, variable ignition timing.

possibilities have been explored to a lesser degree than have those of the poppet valve.

As an indication that interesting developments may be expected, mention may be made of a recent endeavour to discover the limit output of a sleeve-valve unit. The test was inconclusive because the limit proved to be unattainable with the supercharger available. The results are, nevertheless, considered to be outstanding, and it is believed that the powers obtained could not be approached with a poppet-valve unit under similar conditions. With a boost of 14 lb. per sq. in. and a cylinder of 168·8 cu. in. capacity, the brake mean effective pressures obtained were 305 lb. per sq. in. at 2,400

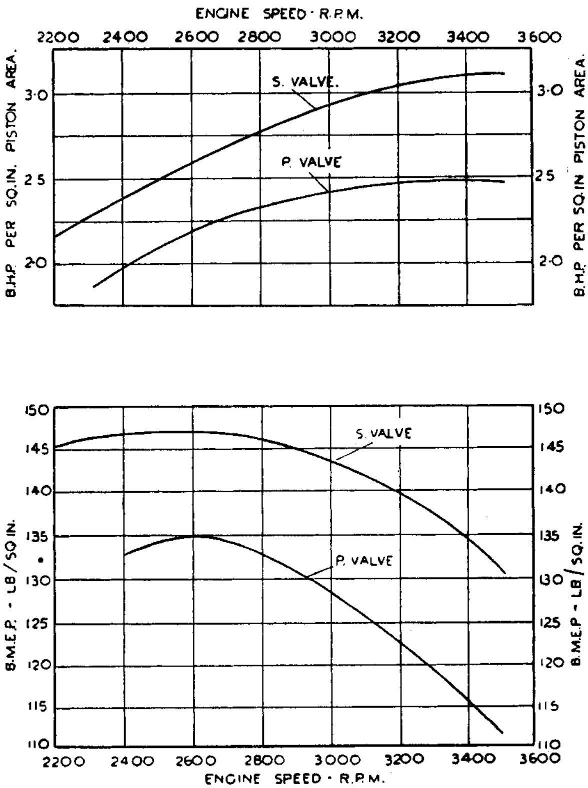

Fig. 10.—Comparative power curves for 98·2 cu. in. poppet-valve unit and 105·6 cu. in. sleeve-valve unit, the compression-ratio being adjusted to give similar detonation characteristics. 87 octane fuel. Fuel consumption, Aquila, 0·48 lb. per b.h.p. per hr.

r.p.m. and 272 lb. per sq. in. at 3,000 r.p.m. The corresponding powers per unit piston area are 6·0 b.h.p. per sq. in. and 6·7 b.h.p. per sq. in. If the above figures are corrected for the power absorbed by the separately driven blower, the break mean effective pressures are 276 lb. per sq. in. at 2,400 r.p.m. and 245 lb. per sq. in. at 3,000 r.p.m., whilst the powers are 5·4 b.h.p. per sq. in. and 6·0 b.h.p. per sq. in.

The conditions of the test were in no way arranged to be unusually favourable for the production of a high output. For instance, the intake temperature was high (95–100° C.), and the fuel was a

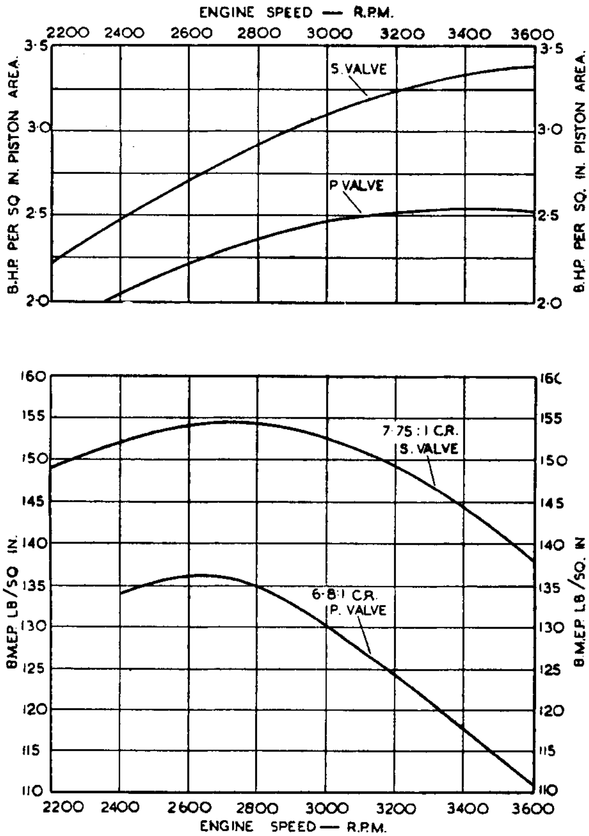

Fig. 11.—Comparative single cylinder power curves for a 98·2 cu. in. poppet valve and 105·6 cu. in. sleeve valve at a compression-ratio of 6·5 : 1. 74 octane fuel.

commonly-used mixture of approximately 100 octane rating. The fuel consumption was 0·63 lb. per b.h.p. hr.

It may be concluded from this test that the main obstacles to the immediate adoption of greatly increased ratings for sleeve-valve engines are the mechanical and lubrication difficulties in converting the gas pressures to a tangential force. The next move in aero-engine progress appears to rest therefore not so much with the designer as with the metallurgist and lubrication specialist.

Cylinder and Valve Design.

The clean appearance of sleeve-valve engines, due to the absence of outside valve gear, is not a superficial characteristic, but is a feature also of the simple internal design.

The cylinder has two exhaust ports in front and three inlet ports at the rear, whilst the sleeve has only four ports, one of which uncovers alternately an exhaust and an inlet port in the cylinder. The sleeve is provided with a spherically seated bearing, which can swivel so as to remain in line with the pin of a small crank. The drive is performed, therefore, by the rotation and sliding motion of the pin in the bearing, and by the swivelling motion of the latter in its housing. The small cranks are driven by a train of gears inside the front cover.

The main features of the cylinder and valve design can be explained by a few illustrations of the Perseus assembly. Fig. 12, Plate XXIV, shows the latest Perseus cylinder and its sleeve. The extensive development of this cylinder can be judged from Fig. 13, Plate XXIV, showing the original aluminium cylinder barrel and the present production type. Research has enabled the cooling to be improved and adequate porting to be provided. Suitable proportioning ensures that parallelism and circularity are maintained under all running conditions.

Fig. 14, Plate XXV, shows stages in the development of the cylinder-head. Cooling air has to be taken down inside the wall of the head to the crown. The original design provided plain fins and a simple deflector.

The first big advance was made in 1930 when the cylinder head was provided with a fin arrangement incorporating a baffle directing the air over the crown of the head, and producing turbulent circulation around the sparking plugs. This general lay-out has been adhered to ever since, and it has been developed to the present form with radial finning, giving circularity under running conditions, together with cooling adequate for all power outputs so far attained. The present head, shown on the bottom right of Fig. 14, Plate XXV, is a die casting in Y-alloy, and is an excellent example of this method of manufacture.

It is interesting to note that the 1930 type of head might be claimed as the forerunner of complete pressure baffling because the whole layout is based on attaining a velocity head at the upper front section and allowing the air to leak through finned cells to the lower pressure air at the rear.

Fig. 15, Plate XXV, shows, on the left, one of the first nitrided sleeves, and, on the right, one of the latest production sleeves. The many detail changes made during the years of development work are not apparent on the illustrations. Increased port area has been provided and control of swirl has been obtained.

The piston also has been subjected to many thousand hours of development work. It is a light alloy drop forging, and carries two compression rings and two scraper rings, as in the case of the Pegasus engine.

The standard driving ball assembly is shown in Fig. 16, Plate XXVI, and a number of experimental types in Fig. 17, Plate XXVII.

This assembly has to be absolutely reliable, and the test rig shown in Fig. 18, Plate XXVI, was employed to facilitate investigations over long running periods under arduous conditions. The present successful type is the result of considerable design and research efforts. Fortunately, it proved to be the simplest assembly tried.

On the test rig it has been found possible to transmit over 4 h.p. through the sleeve drive. As a result of suitable detail design, an appropriate selection of materials, and the nature of the motion, wear has been almost eliminated from the production series of sleeve drive.

Bristol Main Engine Development.

Designs for a complete engine were put in hand only after four years of single and two-cylinder research had been completed.

After a relatively short period of development the Perseus I, a 9-cyl. radial engine of 1,520 cu. in. capacity, was type tested in 1932 at a normal rating of 515 b.h.p., and a maximum power of 638 b.h.p. The rating was subsequently increased to 700 b.h.p., and the engine was endurance tested in a "Bulldog" aircraft. The engine was demonstrated for the first time in public at the Royal Air Force Pageant of 1934.

Considerable setbacks were encountered during the development of a slightly modified engine, the Perseus II. They were due to an incomplete understanding of the fundamental problems involved as the rating was increased. The engine was finally type tested in 1934, and submitted to a 250 hours' cruising test at 420 b.h.p. and 2,150 r.p.m., with a consumption of 0·435 lb. per b.h.p.-hour. The satisfactory condition of this engine at the conclusion of this run convinced the Bristol Co. that the type had great possibilities for commercial operation, and it became apparent that the troubles being encountered by poppet-valve engines with ethylized fuel would be totally eliminated by the adoption of this engine.

Five Perseus II engines were loaned by the British Air Ministry to Imperial Airways, Ltd., and on June 29th, 1935, they were first put into service in a Short "Scylla" type air liner. They were subsequently used in a Vickers "Vellox" freight machine, but the flight tests were abruptly terminated by an accident in no way due to the engines. Over 2,500 hours' running had, however, been accomplished by these five engines. The last engine received back at Bristol for strip had carried out 400 hours' running since the previous overhaul, at a power of 480 b.h.p., with, of course, the usual periods of high power at full throttle for take-off and climb. This engine stripped in first class condition, and, had not the flight tests been terminated by the accident to the "Vellox," it had been intended to step up to overhaul periods between 500 and 600 hours. The engines had fully demonstrated the reliable service to be expected from the mono-sleeve valve in commercial operation.

The Perseus VIII was the first Bristol sleeve-valve engine to be tested by the British Air Ministry under service conditions. The engine was fitted to a squadron of " Vildebeeste " almost two years ago, and it has proved a thorough testing ground for the sleeve-valve engine. The results have been most satisfactory as regards reliability, ease of maintenance, and, especially, continued serviceability.

Other types of Perseus engines have now been produced, and since the Perseus I, the b.m.e.p. has been raised by some 40 per cent. and the b.h.p. per sq. in. piston area by 65 per cent. A number of improvements in design have been introduced, such as the accessory gear-box first adopted as a new policy in 1936. This gear-box is normally mounted on the aircraft bulkhead, only those accessories essential to the operation of the engine remaining on the rear cover. The interchange of engines is greatly facilitated because the aircraft ancillary equipment need not be disturbed during the operation.

Two views of the latest Perseus engine, now in large scale production, are shown in Fig. 19, Plate XXVIII. This engine is being used as standard on a number of new military aircraft, including, for instance, the Westland " Lysander II," Fig. 20, Plate XXIX now in production, and the Blackburn " Skua," Fig. 21, Plate XXIX. Two civil aircraft having this engine are the latest type Short " Empire " flying boat and the De Havilland " Flamingo."

Another single row sleeve-valve engine is the Aquila. This engine was type tested in 1934, and was subsequently submitted to some hundreds of hours of flight development in such aircraft as the Vickers " Venom " fighter, and the Bristol " 143," an experimental civil aircraft, the development of which had to be dropped due to the rearmament programme.

Rearmament caused also the work on the Aquila engine to be suspended for a period, but it has now been resumed, and an Aquila has completed its civil test recently at a take-off power of 710 b.h.p. and a maximum power rating of 725 b.h.p.

The Hercules, illustrated in Fig. 22, Plate XXX, is a double-row 14-cyl. engine of 2,360 cu. in. It was type tested in 1936, and exhibited the same year at the Paris Salon. It was then rated at 1,375 b.h.p. at 2,400 r.p.m. Other types of this engine are to be produced for considerably higher powers, with both 87 and 100 octane fuels.

Endurance flight trials of the Hercules are proceeding in the special Northrop aircraft. The engine installation is illustrated in Fig. 23, Plate XXXI. This view shows the simplicity of the baffling for sleeve-valve engines.

The Hercules is now being fitted to several new aircraft of both military and civil types.

The interchange of engines is facilitated by the accessory gear-box which is to be standard on all new Bristol engines. The operation can be still further simplified by unit engine installations. By this method the engine, cowling, exhaust system and oil cooler are mounted on a framework which is attached to the aircraft at four points. The whole power egg can then be rapidly interchanged, and the unproductive periods of engine and aircraft are reduced to a minimum. Because of their compactness radial engines are particularly suited for this design. For instance, the Bristol "Brandon," produced some fourteen years ago, had a swinging engine mounting and the present-day Vickers "Venom" has a similar installation. The most advanced design in this direction is, however, the Hercules unit exhibited at the recent Paris Salon. Two views of this unit are shown in Fig. 24, Plate XXXII. It will be noticed that the engine and all accessories are mounted as a unit which can easily be interchanged, even between aircraft of different types. The aircraft designer is relieved of all responsibility for the installation in front of the fire-wall.

The latest Bristol sleeve-valve engine to be announced to the public is the Taurus (see Fig. 25, Plate XXXIII). This engine is of a

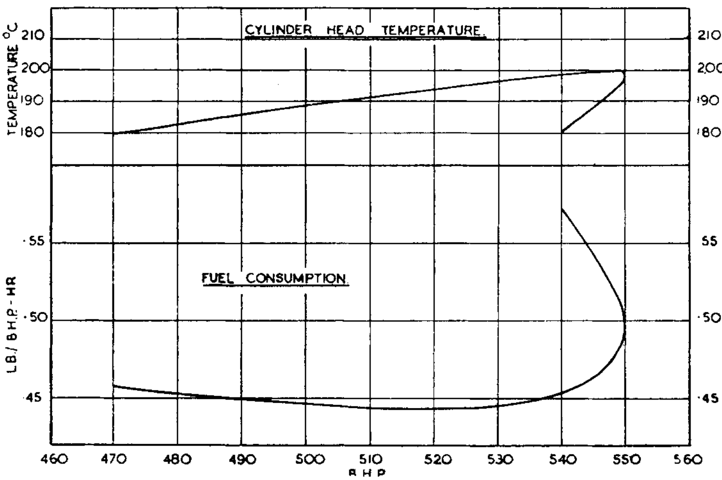

Fig. 28.—Perseus—fuel consumption loop at 2,400 r.p.m.

compact design, very similar to the Hercules, but of smaller dimensions. It is intended primarily for modern types of single or multi-engined high-performance aircraft.

The Taurus was type tested last summer for a maximum power of 1,065 b.h.p., and was subsequently exhibited at the Paris Salon, and is at present undergoing overload and flight development tests.

Fig. 26, Plate XXXIV, gives comparative views and data on the four Bristol sleeve-valve engines mentioned above. The total experimental running on these engines now exceeds 14,000 hours.

Characteristics of Sleeve-Valve Engines.

A most important feature of mono-sleeve valve engines is that the only maintenance required between overhauls is the routine servicing of plugs and magnetos. The man-power required to service sleeve-valve engines has been found to be considerably less than that needed for radial poppet valve engines. Still better results should be obtainable, and strides are already being made towards plug overhaul times of 100 hours and more in service.

Fig. 27, Plate XXXV, shows the relatively small number of parts in a sleeve valve assembly. This reduces the problem of spares and

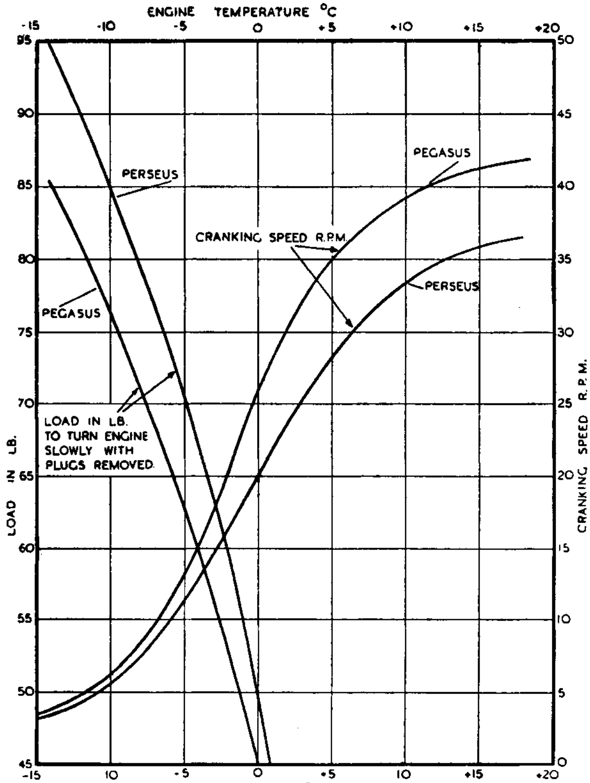

Fig. 29.—Comparative starting characteristics for poppet and sleeve-valve engines.

maintenance required. Not only are the parts few in number, but they are particularly suited to quantity production, the basic design being simple, few castings being employed, and the layout is adapted to the most comprehensive tooling.

The low fuel consumption and flat mixture loops have now been established. Fig. 28 shows, for instance, a fuel consumption loop

40 (2)

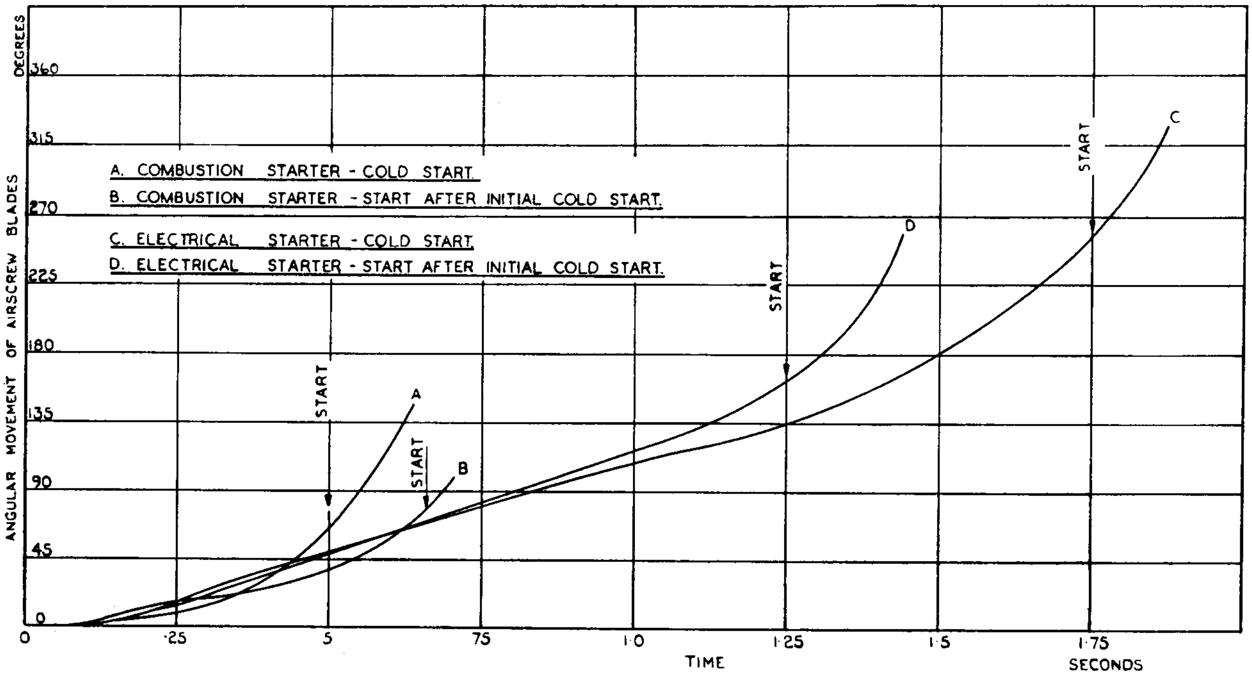

Fig. 30.—Hercules starter tests.

obtained with the fully supercharged Perseus X. On a weak mixture test this engine has been run at 520 b.h.p. during 50 hours on a fuel consumption of 0·448 lb. per b.h.p.-hr.

The low vulnerability of the air-cooled sleeve-valve engine is obvious. It is considered to be less vulnerable than the air-cooled poppet valve engine. The valve gear is robust and well protected. The sparking plugs are surrounded by the junk head.

In the initial stages of the development of the mono-sleeve valve engine it was feared that difficulties might be encountered in starting up engines in cold climates. At an early date, therefore, an extensive series of starting and torque tests were made in a cold chamber kindly placed at the Company's service by Messrs. Joseph Lucas. Sleeve and poppet valve engines were investigated under identical conditions, and interesting results, summarized in Fig. 29, were obtained. Later the cold-starting characteristics of the sleeve-valve engine were successfully confirmed by a series of tests, extending over two winters, on a Perseus engine sent by the British Air Ministry to Canada specially for the purpose.

The easy starting of a mono-sleeve valve engine under normal conditions has been clearly demonstrated by recent tests of different methods of starting. A moving picture was taken of the airscrew motion, and the curves shown in Fig. 30 were obtained by analysis.

Inherent Advantages of the Sleeve Valve Design.

The most important of these are :—

(*a*) Total absence of maintenance except for plug and magneto servicing.

(*b*) Elimination of hot spots in the combustion chamber.

(*c*) Use of higher compression-ratios or boost pressures.

(*d*) Improved volumetric efficiency due to the greater effective port areas.

(*e*) Centrally situated plugs, giving, if necessary, good performance on single ignition.

(*f*) Very flat mixture loops, permitting smooth running under conditions of extreme economy.

(*g*) Smooth running due to the good combustion chamber shape, and to the accurate and simple valve timing.

(*h*) More silent operation.

(*i*) Good accessibility and clean exterior appearance.

(*j*) Complete enclosure of all working parts, absence of external oil leads, and impossibility of oil leakage.

(*k*) Cooler exhaust.

(*l*) Freedom from lead corrosion.

(*m*) Greater freedom from cold corrosion.

(*n*) Regular cylinder shape, permitting the simplest form of baffling.

(*o*) Marked decrease in number of parts, and consequent reduced production and maintenance costs.

(*p*) Relative simplicity of all major parts, permitting accurate repetition machining.

(*q*) Probability of easier operation when exhaust turbo-blowers are used.

(*r*) Greater reliability due to most of the causes mentioned above.

(*s*) Any desired control of cylinder turbulence with its possible application to stratified charges and abnormally weak mixtures, with petrol injection.

The control of turbulence may be the most important factor in the development of the sleeve valve. Experience now available with small high-speed Diesels has shown that direct injection of small quantities of fuel presents no insuperable difficulty. It should be possible to adjust the fuel/air mixture very accurately over a wide range of operating conditions, and to use fuels of low volatility.

Conclusions.

Since the early successes of the Company with which the author is associated on the mono-sleeve valve aero engine, there has been a considerable spreading of the gospel in both air and liquid-cooled form by several prominent manufacturers. The author is glad to see this marked interest because it is desirable for further establishing the successful development of the design.

Many people have levelled what would, at first sight, appear to be a serious criticism against the sleeve-valve type that, in the event of any internal failure, the resultant wreckage is greater than in the case of the poppet valve design. Originally, the author also subscribed to this view, and all aspects of the problem, such as the provision of weak links in the sleeve drive, were thoroughly investigated. However, experience with a number of engine failures which have occurred during development and overload testing has shown that the above theory cannot be supported on any ground. On two occasions, with experimental sleeve-valve drives, failures occurred and were almost entirely localized to the particular cylinder in trouble. In the case of a piston failure both sleeve and poppet-valve engines are likely to be equally difficult once the rod becomes free.

From every aspect, therefore, the author must incline to the view that there is no hidden factor which might prevent the completely successful adoption of the sleeve valve.

None of the high-power running completed to date shows any indication that fundamental difficulties or limitations are being approached. There appears to be no reason why the mono-sleeve valve type should not eventually supplant existing poppet-valve engines which have served so well in the past, but definitely have certain fundamental inherent problems.

While there are a few engine layouts which cannot be conveniently met owing to the inability to provide space for the existing type of sleeve drive, most of the promising geometric forms can be accommodated, and the engine will undoubtedly make its appearance in multi-bank radial, X, and H forms.

During twelve years of mono-sleeve development for aero engines, numerous engineers have warned the author against this form of valve mechanism pointing out the number of firms throughout the world who have tried to make a success of it and have eventually abandoned the design. He is glad to say that he has no fears on this score, and, although he does not claim that it is the only solution for the valve mechanism of high-power reciprocating internal-combustion aero engines of the future, he feels convinced that it is going to be a classic one.

The author must admit, however, that, looking back over the years which have elapsed during his association with the development of the mono-sleeve valve, there were several times when failure to realize complete success after long periods of promising running gave him some qualms and called for a good deal of hard thinking. He then began to realize why other firms had given up the conflict, and he became convinced that the successful solution of the mono-sleeve was a long and deep furrow to hoe.

The author has no hesitation in saying that, had it not been for the loyal support of an enthusiastic design and experimental team, considerable patience and encouragement from the Board, and the continued backing of the British Air Ministry, the present Bristol sleeve-valve development might quite well have had to be discontinued some years ago.

This paper is intended to be historical, and is, as has already been stated, a *précis* of the mono-sleeve development of the Bristol Co. over the last decade, and, therefore, no attempt is being made to discuss derivations of the Burt-McCollum mechanism, nor to investigate possible solutions for the future.

In conclusion, the author wishes to thank the Bristol Aeroplane Co. and the Air Ministry for permission to read this paper, and certain members of his staff for the assistance they have given in preparing the data presented.

At the conclusion of the paper the author showed a slow-motion cinematograph film of the mono-sleeve valve in operation.

THE DISCUSSION.

(LONDON.)

Dr. D. R. Pye, in opening the discussion, said: The author is the unquestioned parent of the mono-sleeve-valve aero-engine. I can perhaps claim the humbler, but useful, *rôle* of the wet nurse who supplied necessary sustenance during the infant's early years.

I thought it would be of some interest to go back to those early years, and I therefore looked up some of the old papers of ten years ago before coming this evening. Prior to 1928, Mr. Ricardo had done a great deal of research on single-cylinder and other types of sleeve-valve engines. He had quite a variety of such engines to his credit even in those days. He had designed a racing car engine for the Vauxhall Company, and certain experimental 'bus engines, and had six or more research units at Shoreham, some of them designed and built to the orders of the Air Ministry. They were all, with one exception, water-cooled units, and some outstanding performances were achieved.

At that time I wrote a paper for the Aeronautical Research Committee about this development. I pointed out that all existing experience in aero-engine design and manufacture lay with poppet valves, and unless there was a clear possibility of achieving a definite step in advance of anything in sight along conventional lines, there would be no justification for breaking away from current traditions. I continued: "The very thoroughness of our experience with poppet valves enables us to foresee with some certainty what are the limits of development along present lines, or, at any rate, what are the present limiting factors in performance, and if it can be shown that the sleeve valve removes some of the limiting conditions without imposing new ones, then, and not till then, will there be a clear case for its further development. Unfortunately, the sleeve-valve cylinder presents peculiar difficulties in air-cooling"—this was written in 1928—" so that at present its claim for consideration as an aero-engine is bound up with the continuation of water or steam radiators."

As a result of that paper the Aeronautical Research Committee appointed a small panel under the chairmanship of Mr. (now Sir Henry) Tizard, and we had the benefit on that panel of discussions with all the well-known men in the aero-engine industry, the author among them, the late Mr. F. R. Smith, Mr. Elliott, Major Green, Mr. Wilkinson, and others, and our chairman this evening, Mr. Kidner, was, appropriately enough, the one witness we had who was outside the Aeronautical community. I may say that he gave us extremely interesting evidence from his connection with the Vauxhall Company and their experience of sleeve valves in road vehicles. We heard many opinions and various degrees of scepticism were expressed. A good deal of it was of the kind which the author quoted this evening, namely, that so many people had tried the device and given it up that surely there could be no prospects for the sleeve valve in aero-engines.

There were other points of criticism, such as the supposed excessive oil consumption. That was a legacy from the double-sleeve valve. Another point was the expectation of carbon building up in the ports. We considered all the evidence before us and came to certain technical conclusions. One was that with the fuels at that time available it was possible to run a sleeve-valve engine at a higher compression ratio without detona-

(Dr. D. R. Pye.)

tion. With a cylinder of a certain size and with a certain fuel, if it would stand a compression ratio of 5 : 1 with poppet valves, it would stand about 6 : 1 with sleeve valves. We therefore concluded that one might expect to achieve a better thermal efficiency with the sleeve-valve engine, partly on account of the higher compression ratio, and partly because it would be possible to run, we thought, with leaner mixtures without the danger of burning the valves, a danger at that time very much in evidence. Another point of interest was that when detonation did begin it appeared to come on more gradually. Instead of falling suddenly into a condition of violent detonation the process was gradual. There was still another point which at that time seemed to us important, though it seems much less important now. In those days superchargers were used for maintaining power up to altitude, but very little thought was given to what we now call ground boosting, the use of the supercharger to increase power at ground level. That meant that research work was almost entirely done on normally aspirated cylinders without superchargers, and therefore the question of getting the best possible cylinder-charging efficiency seemed very important. We concluded that it was possible to achieve a better volumetric efficiency on a normally aspirated sleeve-valve cylinder than could be done with the poppet-valve type.

As to the size and weight of the resulting engine per h.p., we came to the conclusion that there was probably not much in it, and I think that conclusion very likely stands to-day. If the sleeve valve could be built up into an air-cooled radial, however, there should probably be some reduction of the overall diameter.

It appeared to be essential, if one was to make the best use of the supercharger, to do away with the hot exhaust valve. That was the cardinal point which seemed important then, and we thought the sleeve valve was the only solution. It must be remembered that although the liquid-cooled poppet valve had many years before been tried, it had gone completely out of the picture. "On these grounds alone," we concluded—that is, the necessity of getting rid of the overheated exhaust valve—"we think that the sleeve valve is worth development as offering the greatest scope for advance in the production of high-duty engines of low weight per h.p., and we urge the experimental design of a complete engine." This was all based on water-cooled sleeve-valve results. We said, further, that the air-cooled sleeve had definitely not yet reached a stage to justify development to the complete engine, and we concluded that the advantages which it offered would warrant the continuance of the single-cylinder research work. That was the point at which the author and his staff at Bristol took over the problem of the air-cooled sleeve and from which they have carried it on during the last eleven years.

There is one interesting development to which I should like to refer because it has not yet taken place. In 1928 Mr. Ricardo had shown that by direct injection of petrol through a special port in a sleeve-valve cylinder it was possible to reduce the power to three-quarters of the full load by cutting down the petrol supply only, *i.e.*, without any throttling of the air supply. A stratified charge was obtained in the cylinder with a rich mixture at the top and practically pure air at the bottom near the piston. In that way it was possible to get very high fuel economy under cruising conditions. That still remains a possible line of development which would be of immense importance to the aero-engine if it could be successfully achieved.

Finally, there is a reflection which occurs to me and which is a thing one would like enthusiastic inventors to read, mark, learn, and inwardly digest, and that is this, that it is now rather more than ten years since the sleeve valve was taken up by the Bristol Company and a good deal more than ten years since research was first seriously undertaken to get the outputs necessary for an aero-engine. The general lines of the design have scarcely changed in the interval. With all the enthusiasm and the superlative skill available it has taken six or seven years to develop the sleeve valve to a really practicable power plant for aeroplanes. What I wish to emphasize is this, that the success or failure of any piece of machinery which is highly developed and highly stressed as the aero-engine must be depends on a multitude of details, and it is those details which have taken six or seven years to get right. The author and his team at Bristol have got them right, but in doing so they have had to study every aspect of the properties of the materials available. For example, for the sleeves themselves: coefficients of expansion and of conductivity, strength and elasticity at high temperatures, surface conditions, resistance to distortion, etc. No one but those who have been intimately connected with it can be aware of the amount of thought and foresight that has gone to the successful development about which you have heard this evening. I am glad there should be a record of the results in the "Proceedings" of this Institution, and I am sure the author's admirable paper will be studied by a wide circle of engineers.

Mr. J. F. Alcock: As one connected with Mr. Ricardo's early experiments, to which the author has referred, I have naturally taken a great interest in this paper. I am sure that if Mr. Ricardo were not abroad, he would be here to-night to pay a tribute to the remarkable record of development of which we have just heard. By comparison with this, our early work on the air-cooled sleeve engine appears crude, but it was, I think, of use in clearing the ground for later work, and in some ways may be of interest even now.

I think the main reason for the slow initial development of the single-sleeve engine was the head-sealing problem. There was a superstition that split rings could not safely run over the sleeve ports, and the early engines had either no rings at all or unsplit rings similar to those on the Junkers oil engine. An exception was the Barr and Stroud motor-cycle engine, but this had exceptionally narrow ports, and it was considered dangerous to run spring rings over the much wider ports used in other engines. We struggled with these unsplit rings for a long time, but they gave endless trouble. Finally, we fitted in desperation a common piston ring, and it worked. It is a fearful warning of the dangers of crying before one is hurt.

I am glad that the author has made it clear that the vital difference between the single sleeve and the Knight type lies in the oval motion of the single sleeve and its effect in distributing the lubricant, rather than in its avoidance of the double sleeves on the Knight engine.

Some years ago we tried an engine with a single reciprocating sleeve, and this proved very difficult to lubricate. The effect of the oval motion can easily be demonstrated by trying to distribute soap on one's hands with a plain reciprocating motion.

The oil film is also important as regards the transfer of heat from sleeve to cylinder. This has to be carried across the oil film by conduction, since the velocities are far too low to allow of turbulence in the oil, and thus the film must be thin. For this reason it is essential, in air-cooled engines at any rate, to have about the same expansion coefficients for the cylinder and sleeve materials. The sleeve must fit the cylinder *closely* in order to transfer its heat, thus with a carbon steel sleeve and light alloy cylinder, the sleeve temperature must be about twice that of the cylinder, which means that the sleeve runs far too hot. We soon discovered this and turned to the high-expansion austenitic materials now in use, but at that time (1926) nitrogen-hardened sleeves did not exist, and we had trouble with

(Mr. J. F. Alcock.)

scuffing and wear. We tried chromium-plating, but here, again, we were asking too much of the metallurgy of that date.

In an earlier paper the author has mentioned the effect of the sleeve in transferring heat from the recessed head to the outside of the head where there is more room for cooling fins. We studied this by water-cooling the top end of the cylinder, noting the effect on the head temperature, and *vice versa*. This in conjunction with model tests on steam-heated heads gave us the heat conductance from head to cylinder. The conclusion we then came to was that about 30 per cent of the heat received by the head was transferred to the cylinder, the rest being distributed by the head fins. It would be interesting to know whether this proportion holds with the vastly improved head designs now used.

Dr. W. H. Hatfield, F.R.S.: I have been associated with the author for some considerable time. This is not an occasion for paying compliments, but I would like to say that one could not desire, speaking now as a metallurgist, any different attitude on the part of the designing and consuming engineer than one has had from him. He shows great daring in his designs, and he takes our metals and puts them on a brutal test bed and one is made aware of it if everything is not all right. That is no exaggeration. I am not one to suggest that trial and error has been the principle underlying the evolution of this magnificent engine, because the whole thing has been tackled in such an intelligent way. As Dr. Pye has said, the secret of success has really been in the meticulous working out of the details, both on the engineering side and as regards the precise characteriestics of the particular material for a particular job. Indeed, those of us who have been in touch with the author—and this applies to quite a number in the metallurgical world in this country—have had great demands put upon us, though at the same time I think the demands made by him and by other leading aero-engine designers in this country have actually resulted in very material progress in the production of materials for aero-engine building. There is no doubt that materials available to-day were not available, as Dr. Pye has said, eleven years ago. I think I can claim that besides the private industrial research, the collective research on more fundamental matters, such as ingot design, has resulted in great advances, and we are now able to give, and do give, the aero-engine builder material in which we can have very great confidence.

I think that the present position largely is that for the type and power of engine which is being built, the author will concede that he has been given substantially the materials of the kind he required, and of the necessary standard of quality. But I think that with the outreaching of his mind to accomplish greater and greater things, more powerful engines, greater power for given weight, further calls will be made upon the metallurgical world. We shall have to try to respond, and it will mean continuous research. If by the encouragement of the author and his colleagues in the aeroplane engine industry the same encouragement is given to the metallurgical world during the next eleven years that has been given during the last eleven, we shall mark very great advance.

In conclusion, when scientific people like myself, working from the standpoint of materials, are in touch with the designing and fabricating engineer, we try all kinds of things and are able to achieve certain results but the point about the aero-engine industry is that its people are prepared to see that the metallurgical work is handled properly from the economic point of view. In many cases—and this must be emphasised—to ensure the 100 per cent efficiency which must be attained in these big aero-engines, the most meticulous steps have to be taken from the beginning to the end of manufacture, and the production of metals for aero-engine construction must be regarded as on an entirely different basis from the production of metals for what I may call ordinary demands.

Mr. J. D. Pearson: In the introduction to the paper the author refers in general to the shortcomings of poppet valves and later draws a particular comparison between a poppet- and a sleeve-valve cylinder. Firstly, I propose to submit some facts in support of poppet valves in general and later raise a number of points on the comparison of the particular cylinders referred to in the paper.

The limitation on operational speed imposed by push-rod operated gear and the lack of absolute reliability when such gear is not totally enclosed can be appreciated, but with totally enclosed overhead camshaft-operated valve gear the limitation on increased operating speeds does not appear to lie with the valve gear. On liquid-cooled engines the inserted seat gives no trouble from working loose, neither does the use of poppet valves introduce awkward external shapes.

As regards reliability, the modern automobile engine provides one excellent example, another can be quoted from some recent endurance tests carried out on a 4-cyl. unit of 5 in. bore and 5½ in. stroke. This unit has completed a total of 1,318 hours' running, which includes five 100-hour endurance runs under type test conditions corresponding to a maximum power rating of 900 h.p. on a Kestrel main engine :—

250 hours' endurance running at a corresponding Kestrel rating of	1,000 b.h.p.
250 hours' endurance running at a corresponding Kestrel rating of	1,100 b.h.p.

This has involved a total of 283 hours' running at over 200 b.m.e.p. and a maximum b.m.e.p. for take-off of 245.

Coming now to the particular comparison of poppet- and sleeve-valve single-cylinder units, I should like to ask the author whether the comparative tests of breathing capacity were carried out with as far as possible identical induction and exhaust systems, as in my experience the amount of the difference in m.e.p. between the poppet- and sleeve-valve cylinder could be obtained on the same cylinder by varying the induction and exhaust systems. Our own single-cylinder testing has so far failed to reveal any marked superiority in breathing capacity of the sleeve over the poppet-valve engine.

I trust that these facts will be sufficient to show that so far as liquid-cooled engines at least are concerned, there is still a lot of life in the old poppet valve.

Mr. H. L. Hall: Being associated with Imperial Airways, I have enjoyed the privilege of keeping in touch with the development work at Bristol which has been described this evening. I started an adverse critic of the sleeve valve and became an admirer of the development work done by the author and his assistants, and I am convinced that the sleeve-valve engine has a great future and I am looking forward to finding out at first hand what happens to these engines in daily service on an air line.

Mr. T. Thornycroft: Having been present at the lecture on the original Knight sleeve valve at the Royal Automobile Club at 119, Piccadilly, I have always followed the evolution of this type of engine with great interest. I have known the author for a number of years and have greatly admired his persistence, and I contragulate him on his achievement.

In the early days, as a rough sort of guess, it was said that a third of the heat developed in an engine went out into the exhaust, a third into the radiator, rather less than a third into energy, and the remainder was expended just here and there. I do not know how much heat energy is

(Mr. T. Thornycroft.)

obtained now, but I have been told that there is great difficulty in cooling the two-bank radial engine. As they seem to be so successful, I am quite convinced that there can really be no trouble from this source in the present instance, but I should like to ask the author if he can give an idea of the heat balance in this type of engine. There is no doubt in my mind, from what I have seen, that among high-revolution engines the sleeve valve is bound to win.

Mr. G. Morris : We have already heard from Mr. Pearson how reliable the poppet-valve mechanism can be, although it must be admitted that the exhaust valve is a hot spot, but I would like to ask the author if it is possible that the sleeve-valve engine also has its " hot spot." This might be the piston, because it seems likely that more difficulty may be expected here for the sleeve valve-type than for other constructions, due to the more difficult heat path to the cylinder walls.

The author quotes in his paper the results of tests on a sleeve-valve unit which gave 6·7 h.p. per sq. in. of piston area, and it was not thought that similar results could have been obtained from a poppet-valve unit under similar conditions. I would like to mention that a poppet-valve main engine of similar size has been run successfully at 7·9 h.p. per sq. in. of piston area. Allowing for the power this engine was expending in driving its own supercharger, the figure became 9·3 b.h.p. per sq. in. This power was obtained at 3,200 ft. per min. piston speed. That reading, which was not a snap one, rather goes to show that there is still a good deal of life in the poppet engine.

It is claimed for the sleeve-valve engine that on a given grade of fuel higher compression ratios can be used, but is the full theoretical advantage gained from this, or is it partially offset by a possible lower mechanical efficiency ?

Mr. H. Cantrell : We have heard some reference to a comparison between water-cooled engines with poppet valves and air-cooled engines with sleeve valves. My opinion is that it may be that the best condition is for the air-cooled engine to have a sleeve valve and for the water-cooled engine to have poppet valves, and I should like to support the author's figures regarding the superiority of the sleeve valve, which, I take it, very largely referred to air-cooled engines. I think also it may very well be that the air-cooled engine with a sleeve valve has a better application than to the radial engine.

Brief references have been made to materials for sleeves, and the author mentioned KE 965. Is he satisfied with this and does it meet his requirements ? There is one other thing I would like to ask the author. He probably is the only individual who has what is really good comparative information with regard to cylinder temperatures in flight, say, at the hot spot of either type of engine. What is the comparison in this respect between the sleeve-valve air-cooled engine and the poppet-valve air-cooled engine ? I imagine he will express the view that the temperature of the sleeve-valve air-cooled engine, measured at the same position and under the same conditions of engine performance, is very much superior.

The Author, in replying to the discussion, said : I should first like to thank you, Mr. Chairman, for your remarks about the pertinacity of our team. We have certainly had difficult times on this job, and there have been many occasions when we have not known exactly what was the next step to take. The Chairman this evening has always been a keen supporter of the sleeve-valve engine, and I well remember his enthusiasm when I went up before The Aeronautical Research Committee, of which Dr. Pye has told us already. Dr. Pye's reference to the work of that most intriguing six-cylinder motor-car engine that I once had a drive in with Mr.

Ricardo, reminds me that nobody was more sorry than I was to see that that engine did not go on to a great triumph as it should undoubtedly have done.

I thank Dr. Pye, too, for his remarks about our team, and also for his most interesting historical review of the start of this work. That also brings to mind a day which stands out in my life. I remember going up to the meeting of the Committee and seeing Dr. Pye, Mr. (now Sir) Henry Tizard, and Mr. Kidner, together with one or two other designers, including Captain Wilkinson, and we had a long discussion on whether we ought to go on with this sleeve work or not. Mr. Ricardo was also there. He, of course, has been a great supporter of the sleeve-valve engine.

I do not agree that Dr. Pye has been merely a " wet nurse." As I said in my paper, he has always given me great encouragement, and I should call him the fairy godmother who has produced the wherewithal to enable us to carry out our work.

Actually, now that we have got more experience of the sleeve-valve engine, there does not seem to be very much in the question of weight or overall diameter when it is in radial form. On our 25-litre, 9-cyl., single-bank radials, employing poppet and sleeve valves, there is very little difference either in the weight or overall diameter of the two engines.

In reply to Mr. Alcock's remarks, I would say how much we have appreciated help which Mr. Ricardo has given us from time to time. He has read one or two brilliant papers on the sleeve valve, and we have always kept in touch with him and had the benefit of discussing sleeve-valve problems with him.

On the question of control of swirl, I think that at the speeds we are running to-day, up to 3,300 r.p.m., we have always got more swirl than we need.

I regret I am not able offhand to give an answer to Mr. Alcock's point as to whether 30 per cent of the heat flow received by the head was transferred to the cylinder.

With regard to Dr. Hatfield, he, again, has been " in on the ground floor " in the development of this work, and many are the times my colleagues and I have sat around the table on our sleeve problems, and asked him for something more or something better. We have certainly had a great deal of help from those who are making our sleeves, and, if it had not been for the developments of metallurgy, we should not have made the sleeve-valve progress that we now have. I have always been very much interested in the single sleeve valve. I would call to mind examples of the sleeve-valve engine which I saw, both in England and on the Continent, before the War, and I think there is little doubt that the designers of those engines did not have anything like the help that we have enjoyed in regard to material development. We have had assistance both from the ferrous and light alloy sides, without which it would have been impossible to realize the success we have had to date.

What I tried to bring out in the paper was that we had got " something up our sleeve " in regard to breathing efficiency, and if Dr. Hatfield can only produce some further improvements in material, I am sure we shall make further progress.

Mr. Pearson has given us an interesting review of the work done on the Rolls-Royce poppet-valve engine. He has referred to the 5 in. by 5½ in. size of cylinder, which undoubtedly has put up a most remarkable show. I still feel, however, that, in spite of the figures Mr. Pearson has given us, we have, at any rate for our type of engine, the air-cooled radial, a great deal to be thankful for in regard to sleeve-valve development. In reviewing the merits of an engine it is impossible to take figures for b.h.p. only. One must consider the efficiency of the power plant as a whole.

(The Author.)

Overhead camshafts for radial engines are not a very satisfactory solution, and double row engines with push rods are also a difficult proposition. I showed a 16-cyl. double octagon radial of Bristol design which had overhead camshafts, and I explained in the paper why we dropped this type in favour of the sleeve valve.

I admit the most remarkable results obtained with 350 c.c. motorcycle racing engines. It is possible to get from the small bore overhead valve cylinders, performances which are probably superior to, or at any rate equal to, that which could be obtained from the corresponding sleeve valve. But round about the 5 in. bore I believe you get on to the limit of the poppet valve, and on the larger size of cylinder it is considered that the performance is much better with the sleeve valve than with any poppet-valve arrangement.

I thank Mr. Hall for his remarks. He has got some boats with sleeve-valve engines running. They are just starting out on their work, and we are naturally extremely interested in seeing how they perform. I am much obliged also to Mr. Thornycroft for his remarks. With regard to the question of heat balance, work has been carried out on this. The overall thermal efficiency of our engines is round about 34 to 35 per cent, but I would not like to give offhand the actual figures showing how the balance is made up. But I should like to take this opportunity of saying something on the question of cooling. Undoubtedly we have to feel our way with this engine, and we naturally want to have not only satisfactory cooling, but a long life. If the liquid-cooled engine is not satisfactory, so far as the cooling is concerned, in an aeroplane, it very quickly lets itself be heard or seen, whereas the air-cooled engine can be under-cooled and one can possibly go on with very bad cooling conditions for 50 to 60 hours without any obvious trouble. What we are particularly desirous of doing is to ensure that our engines shall have a good life, and, with that object in view, we asked the aircraft constructors to keep down to a given temperature. One is not absolutely certain, however, what that temperature should be. That is the sort of thing which can only be reached by actual experience.

In the measurement of cylinder temperatures, so much depends on exactly where the thermocouple is attached, but we consider that a temperature of about 230° C. where we take our thermocouple reading is what we want to aim at, as against about 190° C. to 200° C. on the air-cooled poppet-valve engine. In the poppet-valve engine the temperature is, of course, taken near the induction port, whereas our reading on the sleeve-valve head is taken in quite a different position relative to the gas flow, and therefore it is rather difficult to compare results.

Comparing two engines, the percentage of h.p. to oil in the case of the Mercury poppet valve is 3·9, and in the case of the Perseus it is 5·5. The oil return in gallons per b.p.h. hour in the case of the Mercury is 0·33, and in the case of the Perseus is 0·37. The heat to oil in an engine like the Taurus is of the order of 70 h.p.

A question has been asked about oil consumption. On the two 25-litre engines in production at the moment, we allow a consumption of 6 to 12 pints per hour. Actually, I think there is very little difference in the oil consumption between the two engines. That, of course, is due to the work done by the metallurgist on the type of material for sleeves, as well as the general finish of sleeves and the detailed technique that we have made on ring development.

Mr. Ricardo made a very interesting statement in a lecture which he gave on the sleeve valve, when he said that the sleeve was transparent for heat flow, and consequently one gets such a good follow up of the sleeve that there is no reason to feel that the oil consumption should be abnormal or varying as compared with the poppet valve.

Mr. Morris, of Rolls-Royce, also made some comments with regard to the poppet valve. I agree with him that the piston is the most difficult problem awaiting solution. He has quoted some interesting figures which are certainly better than I have heard before, namely, 7·9 b.h.p. per sq. in. of piston area. Our piston speed on the Aquila is just about the same as he quotes.

On the question of decrease in mechanical efficiency, a further motoring test which we have done has proved that there is definitely no decrease, at any rate in the speeds in which we are interested, say, up to 3,300 r.p.m.

I thank Mr. Cantrell for his comments. He has been one of the pioneers of air-cooled radials. I agree that the sleeve is particularly suited to the air-cooled inline engine, as well as the air-cooled radial. I believe that we shall see liquid-cooled engines with large bores operating on the Burt-McCollum principle.

The present production of low-carbon KE.965, which Dr. Hatfield undertakes for us, has, I think, given satisfaction at the speeds we are talking about to-day.

With regard to cylinder temperatures, I agree with what Mr. Cantrell says. The temperatures we measure are higher on our thermocouple, but that is undoubtedly due to the different location as I have just explained.

(WESTERN CENTRE.)

Mr. R. C. Cross, in opening the discussion, said : I should like to ask the author why is he able to obtain higher piston speeds with the sleeve-valve engine than with the corresponding poppet-valve engine. One would imagine that the cooling of the piston would be more difficult and that lower piston speeds would be necessary because of this.

I should also like to know whether he has experimented with cylinders having circumferential resilience. In the ordinary engine this would be impossible, but with the sleeve-valve engine the cylinder has only to take longitudinal and piston thrust pressures, the sleeve taking the circumferential loads. It has struck me that such a cylinder would reduce expansion difficulties and provide a better heat flow from sleeve to cylinder because of the more intimate contact.

Has the author evolved any device for measuring the temperature of the sleeve ? This would appear to be very difficult to do.

Mr. G. S. Kimmins : I happen to have worked on the first type-test of the Perseus engine, and I can truthfully say that up till then it was the smoothest we had had. There was not an instant's anxiety. With regard to the Hercules, when it has to run at high speed it is steadier than the poppet valve. Its type-test hour at high speed was run off without throttle adjustment or variation in speed. This has not been possible on any poppet valve with which I have been concerned.

Mr. J. C. Garsett : Can the author say what is the maximum r.p.m. at which the sleeve-valve engine will work, and whether his company has made any operative tests ?

Mr. J. F. Cuss : In connection with the construction of aeroplanes and provision for oil cooling, one point of interest is the temperature of the oil, which will determine whether increased surface is required to effect the cooling. Can the author give any indication of the oil temperatures and also state how the coil consumption compares with that of the poppet valve. This will determine the tankage which has to be provided.

Mr. J. H. Boakes : The author has pointed out the important part which improved fuels have played in the progress in efficiency of the aircraft engine generally. Will he kindly tell us if this also refers to lubrication, and whether improved oils have assisted in the development of the sleeve-valve aircraft engine ?

My only experience of this type of engine was with the Barr and Stroud motor-cycle power unit, and one of the difficulties encountered in those early days was carbon (chiefly from oil), which affected the sleeve and ports.

Mr. C. Todd : I should like to ask which is the chief factor that has speeded the successful development of the single sleeve-valve engine ? Was it solely metallurgical progress or a little of each of several factors, such as :—

1. Improved manufacturing technique,
2. Detail design improvement,
3. Better lubrication ?

Another Speaker : From what the author says the sleeve valve is cheap and economical to make. It would appear, therefore, that if it is successful in aero-engines it will eventually be employed in motor-car engines. Will the author give his comments on this point ?

Mr. N. Rowbotham : The form of the cylinder head is peculiar in shape, and one is struck by the peculiar position of the sparking plugs. I should like to ask if these are the cause of ignition difficulties, and whether temperatures are high, at similar rating, compared with those on the poppet valve ? What is utilized for cooling the plugs ? I should also like to ask if the clearance between the piston and the sleeve, and the sleeve and the cylinder wall varies considerably from slow to maximum running. Does it cause some big variations ?

I would like to endorse entirely the author's opinion of the production facilities of the sleeve-valve engine. I can assure members that the amount of work to produce the cylinder, the sleeve and the head is considerably reduced as compared with the various components of the poppet-valve engine.

Mr. P. White : Will the author say what he thinks are the possible lines of development in the sleeve-valve engine in the next ten years ?

Mr. H. Higgins : Can the author give any indication of the probable form of the future engine ; will it be radial, X, H or in-line ?

Mr. A. E. Stroud : I notice that the base of the head and top of the piston are of convex shape. I should like to know if there has been any attempt to produce a concave shape, as I have always understood that the most efficient form of combustion chamber is as near spherical as possible, and the sleeve-valve design appears to favour an approach to this simple shape.

Mr. W. A. Clarke : Referring to Fig. 7 in the paper, will the author explain why the American two-valve engine has a much higher breathing efficiency at low r.p.m. than the " Bristol " engines ?

Mr. E. C. Williams : I wonder if the author would give us a brief outline of the lubrication of the sleeve-valve piston and cylinder assembly.

Mr. E. R. Hallett : What is the relative amount of power absorbed by the sleeve valve compared with the poppet ?

Mr. S. Culverwell : Can the author give a comparison between the port areas of the poppet vave and the sleeve valve ?

Dr. Fedden, in replying to the discussion, said: Mr. Cross let me off very lightly; he could no doubt have given me some teasers. I have watched his research with a great deal of interest and we have had many talks about his problems. About twelve years ago I had the privilege of riding a motor cycle with his valve, and I would like to say in regard to any effort our team has put into its work he has put in a tremendous amount also. I am glad to see that he has made a success of the rotary valve, which we turned down owing to its small size.

Regarding the question of piston speed, we have found that we can run the sleeve-valve engine at corresponding power at about 10 per cent higher speed than the poppet valve, and we think this one of the great advantages of the mono-sleeve valve. Whether this would be feasible on smaller versions I cannot say, but I think it is possible that if a smaller cylinder was adopted the breathing might be better with the poppet valve.

On the question of heat transference, I cannot do better than refer to the words of Mr. Ricardo in one of his lectures: "We found that the sleeve-valve engine was almost transparent to heat." Owing to the rotary motion as well as the reciprocating motion, you get a remarkable heat flow. The Knight engine has only the reciprocating motion and consequently the oil distribution is not so good. It must be borne in mind that we are always using big bores, and that the paper concerns the 5 in. bore cylinder. Rather than go to resilient cylinders we dealt with special materials and there we had a great deal of help. We have never made reliable temperature measurements on sleeves. I have seen some obtained on very interesting equipment in Germany, at a most remarkable engine testing laboratory in Berlin.

With regard to the next speaker, he represents part of our good team, and it is nice of him to say that the sleeve-valve engine is smooth running and has given him confidence on the bench. He has been very kind and has forgotten some of the times when the whole thing has been smashed up. When these large-bore engines are run fast it is possible for all sorts of extraordinary things to happen; but you do get a sense of confidence from them.

There was a question about automobile engines. I should like to see one built with sleeve valves, and I think it will be done some day. It has not been done so far because the motor car manufacturer and the designer are so much in the hands of groups of people. The times when the amateur firms dashed into many new things do not exist to-day. However, I think the time will come, and I do not think it is divulging any secret to say that several automobile people are now thinking round sleeve valves, and in the not far distant future they may appear on the roads.

In reply to Mr. Carsett, I should say that the sleeve-valve cylinder as we know it to-day will run 10 per cent higher revolutions per minute than the poppet valve.

In reply to Mr. Cuss, the oil consumption on the sleeve and the poppet valves as allowed by the Government is the same, 6 to 12 pints per hour for the "Perseus" and "Mercury" engines. Oil cooling is a more difficult problem, since the heat to oil is greater on a sleeve-valve engine. The percentage b.h.p. to oil is 3·9 for the "Mercury" and 5·5 for the "Perseus" engines.

Mr. Boakes made some interesting remarks about the Barr and Stroud motor cycle. It is a most interesting engine; I had one in 1920 and got a lot of fun out of it when it used to seize up.

I do not think we have had much help from lubricating oils. I think our real help has come from the materials which have enabled us to get better contact and better conductivity. We are using exactly the same oil on the poppet valve as the sleeve valve. Oil has been pretty stationary,

(Dr. Fedden.)

and the standard Government brand is now the same as it was ten years ago.

Mr. Todd asked what is the main reason which has made development possible. Well, apart from the Government's co-operation and the perseverance of the team and the Board, it was undoubtedly materials. I have been most interested in the sleeve-valve problem for years. Before the war I went to an exhibition at Glasgow, and again to Laffans Plain. I bought a Barr and Stroud motor engine ; I saw the Aster, and the Vauxhall, which, I think, was bought and squashed by our American friends. All these engines really fell more from the lack of the right materials and manufacturing technique than from the design aspect. Therefore I put materials first and manufacturing technique second.

In regard to Mr. Rowbotham's remarks, it is a great encouragement to hear that the sleeve valve has great possibilities for production. So far as the plug position is concerned, I actually expected we should have more trouble than we have had. We had to improve our technique and we had to go to ceramic plugs. We are fortunate in being able to get away with the plugs as we do, but I have a feeling that the plug will keep pace with the development of the engine.

On the question of clearances, that is one of the big bugbears of a design such as the sleeve valve, and that is where our earlier friends fell down. Part of our trouble was to find materials which would hit off a happy medium ; to obtain a working clearance that would operate under all conditions.

I was rather anxious about cold temperatures, but the tests I mentioned have gone off very well in Canada, and now we have another machine with a " Perseus " engine running for winter trials in Sweden, and one of our men there the other day reported that they were going on well.

Regarding Mr. White's question, ten years ahead is a long time, and I cannot say as to what will happen by then beyond what I said at the conclusion of the paper, and which he knows better than we do, that we have found no definite advancement on the sleeve valve. I think if we could find a light alloy for the piston and some materials for the sleeve to stand up to the possibility of increased power, the present rating might be improved by 50 per cent—and I am sure we shall ; and the poppet valve would come chasing after us.

I am certain that we shall have further development of the poppet and the mono-sleeve valve. But there are many other more diverting questions to tackle than the actual sleeve.

With regard to Mr. Higgins' views, I expect, as he has been in charge of making experimental engines, he has as many ideas as I have. I feel that I have always been faithful to the radial engine. Two thousand horsepower is about the limit of the radial engine. If one might be allowed to prophesy, I expect that Mr. Higgins will be building engines to go inside wings ; they will probably be of 3,000 h.p. or more, and fan cooled.

Mr. Stroud referred to the shape of the combustion chamber. He is quite right ; the shape is not ideal. We have tried many others but we found at an early stage that this was the best.

I think Mr. Clarke spoke about breathing. I think that the good breathing of the American unit at low r.p.m. is due to that cylinder being set with a special valve timing to suit low engine speeds.

Mr. Williams spoke about lubrication. No problem such as the single-sleeve valve can be tackled without a good many lubrication problems. I do feel that the single sleeve is of enormous help. One thing that struck me was the way in which the marking on the piston skirt showed how well the oil was fed up the piston. Our lubrication problems have been met chiefly by suitable materials and long development of the shape of rings and general clearances.

With regard to a question about efficiency, I think the mechanical efficiency of the "Mercury" and the "Perseus" at 1,700 r.p.m. are practically identical. The radial engine is the most efficient of large aero-engines.

Concerning Mr. Culverwell's remarks about port areas, I think this depends on timing and the size of the cylinders. The larger the cylinder the more difficult the breathing of the valve.

(DERBY CENTRE.)

Mr. A. G. Elliott, in opening the discussion, said: Since the author has stated that this paper is historical, perhaps I may be permitted to go back into the past a little and revive some memories of sleeve-valve development.

First, we had the Knight engine with its two sleeves operating purely in a straight-line reciprocating motion, and those who contacted with this type will remember how much oil was required to keep that engine running, and what happened when things went wrong.

Then the Burt McCallum invention came along, introducing a very big advance, *e.g.*, the use of only one sleeve with a semi-rotary sliding motion. Strangely enough, the single-sleeve engine never really got going. It had some sort of vogue on motor cars, cycles, and small stationary engines after the war, but this development eventually died down.

Sleeve engines at the time were somewhat under a cloud, but very likely they were not well enough made. It seemed to be typical that if any trouble developed it resulted in extensive damage to the engine, due to the close association of the all mechanically moving parts. On this account the sleeve-valve engine does require to be very intelligently designed, thoroughly developed, and well made of first-class materials for reliability of operation.

The radial engine is the ideal case for the application of sleeve valves, but in the case of in-line liquid-cooled engines, where cylinders and valves are grouped, the poppet-valve type forms the lighter and more compact power unit. Take one example of a 5 in. bore 12-cyl. Vee engine. In its liquid-cooled form this can be made with a spacing of 0·625 in. between one cylinder bore and the next, whereas as a liquid-cooled sleeve design the minimum distance between cylinder bores would increase by about 1 in. over this to accommodate gas passages and junk head joints.

The overall engine length would be increased six times this amount, resulting in a considerable addition to length and weight of power plant, in addition to the increase of weight entailed by the use of the sleeve valves themselves.

For this increase of weight there is no compensation in the form of increased output on the liquid-cooled type, as we have failed to find any difference in volumetric efficiency between the best forms of sleeve and poppet cylinders.

Much more could be said in carrying on this comparison, but my own view is that there is room for these two very different types of valve gear to live and develop further in their respective spheres.

Mr. Ellor: In the historical review it will be noticed that the failures to produce a sleeve valve date back as far as 1905. It is only recently that the sleeve valve has really been a success, and this I am convinced is due to the author's ingenuity and the way he has of getting things to work when other people seem to get rather bored with them. I am afraid, however, that the poppet-valve engine will die very hard, and I personally

(Mr. Ellor.)

am not convinced that the sleeve-valve engine has merits over the poppet valve.

The foremost consideration when changing an engine type must necessarily be the advantage accruing to the customer. It may be quite interesting as an engineering feat to evolve a new type of engine or to modify an existing type, but the primary object of the engine is to satisfy the requirements of the customer, whether he be the Air Ministry or a civilian. The essential factors from the customer's point of view are whether the modifications result in improved performance or better accessibility, a simplified cooling system or reduced drag, or do they provide a cheaper engine due to reduced production costs.

I am not yet convinced that the customer derives any material benefit from the sleeve-valve engine. I can see that for the radial type, the sleeve valve has simplified the engine by eliminating the valve gear, providing its introduction has not added any other difficulties and providing reliability is not reduced.

I can only speak, of course, of those factors that are associated with our engines, but I must say that some of the figures that have been shown on the slides when a comparison has been made between a sleeve- and poppet-valve engine do not quite represent the results we are getting with 4-valve liquid-cooled engines.

I notice on some of the naturally aspirated poppet-valve engines, the M.E.P.s that compare with the sleeve valves were in the region of 130 to 135, whereas we are able to obtain about 145 to 150.

Also as regards performance at the higher piston speeds, I have not yet seen any increase in load relative to the poppet-valve engine to indicate any benefit from more efficient breathing. On the curve that was shown to-night the breathing is indicated by the gradient of the curve, rather than by the magnitude of the M.E.P. The figures I have in mind for the poppet-valve engine can be lifted up to the same value as for the sleeve-valve type.

I should also like to ask the author whether improved cooling is obtained by the sleeve valve compared with the poppet valve in air-cooled engines.

From the view point of servicing, better poppet-valve engines are being produced, which is only to be expected in the light of experience, and the time is imminent, when even sparking plugs will complete 120 hours without attention. It is unlikely that the service would require a longer inter-maintenance period than this.

In conclusion, I would like to ask the author what are the major troubles that he would anticipate with the sleeve-valve engine. Even the best engines have their troubles, and I cannot think that sleeve valves are going into service and running for lengthy periods without encountering some form of trouble.

Mr. Lovesey: One particular aspect of the sleeve-valve *versus* the poppet-valve engine is the question of volumetric efficiency at high piston speeds.

The usual criticism put forward is that the poppet valve does not compare favourably with the sleeve valve at high piston speeds; but on comparing the various published performances of sleeve-valve engines there seems to be very little difference between them when allowance is made for the degree of supercharge.

I have compared a number of full-scale engines on the basis of M.E.P.s for varying piston speeds, but at the same time taking into consideration the supercharger compression ratio, and when these corrections are made, the poppet valve seems to be at a slight advantage compared to the sleeve valve, in spite of the greater area of port opening of the latter, and the reason may be a better coefficient of orifice of the poppet valve.

The other point is the limitation in possible cylinder outputs which may be imposed by such things as hot spots. The figure quoted by the author of about 6·2 h.p. per sq. in. of piston area has, I think, been exceeded on the full-scale engine, and we have had results in excess of 9 h.p., and so far as temperature is concerned it does not seem to impose any limitation, and I have no doubt that our exhaust valves would permit of this output being still further increased.

I quite agree that in making comparison between the sleeve- and poppet-valve engine no clearly cut comparison can be obtained as you have to consider it upon the particular application to which each form of engine is applied.

Mr. Cantrell : I feel, myself, as I think Mr. Elliott indicated, that the sphere of the sleeve valve is undoubtedly with the air-cooled engine, and I think there is no question that the best valve gear for the water-cooled engine is the poppet valve.

Long discussions are held about the relative merits of either type in connection with breathing, and figures are quoted for horse-power per sq. in. (this is rather a modernism, I think), completely ignoring stroke. Two or three years ago we heard a lot about horse-power per litre without reference to engine speed, but I think finally, in weighing up the relative merits of these things, there are probably only two things that matter. One is installation drag, and secondly, installation weight, with the same engine performance.

I think that a very interesting duel will take place in the near future between sleeve-valve, air-cooled engines and water-cooled poppet-valve engines. I feel that in this particular direction it is quite probable that the radial engine will not be so well placed as other possible engine arrangements with air-cooled sleeve valves.

The author refers to the multi-bank radial engine. I agree with his other applications, but how is the sleeve-valve design to be fitted into a multi-bank radial engine, and unquestionably, I think the other forms of engine mentioned have better advantages in the installation of the sleeve valve than the radial type.

Regarding material for sleeves, does the author feel that the N.M.C. application is satisfactory ? Referring to cylinders, will he state why he removes the fins completely from the root or base of the cylinder or the cylinder barrel adjacent to the bolting flange ?

I also noticed that the author does not allow his piston rings to run into the sleeve ports. Why is this done ? Further, is the formation of carbon in sleeve ports serious, or is it removed through the normal varying conditions of the use of an engine without damage ?

I notice that the author gave a statement on easy starting, but his graphs conveyed the fact that starting was more difficult. I would like to ask whether he has experience of not being able to establish the same induction depression at slow speeds with sleeve valves, and whether that type of leakage is responsible for any other difficulties in operation ?

Mr. Pearson : There are two questions which I should like to ask the author. The first is concerned with the sleeve drive. He showed two sleeves on a slide. The one on the left (which he referred to as the earlier design) had an integral ball, and appeared to be the better job, but he told us that that was the early design. I should be very interested to know the reason for departing from what appeared to be the sounder job and going to the detachable ball housing. Was it associated with the assembly of the engine, or for other reasons ?

The second question ; this is in connection with the effect of size on sleeve-valve engines. We know that at the present time the coefficient expansion of the sleeve and cylinder material is not the same. The cold

(Mr. Pearson.)

clearance has got to be fixed up in order to obtain starting under zero conditions, which means that the larger the cylinder the greater the actual clearance between the sleeve and cylinder under operating conditions.

It would appear to me that the functioning of the sleeve-valve engine and the transference of heat from the sleeve to the cylinder is dependent largely on the absolute thickness of the oil film. This will mean that the larger cylinder may be at a disadvantage compared with the smaller cylinder, and I should be very interested to have the author's views as to whether this is so, as he has had extensive experience with two cylinders—one of 5 in. and one of $5\frac{3}{4}$ in. bore—and whether he considers the latter about the limit of cylinder size for sleeve-valve operation.

Mr. J. R. Read: The high outputs that the author has obtained from his engine, as shown in Fig. 10, are very interesting. Will he state if the cooling air pressure was normal for these tests, and also if he used any auxiliary method of cooling the piston?

Will the author amplify his remarks regarding control of swirl and state whether he finds this at all critical, and also whether the sleeve-valve engine has been found susceptible to the length of its induction pipes?

I should also like to ask if the out-of-balance effect of the sleeve causes any vibration trouble, particularly in the multi-bank engine?

In conclusion, I thoroughly and unreservedly agree with the author regarding the future of the sleeve-valve engine.

Mr. Parkinson: The author speaks of several 100-hour runs. Was the power maintained throughout that time? I should like to know what percentage of power loss is experienced due to the carboning up of exhaust ports.

Mr. Towle: Some operators state that the most marked difference noted on changing over from poppet-valve to sleeve-valve engines is the considerably increased smoothness of acceleration and elimination of what is popularly called the "kick in the back" feeling.

With regard to low-speed running of sleeve-valve engines, in my own mind I associate it with much more severe conditions with regard to plugs, required magneto performance, etc. Could the author give any idea of the difference between sparking-plug maintenance times, etc.?

I believe that the early disappearance of many of the single-sleeve automobile engines was due to the fouling up of the sleeve ports, in some cases it being impossible to run satisfactorily for more than a thousand miles without scraping these out. How has this been overcome?

Mr. Dorey: On the charts showing the turning effort required for the poppet-valve engine against the sleeve-valve engine I believe the figures shown compare the torque applied to the engine when in motion, and there it was admitted that the sleeve-valve engine took more to turn it. What is the difference from the starting torque point of view, particularly on a cold morning?

In putting what amounts to an overcoat of steel plus two layers of oil between the piston and the cooling medium, I should imagine that the piston temperature has suffered somewhat. Will the author give an idea of the increase in piston temperature of the sleeve valve compared with the poppet valve? That also would have a direct effect upon the oil cooling, and from the illustrations I noticed what was rather an outsize in oil coolers.

The author claimed another point regarding the sleeve-valve engine, namely, reduction in diameter. Will he state whether he is not rapidly approaching the day when, in order to get the air in, a little additional diameter would be welcome—in other words, with the advent of variable pitch and constant speed airscrews, the blanking space from the airscrew roots is increasing, and there is a dead area around the centre of the airscrew which, it would appear, is having to draw the air for cooling the cylinders.

In the paper he claims cooler exhaust, and by now I should say there should be some evidence from the reliability of exhaust manifolds under service conditions, which would give us an indication as to the percentage of reduction in exhaust temperature.

Mr. Mallinson : In connection with the amount of heat lost to the oil I have seen some interesting figures which quote an increase of 2 lb. per sq. in. M.E.P. at the lower end of the operating speed range and 5 lb. per sq. in. at the top end for motoring losses of a sleeve-valve engine when compared with a poppet-valve engine, under running conditions, where the sleeve has a gas load to take care of. I fancy that the disparity in the frictional losses may be greater.

These differences in frictional losses do not appreciably affect the mechanical efficiency at about 200 M.E.P., but the heat loss has to be accounted for, and I believe it goes into the oil.

I have seen a device for measuring the power required to drive the sleeve under motoring and firing conditions, and it would appear there is a definite increase in the latter case.

One further interesting point is that if an air-cooled sleeve-valve engine and a good liquid-cooled poppet-valve engine are compared at the same compression-ratio, there is practically no difference in the limiting power before detonation occurs in either instance.

Mr. Fedden, in replying to the discussion, said : Dealing with Mr. Elliott's point, I most certainly would like to subscribe to the opinion that there is an opening for both types of valve gear. Obviously that must be so. We had a stiff problem to make a new radial engine of more than one row that would breathe and give an output at all comparable with the Derby engine. As it seemed almost impossible to accomplish with four valves, I came to the conclusion that we had better tackle it in some other way.

Mr. Elliott referred to his experience with the lighting set made by Barr and Stroud, which was really a remarkable little engine. Undoubtedly the troubles with the latter were due to materials, and I would acknowledge the outstanding assistance that has been given to us subsequently by the material people in our work.

I have always been very interested in sleeve-valve engines, and had the privilege of a talk with Sir Henry Royce on the subject some years ago.

I quite agree with Mr. Elliott's remarks about noise. I can assure him—and I was very interested to hear another gentleman refer to this—of the quietness. If anything, our problems of noise as regards tuning-fork effect should be worse, but I consider that the sleeve valve is quieter in operation than the poppet valve.

I was most interested in Mr. Elliott's remarks about the respective lengths of the in-line engine with sleeve and with poppet-valve operation, and I fully realize the great importance of keeping the length down, not only from the weight point of view, but in connection with the crankshaft.

We all have our personal intimate problems, and ours is on the double-row engine. It would be very interesting—and we are hoping to do the test shortly—to run a sleeve-valve, air-cooled engine side by side with a liquid-cooled poppet-valve engine, with the same bore and stroke, to compare the possible outputs. We think quite definitely that with 5 in. bore and above we get better breathing conditions, and we can run the

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sleeve-valve engine faster and maintain power to a greater r.p.m. and higher piston speed than with the poppet valve. We are very great believers in the large sleeve valve as being the best means of getting the highest output from a large cylinder.

Mr. Ellor asked : " What does the customer get out of a sleeve-valve engine ? " For the purpose of argument I seriously submit that in our form of radial engine—and particularly with the present bores and strokes —we can get higher output than is possible with push-rod-operated valves. An overhead-camshaft engine is not a very practical form of radial engine owing to weight. Even supposing there was no advantage in output from the sleeve valve, the engine costs less and requires no maintenance at all. It is absolutely free from oil leaks (and I think it must be admitted that very few poppet-valve engines are ; even in-line engines, and certainly no radial engines), and is generally a cleaner and better job to install. Even leaving out all the other considerations it has great advantages for a war-time engine, which has to be produced in large quantities, and maintained and serviced by unskilled men.

Mr. Ellor asked what were our major troubles. That is asking a lot in many senses of the word. I think our main troubles have been what you would expect them to be—pistons, ball drive, and how to make the sleeve. As I said in the paper, it has taken our team much longer to develop these than was anticipated. I am glad we persisted because the sleeve valve gives a new field for the air-cooled engine, and I believe other firms may find it interesting for the liquid-cooled engine.

Mr. Lovesey says he has made a careful analysis of different types of cylinders, but he cannot find any advantage for the sleeve-valve engine. We have, but I must emphasize that we are attacking the poppet-valve cylinder problem equipped with push-rods. You, in Derby, are tackling the in-line engine with overhead camshafts, and are not worried about valve bounce as badly as we are. If there is no advantage for the sleeve valve in single-row engines, we have certainly been right in adhering to sleeve-valve operation when tackling the two-bank engine.

On the question of the limitation of output, we are naturally feeling our way when quoting figures. When we talk about 6·7 h.p. per sq. in. of piston area we have to watch our step not to overdo it, and whereas we have an enormous regard and respect for the Rolls-Royce engine, we do feel that that engine, when giving 9 h.p. per sq. in., is purely a racing engine possessing perhaps a 5 to 7-hour life ; but when we look at the normal outputs from R.R. engines and our own, we do not find a terrific difference. When we feel our feet with the sleeve-valve engine perhaps we may try running it a little faster.

Mr. Cantrell thinks the sleeve valve is the right solution for high-power radial air-cooled engines, and he has struck a very important point. Quite obviously we were hard put to it in designing a neat double-row engine because we did not know how to breathe fast enough on two valves. Consequently, when it came to double-row engines we went solidly for the sleeve valve.

The sleeve valve does appeal when air cooled, but I hope, and believe, that even the liquid-cooled people will consider a liquid in-line engine with this type of valve gear.

I agree with Mr. Cantrell it all comes down to what is the installation drag and installation weight of the two types of engine, and we rather think that we have got a little in hand with the engine on which we are working ; but, even if we had not, we do feel there is the neatness of the lay-out, cleanliness, and ease of production, which are so vitally important.

I will not attempt to go into a discussion on liquid cooling ; I think there is an opening for both methods of cooling.

When I spoke about multi-bank engines I meant radial engines of two, three, or four banks, and with all these layouts of radial engines I think the sleeve has big advantages.

Mr. Cantrell asked me about the material for our sleeves. We are using at the present time D.T.D. 49 B low-carbon steel, and that is working very well for the mean effective pressures and powers obtained to-day. I am not going to say we are not thinking about better materials for the future, because obviously we are.

The fins were left off at the bottom of the barrel to improve the accessibility to the nuts. No trouble has been experienced at all due to carbon formation, and this phenomenon has no bearing on the period of running between overhauls.

Again the question of noise was raised. I would like to repeat that our pilots were very impressed with the quietness.

Mr. Cantrell raises an interesting point about starting and induction-depression, and I may state that I was quite concerned about this at one time. All I can say is that with the electric starter, cartridge starter, and other crank-turning gear the conditions are very similar for the poppet-valve engine and the sleeve-valve engine, and I do not think any trouble will be experienced.

Mr. Pearson said, quite rightly, that it was better to have the sleeve and ball housing in one than to have a detachable ball housing. The change was made because of the difficulty of making the sleeve and the question of assembly. We then produced a detachable ball drive, which caused a lot of trouble before we got it right. The ball was made separate from the sleeve for two reasons : (*a*) cheapness, (*b*) assembly.

He asks whether we feel worried about the oil film with the larger size of cylinder, and I can say that up to the size of cylinder we have run ($5\frac{3}{4}$ in. by $7\frac{1}{2}$ in.) we have had no trouble in this respect at all. This moving oil film is the saving grace of the whole problem.

I should not like to answer Mr. Parkinson's point quite definitely, but I do not think we are getting more than about 1 per cent drop on the 100-hour test, and occasionally we do actually find an increase in power at the end of a type test. The same occurs with poppet-valve engines.

Mr. Towle mentions the improvement of acceleration found with Imperial Airways. Up to the present we have only had a limited experience with sleeve-valve engines on civil air lines. We feel that we have so many advantages in other respects that we shall be satisfied with an acceleration equal to that of the poppet-valve engine.

I do not think the plug position on sleeve-valve engines is quite as good, from the point of view of fouling, as that in our poppet-valve engines ; we have had to develop a special plug for the former, but I think this is a normal thing to do. There is no trouble at all with slow running and idling.

As regards fouling of the sleeve and ports, we have not had much trouble in this respect. This is bound up in two things—the material of the sleeve and cylinder, and the method of finishing the sleeve to make it round.

Mr. Read commented upon the powers. These were not stunt powers, and were obtained with the normal cooling air stream and without any water injection, but with fuel of 100 octane, or a little better than 100 octane, whilst entirely normal lubrication was employed on the single-cylinder unit.

Regarding control of swirl, I think our problem has been to control swirl sufficiently, and the difficulty is not to get excessive swirl.

Mr. Read mentioned the ramming effects of the sleeve valve and advantage of this has been taken in the shape of our induction pipes.

Mr. Dorey has put up one or two pertinent points. We were certainly

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worried about the difficulties of starting, but I think our tests in the cold chamber and in Canada have shown that there is no need for anxiety.

The "overcoat of steel" is not such a serious overcoat as would appear, and I must again emphasize Mr. Ricardo's remarks about the transparency of the sleeve and the rubbing motion of the oil film, which is the real crux of that problem. As I have said, the piston has been one of our problems, but I think that, generally speaking, our piston problems are about the same for sleeve and poppet-valve engines of equal output. We have never done any piston temperature comparisons, so I cannot say anything about that.

In regard to oil cooling problems, I think one has to be fair, and when comparing these problems one must always realize what the output of the engine is.

As regards heat balance, we consider the heat to oil is 2 per cent, to exhaust 45 per cent, to cooling and friction 23 per cent, and to useful power 30 per cent, making a total of 100 per cent. We find that the oil consumptions of our " Mercury " and " Perseus " engines are about the same—6 to 12 pints in both cases. The oil circulation of the " Perseus " is higher than that of the " Mercury," chiefly because we have a greater output from the former, and when one considers the way the oil circulation has gone up on the radial air-cooled Amercian engines, I do not think there is any snag in this respect on the sleeve-valve engine.

I do not think I claimed that we reduced the diameter of our engines with the sleeve valve. For a given swept volume the diameters of the two types of engine are about equal.

I entirely agree with Mr. Dorey's remarks about the diameter of engines, and I consider we have estimated fortunately in choosing the diameter of 47 in. for the " Taurus." Those people who try to reduce the diameters of their double-row engines excessively are up against the cooling problem fairly seriously. I think that to cool some of these engines, schemes such as the ingenious arrangement on the De Havilland " Frobisher " will have to be employed.

We think we have a cooler exhaust, insomuch as we can run about a half to three-quarters compression-ratio higher than with the poppet valve. We do not know enough about exhaust rings yet, because poppet-valve exhaust rings last a long time—anything up to about 2,000 hours—and we have not yet had long experience with sleeve valves in service. I feel sure we are getting cooler exhausts. We have done a lot of temperature tests on the bench.

In reply to Mr. Mallinson, the mechanical efficiency is pretty high on all radial engines owing to the type of bearings. There is no measurable difference between the " Perseus " and the " Mercury."

In regard to detonation, I do not think we are likely to experience any trouble there. We think that probably the sleeve-valve engine takes to a spot of detonation more kindly than the poppet-valve engine. We have made some tests with remarkably weak mixtures owing to lack of experience, and the way the engines have tolerated these, and the way the sleeves have operated, has been very remarkable. I do not anticipate any difficulty in this respect.

In view of the progress made I am quite convinced that the sleeve valve is the best line of attack, and although we did feel worried about four or five years ago, I now feel that we have worked along the right lines.

(Coventry Centre.)

Lt.-Col. L. F. Fell, in opening the discussion, said : This is one of the most important papers on aero-engines that has been presented since the War. It describes the development of what is really a new technique for aero-engine development, and the progress which has been made reflects the very greatest credit on the author and his staff.

We may not all be convinced that the sleeve valve will take the place of the poppet valve, but I think we must all admit that the sleeve valve has most certainly come to stay. So far as I am concerned, I am afraid I am not convinced that it is going to take the place of the poppet valve altogether, and I have three points on which I should like to ask the author for further information to help me make up my mind whether it will or whether it will not :

(1) Aircraft constructors still buy their engines by the lb. and not by the litre. Is it a fact, or is it not a fact, that the sleeve valve, at any rate, as at present developed, is slightly heavier than the poppet valve of the same power ?

(2) On the question of simplicity, I notice that the photograph comparing the cylinder itself with its sleeve, and a four-valve poppet cylinder (Fig. 27, Plate XXXV), does not contain the sleeve-driving mechanism. I have a feeling that if this were added and the comparison made with the equivalent parts for the four-port poppet valve cam-operating mechanism, that in numbers of parts there is not a very great deal of difference.

So far as simplicity of manufacture is concerned, I think there can be no doubt whatever that the two-valve poppet cylinder is a very much simpler production proposition than the sleeve. As the author mentioned, I had to do with the beginning of the sleeve valve in the after-War period, and my impression is that it has taken over 10 years to develop the technique of the production of the sleeve valve, and it still is not a job which could be put out to anybody coming into the business new, with the expectation that results would be obtained as readily as if the manufacture of poppet valves were involved. I should like, therefore, to have some further remarks on the actual difficulties of production of sleeves.

(3) The other point which I think was not mentioned is the question of oil consumption. I have the impression that the oil consumption of the sleeve-valve engine must always be considerably greater than the poppet valve, because there are two surfaces to lubricate at high temperature, instead of the one as in the poppet valve. I should like, therefore, to hear something further about relative oil consumption of the sleeve-valve and poppet-valve engines.

Mr. A. C. Sampietro : Most of the advantages claimed for the sleeve valve are based on comparison between the latest practice on the single-sleeve engine and engines which, although of a very successful design, do not represent the best of poppet-valve production. Should we compare one of the first sleeve-valve engines made by the author's Company and poppet-valve units of very recent design very different conclusions might be made. I cannot help thinking that had this research work been carried through under more normal commercial conditions, the results obtained might have been found wanting in respect of the cost.

I should like to ask the author how the portion of frictional b.h.p. required to drive the sleeve varies in function of load and speed in a single sleeve-valve engine ; Fig. 29 gives only a representation of starting conditions.

It is known that while the power required to operate a poppet-valve gear is very nearly a linear function of speed, and at any given speed increases but slightly with load, this does not appear to be the case with a sleeve valve. There is a very considerable increase of sliding surfaces, and the side thrust of the piston is transmitted through the sleeve to the

(Mr. A. C. Sampietro.)

cylinder barrel. On the usual assumptions, the frictional b.h.p. required in this case should be nearly a cubic function of speed, and a linear function of side-thrust ; but I should be very grateful if I could be enlightened on this subject.

At the end of page 619 the author gives some figures on ultimate performance reached ; so far, good as these are, engines were flown a few years ago which did show even better results—they were, however, in-line water cooled, although some in-line air-cooled units are nearly as good.

May I enquire what was the life of the piston in the experimental engine referred to in this part of the paper ?

In the last line of page 612 the author states " during one of the recurring periods when the in-line air-cooled engines came into the picture." Somehow I always remember successful in-line air-cooled engines being built, and does not the author think that even as an air-cooled unit the in-line engine is here to stay ?

Lieut. A. E. Bush : I have been closely in touch with the sleeve engine from the very earliest days, and while I cannot agree with all that the author has said about the double sleeve engine, I do appreciate the reasons for changing.

I would like to ask for further information regarding lubricating arrangements, and the relative oil consumption, as compared with the poppet valve. In the double-sleeve valve engine at the time of highest pressure there was very little motion in the sleeves. It does seem to me that there may be a greater loss with the single-sleeve valve due to this. I would like to know whether any trouble was experienced from this cause.

Mr. Geo. H. Lanchester : Lieut. Bush mentioned the question of lubrication. The author does not say much about lubrication of the single-sleeve engine. Does this imply that he has no troubles with lubrication, or if it does not, can he give us any information of what the troubles were, and how he has got over them ?

Early in the paper there is wording which implies that the poppet-valve improvements are the result of fortuitous circumstances in relation to materials. This is not quite fair to the poppet-valve designer. When the sleeve-valve Knight engine became an established design, it acted as a stimulus to the designers of poppet engines, and the improvements were the result of very hard and strenuous search for better materials, and better design of cams, of valves, valve port shapes, and valve-actuating mechanisms, thus the sleeve-valve engine helped to bring it to its present state of development.

I think that the author is fairly near the mark in his contention that the poppet-valve design has come pretty nearly to its final state of development. Unless anything unforeseen in new materials is introduced, it seems difficult to forecast any further improvements that can be made with poppet engines, whereas the sleeve valve seems to have greater possibilities of further development, and it is possible, assuming there are no lubrication difficulties, that it will give the poppet-valve engine its knock-out blow. If, however, it should transpire that the smoky exhaust, hitherto inseparable from sleeve-valve engines, is incurable, I see no prospect of extinction of the poppet-valve engine for automobiles.

I should like to ask the author, on the question of cold starting tests, whether the sleeve-valve engine requires a special oil at temperatures in the region of minus 20° C., and, if so, whether it will run satisfactorily on the same oil after warming up.

Mr. J. H. C. Atkins : If there is any increase in oil consumption with the sleeve-valve engine, it would seem probable that a good deal of oil would go into the combustion chamber, and gumming-up would be a result.

Then there is the large rubbing surface, and I should like to know whether the oil consumption increases to any considerable extent in service after, say, 100 hours.

There appear to be possibilities of trouble with regard to the valve-driving mechanism, for whereas that would work very satisfactorily when the parts were new, it would seem that after a time the wear in the parts, due to both rubbing and sliding in the ball, would cause trouble in the mechanism.

The clearances between the edges of the sleeve and cylinder ports are fine, or appear to be, from the film, and I could quite foresee the charge blowing straight through, and, if so, has any trouble been experienced with corrosion of the opening edges of the sleeve and the cylinder ?

Mr. P. W. Lambell : With regard to sealing of the combustion head, I noticed in the film showing the assembly of the junk head no particular care was taken with the junk head rings. Is any particular care necessary with the gap of the rings in relation to the ports on the sleeves, such as pegging the rings to avoid the ends fouling in the ports ? Is any great trouble experienced in blowing down between the sleeve and the cylinder into the crank case, thus putting up crank-case pressure, and, if so, how is this point dealt with ?

Mr. L. H. Dawtrey : The effects of Ethyl fuels in their lead attack on very hot valves are well known. Could the author give any indication of whether this occurs in the sleeve valve or has this trouble been overcome in the new design ?

Mr. L. J. Shorter : If it were decided that this type of engine could be developed for automobile work, oil consumption would be of primary importance. In the modern car engine, up to 16 H.P. or more, the usual figure is from 2,000 to 3,000 m.p.g., and sometimes more. In the sleeve-valve type of engine, consideration would have to be given to the different conditions under which this engine would work in automobiles. Wide variation in speed range would be necessary and oil economy would be demanded, especially at low speeds. The car engine must also be capable of rapid acceleration and deceleration, which is another problem in connection with oil control. It is very satisfactory to see that this aero-engine has passed through its trials and tribulations, and emerged so successfully. This may encourage some of us to think of it as a car proposition, as it would be silent and reliable in operation, but the primary point would be, could it be produced in an economical manner and whether it would give economy in fuel and oil consumption ?

Mr. C. R. Crosher : One disadvantage I have noticed with the four-in-line sleeve engine is the out-of-balance due to the weight of the sleeves themselves giving a rocking motion fore and aft. The Argyll engine was rather bad in that way. Presumably this lack of balance is cancelled out in a radial engine. I should be interested to hear if this disadvantage can be overcome in a four-in-line engine.

One point which has been raised is the question of the power absorbed in driving the sleeves in a single-sleeve engine. I remember the first Caledon single-sleeve lorry engine happened to seize the centre bearing of the sleeve-shaft just as the vehicle was being dispatched to the Commercial Show. The shaft was freed with some difficulty, but the engine ran badly and was obviously damaged. There was, however, no time left to investigate. Afterwards, this vehicle was driven under its own power from the Show in London to the works in Glasgow. On dismantling the engine we found that the seizing of the sleeve-shaft had sheared the driving key right through. Friction alone must therefore have driven the

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sleeve-shaft and the four cast-iron sleeves throughout this distance (the half-time wheel was not fitted on a taper, and was not a press fit on the shaft).

Mr. H. O. Vaux: Regarding the reconditioning of these engines, is it possible to fit any single new part to slightly worn cylinders, or does it mean a new set of parts when these are worn?

Mr. S. H. Troughton: I should be very interested to know how the life of the sparking plug compares with the plugs of normal types of comparable engines. On the car type of double sleeve-valve engines considerable trouble was experienced in keeping the plugs cool, and in the illustrations we have seen the plugs of the engines concerned appear to be deep in the head.

I should also be interested to learn whether the sleeves are grooved in any way to assist lubrication, as the illustrations show them as being quite plain. The double sleeves that used to be used were grooved in an elaborate manner.

Mr. R. A. Fearnley: Can the author give particulars of the compression ratio when operating with 100 octane fuel, and also say whether there is any comparison in reliability, *i.e.*, can the monosleeve valve be run longer than the ordinary poppet valves?

Mr. C. H. Fisher: The question raised by Mr. Fearnley in regard to compression ratios employed appears an important one, in view of the phenomenal m.e.p. figures shown in the curves. I notice from the illustrations that the shape of the cylinder head is slightly convex. Is it possible for the author to tell us something of the cylinder-head design, and whether this particular shape is a contributory cause of these high m.e.p. values on a naturally aspirated engine?

Mr. E. W. Cox: Can the author say how the cylinder barrel maintains its shape in running? I should like to have some idea of the fit of the sleeve in the cylinder, and to know whether it is necessary to have an extremely fine finish on the aluminium cylinder barrel in order to give a satisfactory running condition.

The piston and ring conditions are different. I am wondering if they have any beneficial effect on the life of the port, and whether it is necessary to adjust the port opening on assembly.

Mr. A. G. Pendrell: I should like to refer to the opening remarks in the paper about cam and spring mechanisms for high speeds. It seems to me that, due to the method employed, aero-engine designers cannot say at what portion of the cam the tappet is in contact when the valve is seated, and the valve may therefore be hammering the seat badly. Hispano-Suiza have a much better way of closing the valve on to its seat at a proper rate.

Because of this I think the author is not quite fair in comparing the sleeve-valve engine with a poppet-valve engine, the mechanism for which is not of the best design.

Mr. A. D. Comrie: How does the sleeve-valve engine compare with the poppet-valve engine when operated on inferior grades of fuel?

In the event of war, I imagine that the supplies of 87 octane fuel would be insufficient, and aero-engines would be forced to use fuels of lower octane rating. It is known that the poppet-valve engine could be made to operate satisfactorily on these fuels, and I should like to know whether the sleeve-valve engine could do also.

Mr. Evans, replying to the discussion in the absence of the author, said: In answer to Colonel Fell, we must admit that the sleeve-valve engine, size for size, of a given lay-out is very slightly heavier than the poppet-valve type in its present stage of development. There are 30 years of development behind the poppet valve, and only 10 years behind the sleeve-valve engine.

I am now thinking only of our own Bristol " Mercury " against the " Perseus " engine, which is 50 lb. heavier, both being of 25 litres capacity. A point Colonel Fell raised was on the subject of cost. I entirely agree with him, when we come to the experimental manufacturing cost of sleeve-valve parts, as we have found out ourselves. The sleeve-valve manufacturing technique has taken a long time, and large sums of money have been spent to get to the bottom of it. Our experience shows that the sleeve valve can be made more cheaply than the poppet valve, should we intend to market the engine to meet competition with the poppet-valve type. So far we have built 400 engines and are building a further large number, which I cannot disclose, for the armament programme.

I agree with Colonel Fell that theoretically the oil consumption of the sleeve-valve should be greater than that of a poppet-valve engine. In practice, however, this has not been the case. We obtain consumptions of the same order of magnitude for both types. In the case of Perseus and Mercury engines this is 6 to 12 pints per hour.

In reply to Mr. Sampietro, I can say quite truthfully that there is no measurable difference in mechanical efficiency between the Perseus and Mercury engines. Up to any speed that we have been able to motor these engines it has been found that the poppet valve and sleeve valve are comparable. I cannot give an answer on the piston life in the instance that he mentions ; Mr. Mansell will probably speak on that later.

When Mr. Sampietro compared the in-line air-cooled engine and the output obtained from it some years ago in France, as compared with the output we were obtaining from the smallest sleeve valve we were running at that time, one must remember that the former was a racing engine. Similar considerations must be made when comparing liquid-cooled engines with a life of only a few hours.

With regard to Mr. Sampietro's last question, it is agreed that the in-line air-cooled engine always has been and, in all probability, will continue to be built. The passage referred to was not meant to imply the contrary.

Lieut. Bush queried the lubrication arrangements and oil consumption. With the sleeve valve the difficulty has always been to prevent over-lubrication, but we have been able to cope with the problem. As an instance, I would mention the sleeve valve or sleeve ball rig which we use on a mechanical breakdown test. Mr. Mansell had a great deal of trouble with overflow from the sleeve of this rig, and we had to fit a cover. The single sleeve acts as a good oil pump, unless the oil flow is controlled at the bottom end.

With regard to the sleeve and piston motion, when the piston is at the top of the stroke, the sleeve is moving almost horizontally. We have had no difficulties on this score, except in one instance, when the material was " soft." With really hard sleeves we have had no trouble whatsoever.

Mr. Geo. Lanchester raised some very interesting points with respect to the effect of the early sleeve-valve engine on the acceleration of the poppet-valve development. I think that that is always the case. When someone develops a new form of mechanism, the old mechanism puts its best leg forward.

I can inform Mr. Lanchester that we have carried out cold-climate tests in both Canada and Sweden, where it is standard practice to use a very low viscosity oil, say, 62 sec. oil, specially provided for this cold-climate work.

We have started engines without external heating at temperatures down to $-20°$ C. using such oils, and it is the current practice to use

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excessive oil cooling and operate with exceedingly low oil temperatures which, with the lower viscosity oil, gives the same viscosities under operating conditions as the higher viscosity oils working at the normal and considerably higher temperatures.

Mr. Atkins queried the effect of oil consumption and ring gumming. As regards piston gumming, we have had no trouble. We used to get this trouble, however, on junk head rings, and usually found those rings either gummed in solid or partially gummed, but they looked the same after 250 hours. This trouble has also been overcome by improved ring design. In reply to Mr. Atkins' second query, we have no trouble with ball drives. The movement of that ball is such that it seems to have a most simple sliding motion. We have seen balls which have done many thousands of hours' service, and have never been renewed. We have experienced no corrosion at all on the internal or external edges of the sleeve ports or barrel ports, because they run at a low temperature. The same cannot be said of the poppet valve, certainly not at the neck. There is a certain building up of carbon round the port edges, but in view of the fact that we find as much after 20 hours as after 250 hours, it is safe to assume that the carbon is unable to remain unsupported and is blown away.

In reply to Mr. Lambell I can say that we have found it necessary to radius the edges of junk head ring gaps, but that having determined the amount of radiusing, we let them rotate as they like in the head. We find that there is no blowing past on the outside of the sleeve.

Mr. Dawtrey raised a point which is one of the chief advantages of the sleeve-valve engine. As we all know, lead attack on a poppet valve can be a fearsome thing at high temperatures. On the sleeve-valve engine, owing to the protective film of oil inside the combustion chamber, we get no lead on the sleeve. We seem to have an abnormal deposit of lead oxide, which I have not seen in a poppet-valve engine, but this does not give any trouble through incandescence. We think that the sleeve-valve aero engine ought to be particularly good with regard to hot corrosion.

Mr. Shorter's remarks are relative to the mono-sleeve valve as applied to automobiles, and I am afriad I cannot enlighten him at all. The points raised are extremely important, with regard to the introduction to car mechanisms, but we have never had any experience on this subject. I think possibly the production problem might be a difficult one for automobiles. I am not suggesting that automobile manufacturers work to coarser limits than we do, but it might be a difficult problem for mass production. It is an easy problem for aero engines. Properly tooled, you can meet any manufacturing tolerances.

In reply to Mr. Crosher, I believe that the 4-cyl. in-line would be extremely difficult. I regret I cannot give any more information on this point. Mr. Crosher's experience with the sleeve drive helps to confirm the fact that the power required to drive the sleeves is quite low.

I find it difficult to answer Mr. Vaux because our experience on reconditioning sleeve-valve engines is comparatively short. However, we do not anticipate any trouble from that aspect.

I think Mr. Mansell can answer Mr. Troughton better on the ignition troubles. On main engines the plug problem was difficult at first. We had to develop a special plug for the sleeve-valve engine, and now we get as good service as anyone in the aircraft world. Also, in reply to Mr. Troughton, there are no grooves in the sleeves.

The reason for the slight convexity of the cylinder head is that we wished to obtain a certain compression ratio and were anxious not to mask the ports. We have also tried heads with flat surfaces and found that practically no variation in power output occurred.

To Mr. Cox I would say that sleeve and barrel clearances are almost negligible. The sleeve is almost a push-fit in the barrel, but there is no difficulty in producing sleeves and barrels to the tolerances we require. The pistons and rings have no apparent effect on port life ; no adjustment is or can be made to the port opening on assembly.

In reply to Mr. Pendrell, as was mentioned in the paper, we have used overhead camshaft cylinders and made a direct comparison with the sleeve valve. It was proved conclusively that the sleeve valve was superior. The increased speeds we have been able to obtain with the sleeve valve have transferred the troubles elsewhere. We are limited on the bore, but there are other mechanical difficulties which have still to be overcome.

I think I am right in saying any drop in octane number during any particular emergency will have an equal effect on both poppet- and sleeve-valve engines if these engines are run under the original conditions. The absence of the hot exhaust valve, however, makes the sleeve valve less sensitive to detonation than the poppet.

Mr. Mansell, amplifying the reply in the absence of Mr. Fedden, said : There is the general question of oil consumption apparent in most of the speakers' comments. Before treating oil consumption specifically I would explain that the sleeve-valve engine has certain peculiar features in its lubrication ; in the case of the piston within the sleeve there are two motions, that of the sleeve in a circular path, and that of the piston with plain reciprocation. This combined motion is rather similar to the case of a car with spinning wheels, when it is known that the slightest side force will make the car skid. This feature leads to extraordinarily good working conditions for the piston and rings. Piston ring wear is virtually non-existent and no difficulties are experienced with the bearing surfaces of the piston skirts. Actually the pistons are made as short as possible when allowance has been made for accommodation of the rings and gudgeon-pin.

The sleeve driving member is also subjected to rather similar motions, in that the ball portion both slides and rotates, both on the sleeve drive crankpin and in the housing.

Due to this good bearing condition, lubrication is maintained and extremely low oil consumptions can be realized, although, as pointed out, there is an additional surface on which an oil film has to be maintained.

Sparking plugs for the sleeve-valve engine have suffered from the same troubles as in the poppet-valve type, and I do not think the conditions are more severe. The arrangement of the cylinder head is such that a flow of air is induced across the body of the sparking plug, and whilst the flow is probably not so great as with side plugs, as in the case of the " Pegasus " engine, it is probably superior to that of a liquid-cooled engine or the rear plug in a two-valve cylinder. Newer sparking plugs with the aluminium oxide type insulating material promise to give considerable further extension of the heat capacity of sparking plugs and considerable improvements have been made to the general ignition system. Actually the ignition is particularly important in the case of the sleeve-valve type, as attention is focused upon it owing to the fact that it is the only component requiring attention on the cylinder during ordinary service.

Ethyl fuel effects extend from the actual combustion chamber right to the exhaust pipe, but the sleeve-valve cylinder assembly itself has not given any difficulty in respect of corrosion. The whole interior of the sleeve and cylinder bores have an oil film maintained by the action of the sleeve and the fact that in the sleeve bore the complete length of the sleeve is swept by either the piston or junk head rings.

Finally, although the two-valve poppet-type engine has been quoted as being simpler than the four-valve and as simple as the sleeve valve, I believe there are definite limitations to this type in the large cylinder sizes

(Mr. Mansell.)

when the valves become of, say, 3 in. dia., particularly in the direction of increased speed. The power curves shown in the slides illustrate the capabilities of the large sleeve-valve cylinder in this respect.

COMMUNICATIONS.

Mr. W. Ferrier Brown wrote: I have often regretted that the merit and possibilities of the mono sleeve had not been thoroughly explored. The recent development of the Bristol Co. has now removed these regrets, and incidentally has made my "prophecy" on page 238 of Vol. XX of the Proceedings come true.

In my paper on the Development of the Sleeve-Valve Engine I stated: "Time has strengthened my opinion that, had that engine [*i.e.*, the mono-sleeve valve of to-day] been developed, it would be second to none for power, steady running, and reliability, and that it is highly probable that single-sleeve valve engines for aviation purposes will be a development of the near future."

The remarkable mean effective pressure obtained from sleeve-valve engines was indicated even in the early days, and the high figures for the modern product are a compliment to the latest developments, because the problems to be attacked and overcome must have been of a serious nature.

Referring to the paper (p. 610), it would seem to be suggested that Peter Burt, the inventor of the single-sleeve valve, was at the time of his invention associated with the Argyll Co., but that is not so, his association was subsequent to his invention being taken up by that company.

In the early designs, similar problems with regard to sleeve material and cylinder head cooling and sealing had to be faced, but the solution, with water-cooled engines, was comparatively simple.

I can well imagine the criticisms that have been levelled at this latest development of the sleeve-valve engine, but most of them have been tried before and found wanting.

Some time after the date of my paper on sleeve engines, the annual inter-Centre discussion between Birmingham and Coventry Graduates took place. The Birmingham Centre proposed the motion that "the day of the sleeve-valve engine is over," which was lost, and now time has proved the truth of that decision.

Mr. C. F. Dendy Marshall wrote: In the list of disadvantages of the poppet-valve engine at the beginning of the paper, one is omitted which is most important, namely, the large amount of power absorbed in compressing the valve springs, which there is not time to recover *via* the camshaft on their rebound.

I would suggest that some inclined slots in the lower part of the sleeve would be advantageous. They would lighten it, and perhaps help lubrication.

MONO-SLEEVE VALVE FOR AERO ENGINES.

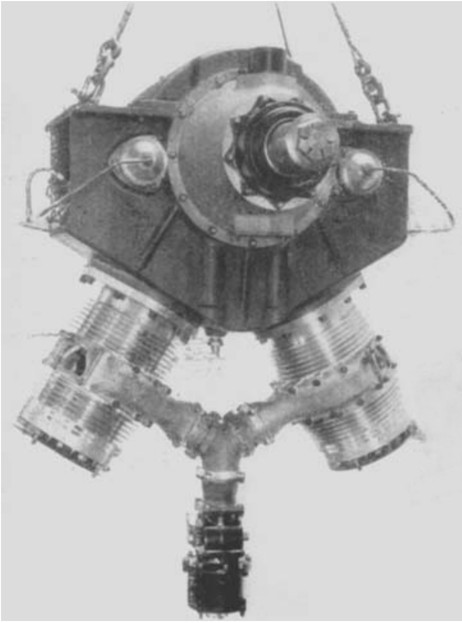


Fig. 1.
For text reference, see page 612.

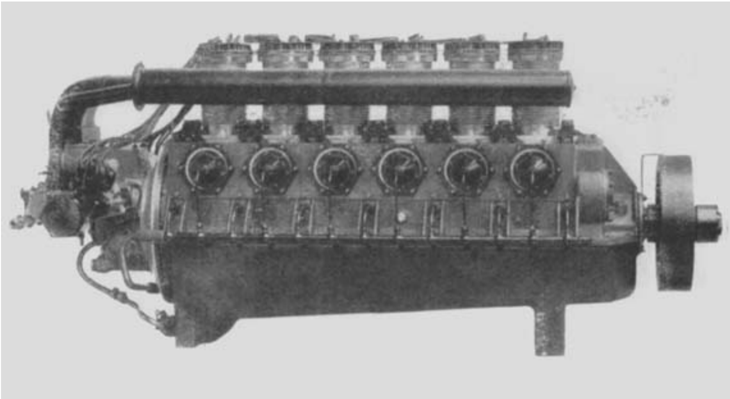


Fig. 3.
For text reference, see page 613.

MONO-SLEEVE VALVE FOR AERO ENGINES.

Fig. 5.

For text reference, see page 615.

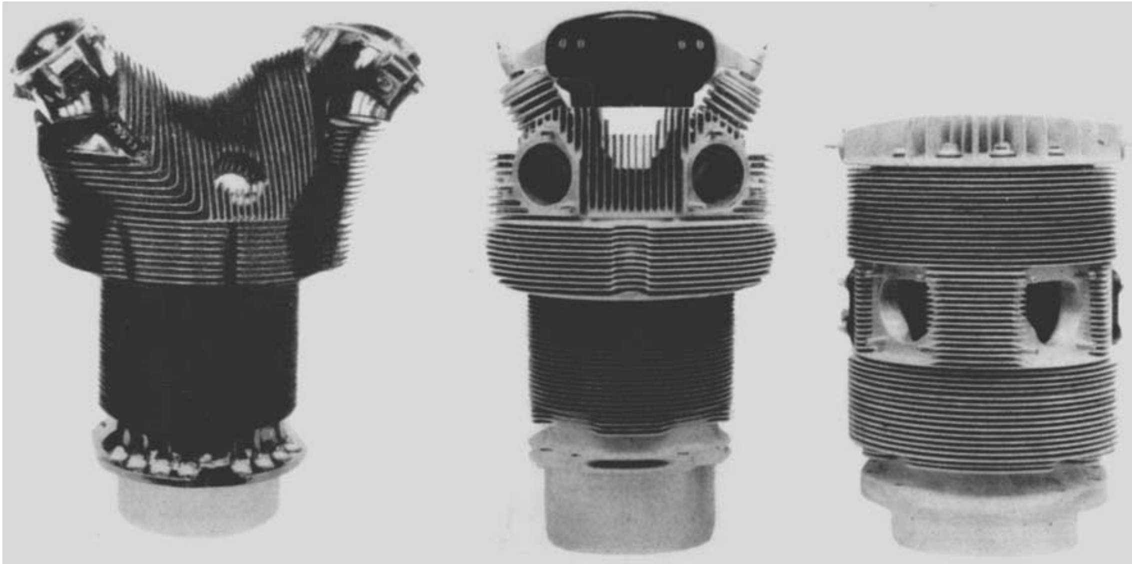


Fig. 8.
For text reference, see *page 616.*

Cylinder type	AMERICAN	MERCURY	PERSEUS
Valving	Two poppets with push rods	Four poppets with push rods	Sleeve
Bore and stroke	$6\frac{1}{8}$ in. × $6\frac{7}{8}$ in.	$5\frac{3}{4}$ in. × $6\frac{1}{2}$ in.	$5\frac{3}{4}$ in. × $6\frac{1}{2}$ in.
Displacement	202·6 cu. in.	168·8 cu. in.	168·8 cu. in.
Weight	47·576 lb.	46·0 lb.	42·1 lb.

Perseus weight includes :—Cylinder head, sleeve, ball and housing.
Mercury weight includes :—Cylinder, head, rocker and valve gear, push rod assembly.

MONO-SLEEVE VALVE FOR AERO ENGINES.

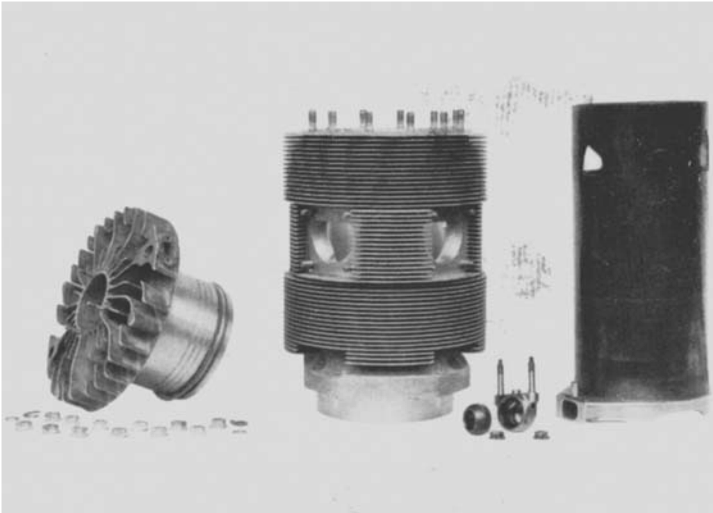


Fig. 12.
For text reference, see page 622.

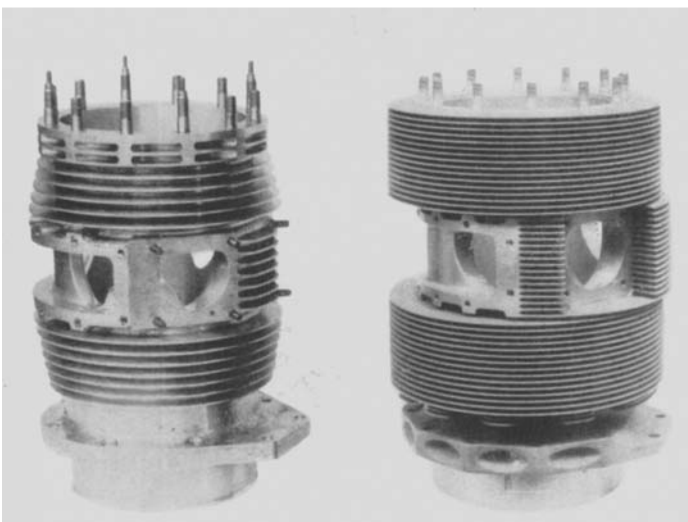


Fig. 13.
For text reference, see page 622.

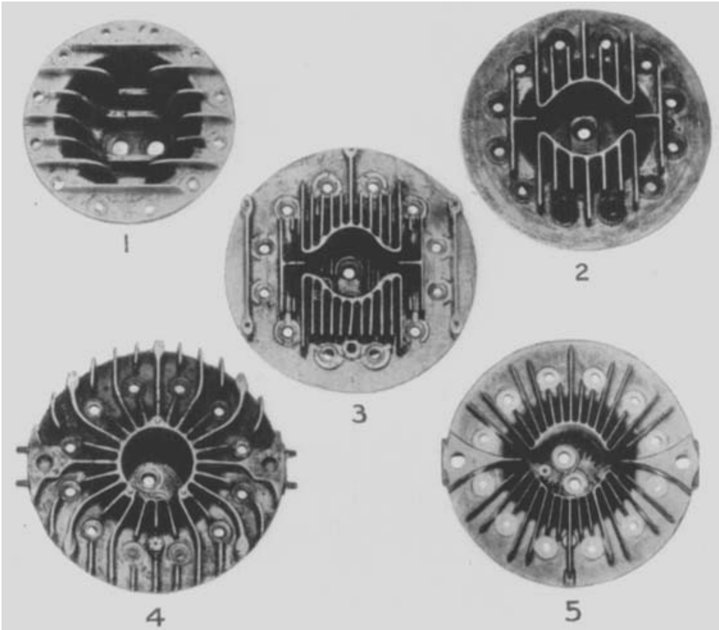


Fig. 14.
For text reference, see page 622.

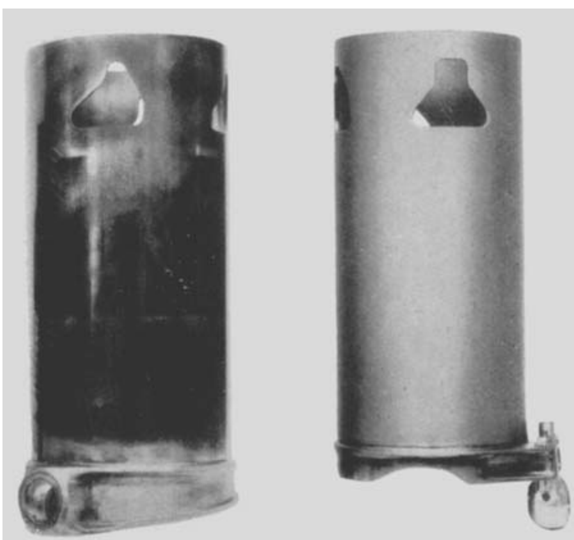


Fig. 15.
For text reference, see page 622.

MONO-SLEEVE VALVE FOR AERO ENGINES.

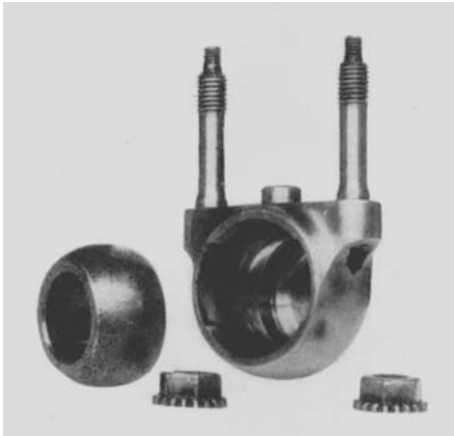


Fig. 16.
For text reference, see page 623.

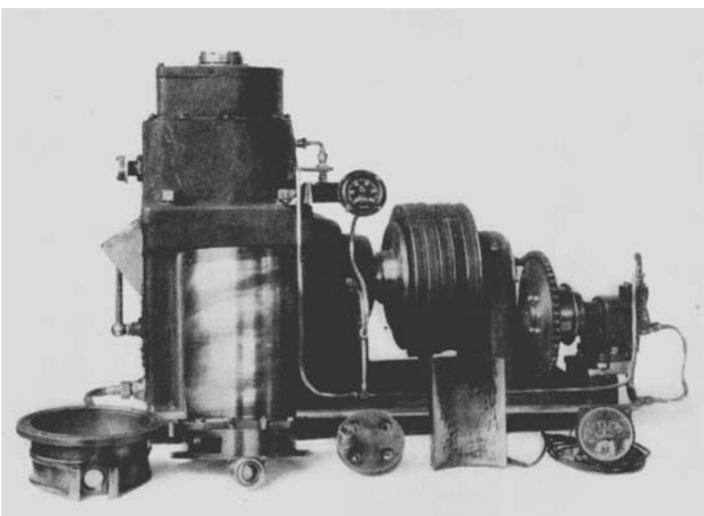


Fig. 18.
For text reference, see page 623.

MONO-SLEEVE VALVE FOR AERO ENGINES.

Fig. 17.

For text reference, see page 623.

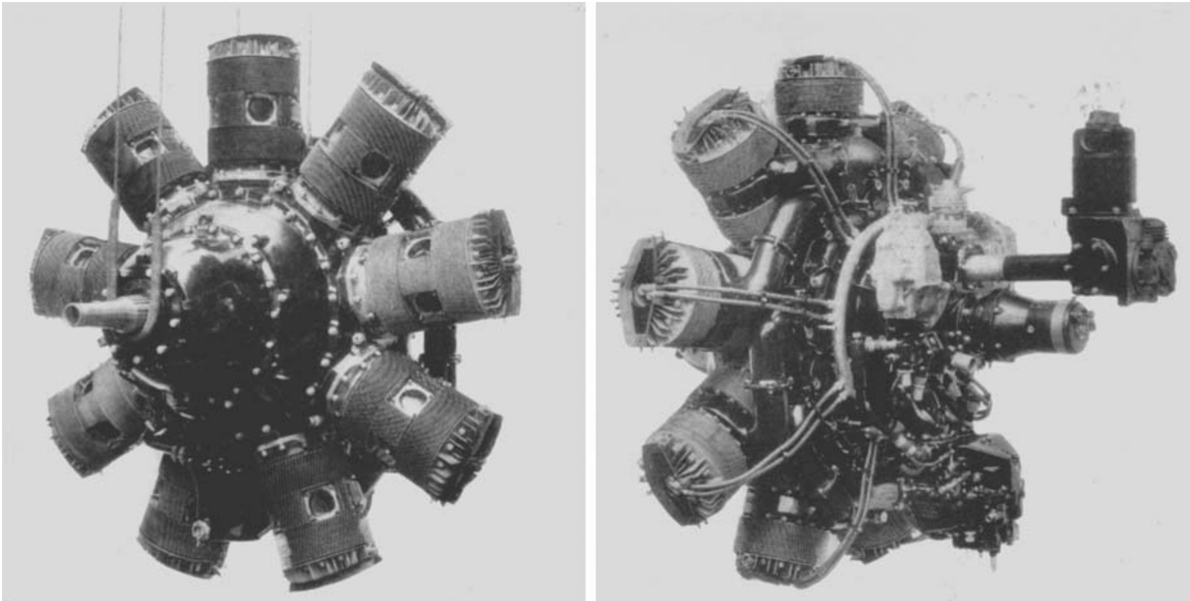


Fig. 19.

For text reference, see page 624.

MONO-SLEEVE VALVE FOR AERO ENGINES.

Fig. 20.—Westland "Lysander."
For text reference, see page 624.

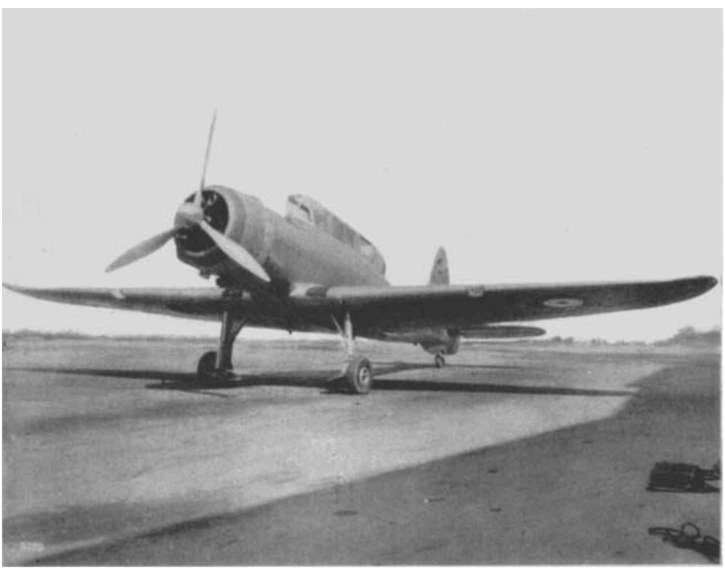


Fig. 21.—Blackburn "Skua."
For text reference, see page 624.

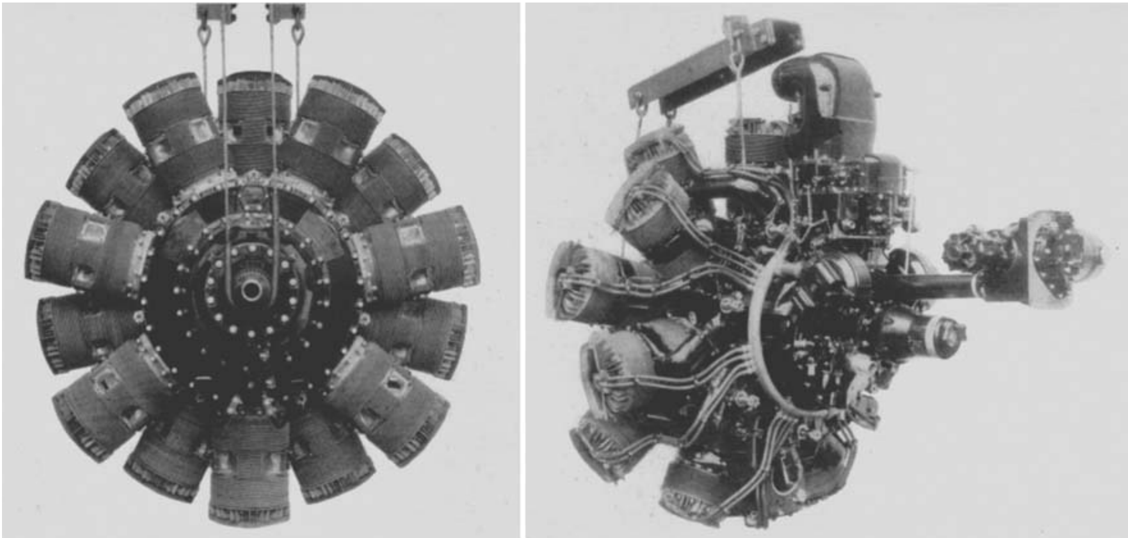


Fig. 22.

For text reference, see page 624.

MONO-SLEEVE VALVE FOR AERO ENGINES.

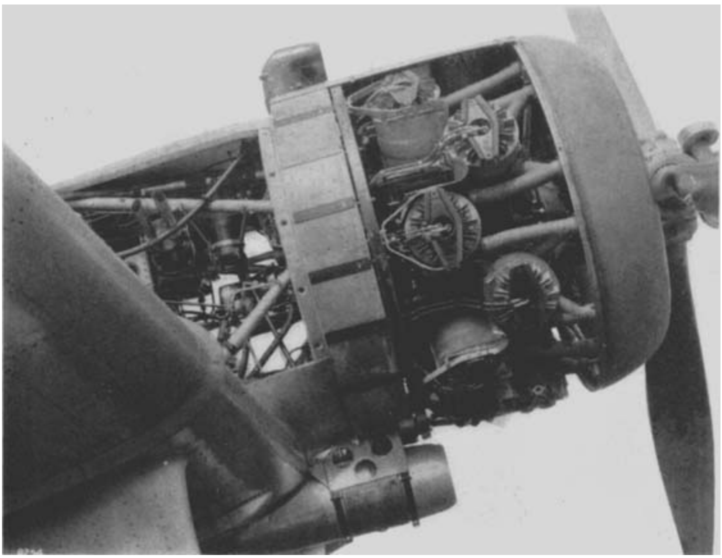
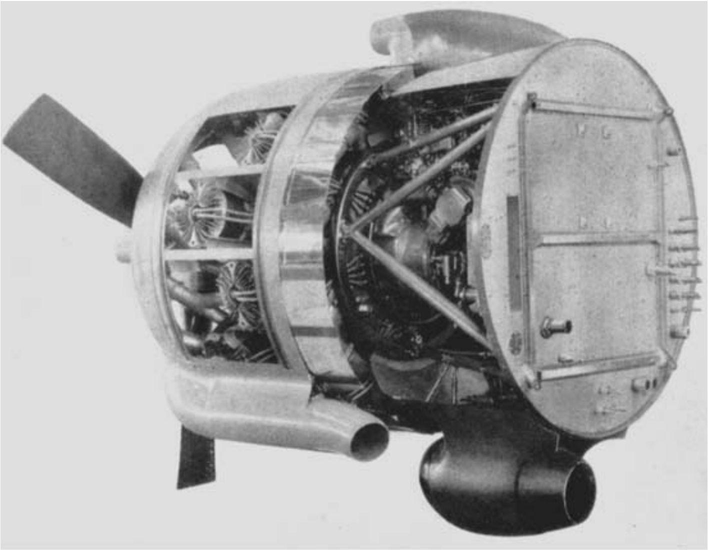


Fig. 23.

for text reference, see page 624.

MONO-SLEEVE VALVE FOR AERO ENGINES.



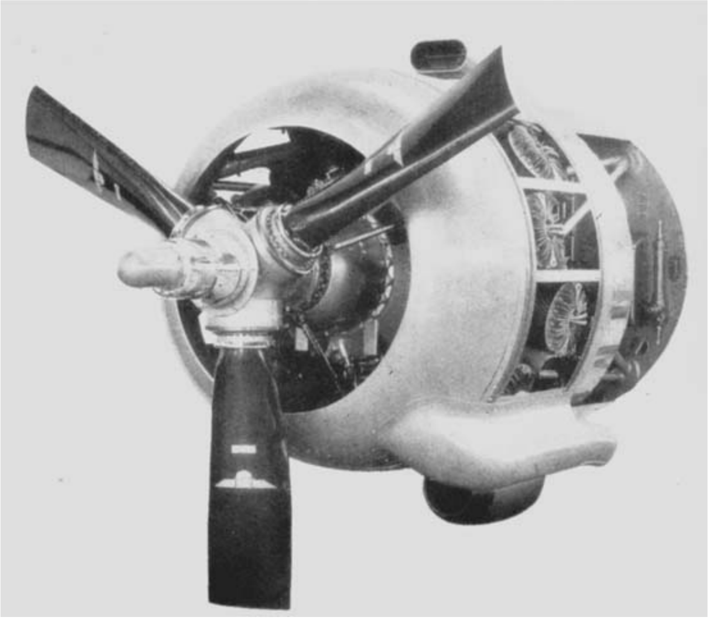


Fig. 24.
For text reference, see page 625.

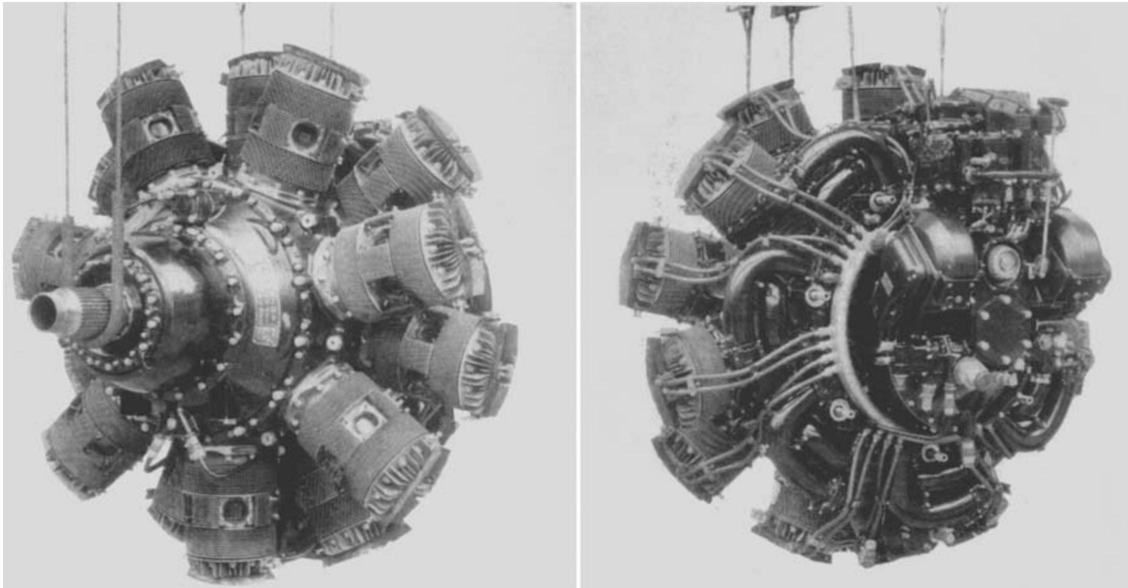
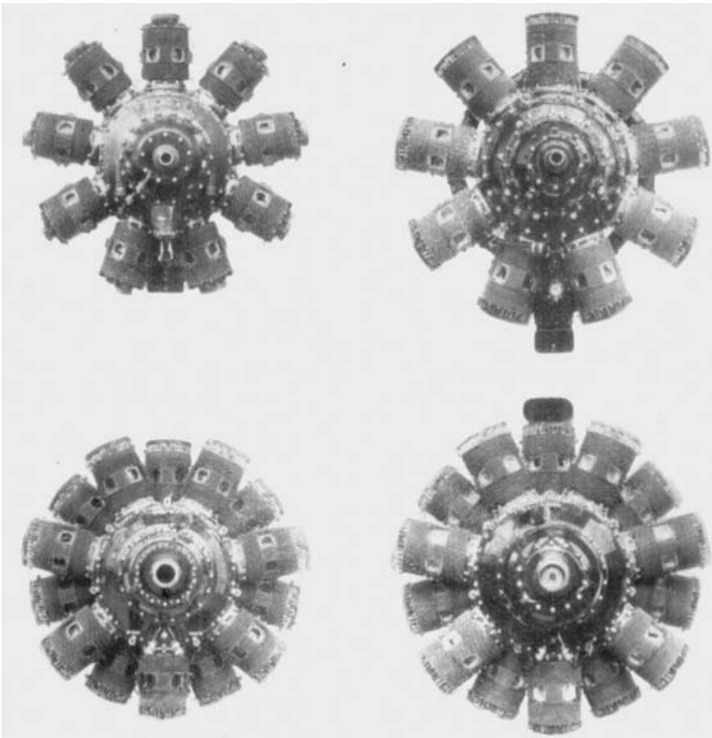


Fig. 25.

For text reference, see page 625.

MONO-SLEEVE VALVE FOR AERO ENGINES.

	AQUILA.	PERSEUS XII.
Capacity : Litres	15·6	24·9
Cu. in.	950	1,520
Take-off power	—	830
Maximum rated power	—	905
Weight	795	1,105



	TAURUS.	HERCULES II.
Capacity : Litres	—	38·7
Cu. in.	—	2,360
Take-off power	1,010	1,300
Maximum rated power	1,065	1,375
Weight	1,280	1,650

Fig. 26.

For text reference, see page 625.

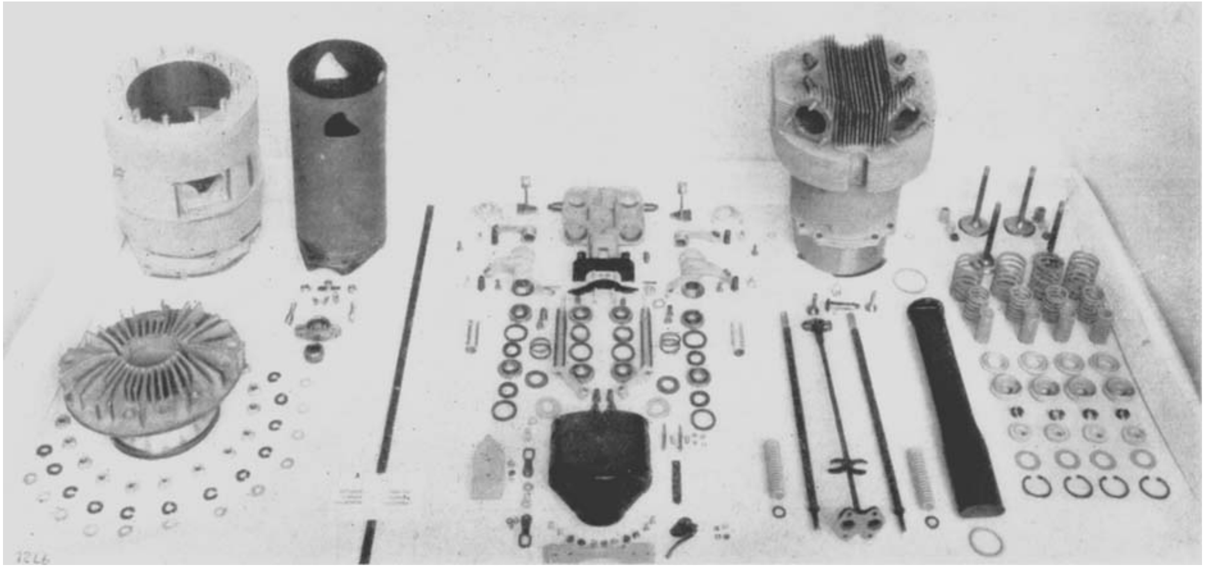


Fig. 27.

For text reference, see page 626.