Comparison of Sleeve and Poppet-Valve Aircraft Piston Engines

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April 2005

1. Preface

The development of the high output aircraft piston engine through the first half of the twentieth century represents a high point in the art of mechanical engineering. No single mechanical device had advanced its various disciplines as much as during that period; nor has any since. The piston engine, as it existed at the beginning of the age of powered flight, was inadequate to the task and required Herculean developmental efforts to meet the constantly increasing demands of larger and faster aircraft. The coincidence of two world wars during its evolution added greatly to this effort but also meant that there was enormous government support available for every aspect of engine development, which resulted in advances in most of the disciplines of mechanical engineering. These advances were the product of work carried out at the engine companies, at government facilities, and in universities.

My own career as a mechanical engineer came too late for any professional involvement with aircraft piston engines, but it has been almost exclusively involved with engines of many types and not restricted to a particular discipline. I suppose my early experiences around aircraft at the small airport my father managed and close observation of the giant Strategic Air Command bombers stationed nearby with their six twenty-eight cylinder engines had some influence on my subsequent interest in these engines, but the primary catalyst was in being associated with certain of the professors at the university I attended, the Massachusetts Institute of Technology. Professor C. Fayette Taylor was my advisor and I worked in the Sloan Laboratory for Aircraft and Automotive Engines, of which he was the director. Taylor had had extensive experience in the aircraft engine field dating back to the early post World War I period both directly, for the army at McCook Field and Wright Corporation, and as a consultant after he took up his post at M.I.T. At the time of my arrival (c 1956) the Sloan Laboratory still contained a significant collection of aircraft engines dating from WWI through the early 1950s, and the associated drafting room contained many components from then modern aircraft engines to illustrate good design practice. Taylor's teaching technique involved generous doses from his consulting experience, which was in large part, connected to aircraft engines. A very significant portion of the sponsored research at the Sloan Laboratory had been related to aircraft piston engines in as much as it was sponsored by the National Advisory Committee for Aeronautics (NACA) and led to the establishment of the Gas Turbine Laboratory directed by Edward S. Taylor, C.F. Taylor's brother, who had also done much work in aircraft piston engines and used this experience in his teaching technique as well.

I also had the experience of flying in commercial aircraft before the transition to turbo-prop and jet-powered aircraft. The dramatic change in aircraft performance with the advent of the gas turbine served to point up the tremendous strain under which the piston engine had been laboring since the time of the Wright Brothers.

The seeds were planted and more leisure time in recent years has allowed them to germinate. I began by reading the available histories of aircraft piston engines and have found them useful. They are, however, directed at the general reader, following a chronological development with considerable emphasis on the many detours and blind alleys this development occasioned. As an engineer reading these accounts I inevitably felt some significant analysis was missing. Even such a fundamental question as engine induced aircraft drag with liquid-cooled versus air-cooled engines appears to remain unanswered. In many cases it appeared that claims made at the time of the introduction of an innovation are simply repeated in the historical account rather than analyzed, even in cases where the innovation was later abandoned, leaving the question as to why.

My own intention is to attempt to analyze various aspects of aircraft engine development. This implies looking at some aspect of this development that I find interesting and trying to resolve questions that arise. This approach to engineering history is, as far as I can tell, novel, but I have few illusions that I am in the vanguard of a revolutionary movement. Significant engineering analysis is often required, which limits the number of people who are likely to read it, and engineering insight is required even to realize that some such questions are of any interest.

In the case of the present monograph I have chosen the sleeve-valve versus poppet-valve story because it should be of general interest to the enthusiast of aircraft engines and most of the arguments can be understood by non-engineers, although the analysis may be out of reach to some. The story also illustrates the difficulty in introducing a major variation into the design of a device already well along in its evolutionary development, a subject that should be of interest to engineers and particularly students of engineering. Historically such innovations have often been driven by the force of a single personality, which, if given the resources, could take it far beyond what would be achieved if the idea was promoted by a team of dispassionate engineers. In my experience such individuals are fairly rare but they have an outsized influence; sometimes for the better and sometimes not. Harry Ricardo and Roy Fedden were two such personalities, without whom the sleeve-valve aircraft engine would most probably have never happened.

2. Introduction

By 1918 a clear outline of how the high output aircraft engine would evolve had begun to emerge. Large liquid-cooled engines had begun to move to the cast mono-bloc construction which would characterize them until the end of the era, gradually abandoning the individual forged steel cylinder with welded water jackets that had been typical through World War I. The rotary air-cooled engine built in very large numbers during the war had become an obvious dead end. Its inefficiency due to windage losses, oil consumption and excessive rotating inertia were insurmountable obstacles to higher horsepower. Systematic research into air cooling of fixed cylinders carried out in Great Britain by Professor A. H. Gibson and Sam Heron at the Royal Aircraft Factory led to the design of a 300 hp fixed air-cooled radial engine that incorporated most of the design features of all future radial engines. This engine would become the Armstrong- Siddeley Jaguar after the British banned aircraft and aircraft engine production as a government activity and the Royal Aircraft Factory became the Royal Aircraft Establishment (RAE). Sam Heron immigrated to the U.S.A. shortly after WWI where he and C.R. Lawrance, a pioneer of fixed air-cooled engines in the U.S.A., eventually joined forces at the Wright company. This resulted in a very successful line of engines at Wright and, a few years later with the removal of part of the team to Pratt & Whitney, the two most important firms building large air-cooled aircraft engines in the U.S.A.

Another British firm, the Bristol Aeroplane Co. had, at the end of WWI, absorbed the aircraft engine portion of Cosmos Engineering Co., which brought Roy Fedden and his fixed nine-cylinder air-cooled radial to that firm. Fedden's engine was somewhat different in configuration than those whose origins lay at the Royal Aircraft Factory, containing two inlet and two exhaust valves rather than one each as in the other engines. It also retained a closed steel cylinder with an aluminum cylinder head clamped to it rather than the open steel cylinder with a threaded and shrunk cylinder head design from the Royal Aircraft Factory. The Armstrong-Siddeley Jaguar and Bristol's Jupiter were the two most important large air-cooled engines of the early 1920s.

As these new engine designs were evolving in the late WWI period, Harry Ricardo established a research laboratory in Shoreham, England. Ricardo and Co. is still in existence and is world renown. Ricardo had done pioneering work in the development of an understanding of detonation in spark ignition engines and generous support from Shell Oil Co. helped to launch the fledgling company. Ricardo also had generous support from the British Air Ministry to do pretty much as he pleased if it might result in significant improvement in the efficiency of aircraft engines[2]. Ricardo knew that an engine's compression ratio and hence its efficiency was limited by detonation. He was also of the opinion that the poppet exhaust valve probably limited the compression ratio due to its high temperature. This thought apparently led almost directly to the idea of replacing the hot poppet-valve with a sleeve-valve which should allow much lower surface temperatures in the combustion space and allow higher compression ratios.

Ricardo chose to pursue the single sleeve-valve embodied in the patents of Peter Burt and James McCollum but was unable to get much useful technical information on their design aside from what was evident in the Argyll automobile engine of some years before, and so began a long and very impressive piece of research and development. Early experiments indicated the possibility of operating at one compression ratio higher with the sleeve-valve, which would have meant a very significant improvement in power and efficiency at a time when typical compression ratios were five-to-one. This work is detailed in the many editions of his book[1] and was largely confined to liquid-cooled engines.

In the later 1920s the British Air Ministry extended its support of the sleeve-valve to the Bristol Aeroplane Company who, presumably, had complete access to Ricardo's work. Thus were joined two very dynamic and forceful personalities in a development which, if successful, would result in a major deviation from conventional practice in aircraft engine design. Fedden had already collaborated with Ricardo in the early 1920s (also with British Air Ministry support) to solve a major problem with the crankpin bearing of his Jupiter engine. The solution, a floating bushing between the master rod and crankpin rather than the conventional bushing fixed in the master rod, led to the adoption of a one piece master rod and built-up crankshaft. Ricardo claimed credit for this innovation[2], but it was not the first departure from normal practice by Fedden and Bristol. In addition to the four-valve cylinder head (rather than the conventional two-valve head of the air-cooled engines that traced their lineage back to the RAE), early versions of the Jupiter engine had employed a unique counterweight arrangement to reduce the crankpin bearing load. This consisted of counterweights attached to the master rod big end which could move in a slider arrangement on the fixed crankshaft counterweights. This device had apparently been abandoned when the floating crankpin bushing was developed by Ricardo. All of these innovations and departures from the mainstream of engine development indicate Fedden was likely to have been quite susceptible to the idea of the sleeve-valve, particularly since he was having trouble adapting his four-poppet-valve arrangement to a two row engine[3]. This meant Bristol must revert to a conventional two-valve design or adopt a different approach or be limited to relatively low horsepower. The Armstrong- Siddeley Jaguar was already a 14-cylinder two-row engine of smaller cylinder displacement than the 9-cylinder single-row Jupiter and by the late 1920s larger two-row radials were on the drawing boards at other firms.

It appears that the impetus for developing the sleeve valve for aircraft engines was provided solely by Harry Ricardo who encouraged the British Air Ministry to finance his development activity. With encouraging results from his work the Air Ministry was no doubt looking around for an engine manufacturer to adopt the sleeve valve and found a likely candidate in Bristol and Roy Fedden. Both Napier and Rolls-Royce adopted the sleeve valve in the U.K. well after Bristol, but their designs do not appear to differ much from Bristol practice. They utilized the same crank mechanisms for operating the sleeve, and the number and configuration of the sleeve-valve ports appear very similar. Ricardo went on to design a number of advanced liquid-cooled sleeve-valve aircraft engines[1], notably a two-stroke engine that never saw production. They also designed a high speed compression ignition sleeve-valve engine for industrial applications and were able to market their design to manufacturers; Peter Brotherhood of the U.K. was among them. Activity in the U.S.A. was much more limited and did not lead to a production engine. Continental built an air-cooled

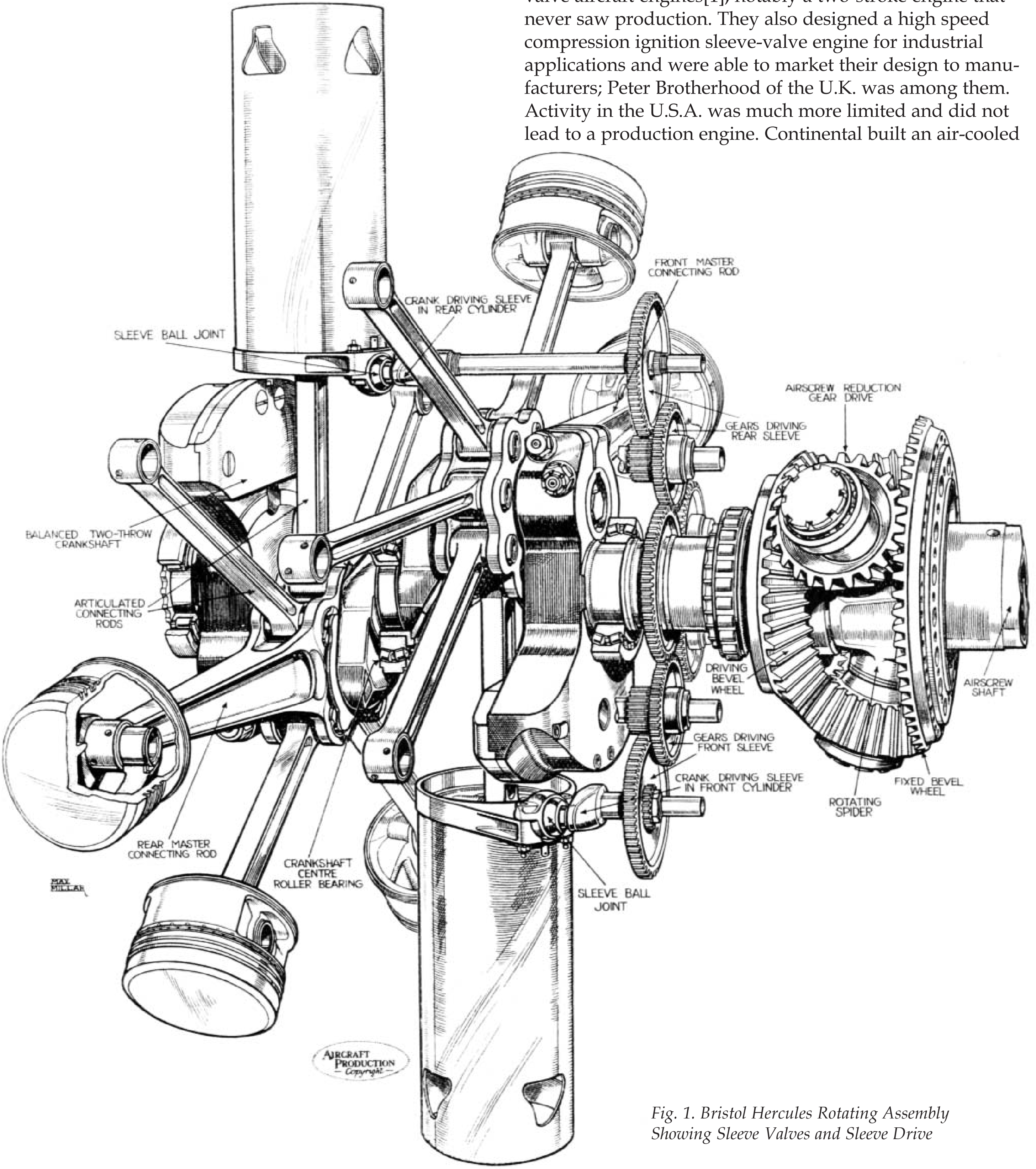


Fig. 1. Bristol Hercules Rotating Assembly Showing Sleeve Valves and Sleeve Drive

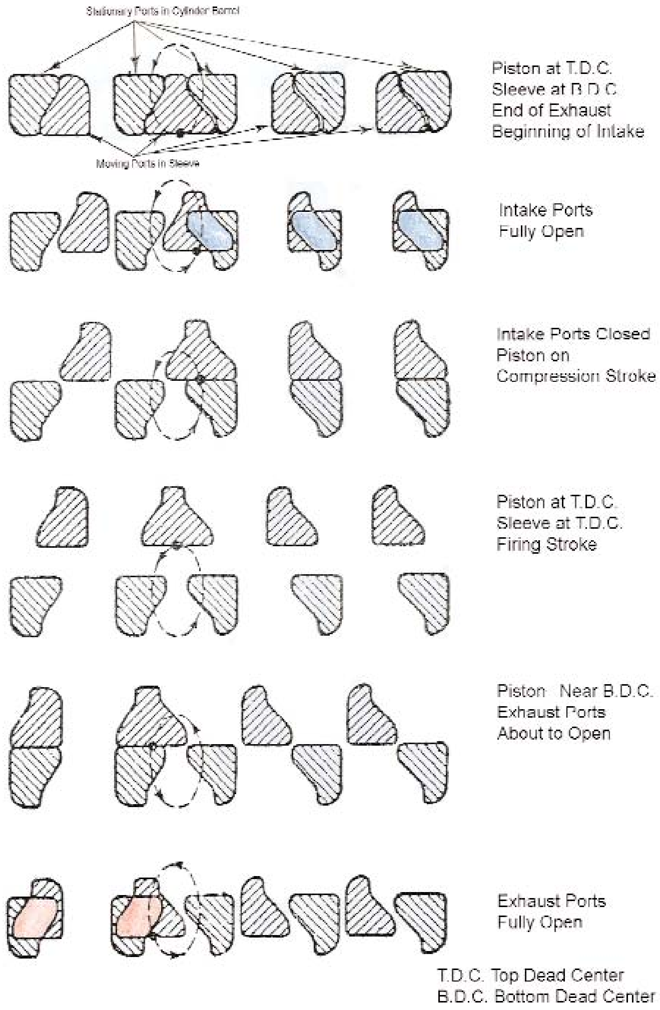


Fig. 2. Porting Sequence: Four Stroke Sleeve-Valve Engine

sleeve-valve radial engine in the late 1920s and then abandoned the project[4]. Pratt & Whitney (P&W) carried out extensive development work on liquid-cooled sleeve-valve engines but this was also abandoned[5].

While a detailed description of the technical development of the single sleeve-valve for aircraft engines would be a worthwhile contribution to the history of mechanical engineering, it is very much beyond the scope of this paper. The author's intent is to compare the characteristics of the well developed poppet and sleeve-valve engines so as to examine the results against common criteria and come to some conclusions regarding the claims made for each arrangement. Publications concerned with the history of the high output aircraft piston engine and written after that era had passed tend to repeat claims made by proponents of one valve arrangement or the other when that era was still in full swing. This is especially true of claims for the sleeve valve. There is very little hard analysis given to show how the two types actually measured up to each other, and whether or not the claims for the sleeve-valve were justified. The author will also attempt to examine the characteristics for which few claims were made in favor of the sleeve-valve, in particular size and weight, the two most important variables for an aircraft engine. Any deficiency in this area must be made up in operating at higher brake mean effective pressure (BMEP) (see Appendix I) and piston speed, which implies higher mechanical and thermal stresses.

In what follows, more emphasis is placed on the air-cooled sleeve and poppet-valve engines than on liquid-cooled engines. This is mainly due to the fact that only air-cooled engines survived in the commercial market to the end of the era. The liquid-cooled sleeve-valve engines were designed for military applications and only one, the Napier Sabre, saw any significant production volume.

Table 1
Dimensions and Performance of Two Sleeve-Valve and Two Poppet-Valve Engines
Circa 1958

		Bore B (in)	Stroke L (in)	Number of Cylinders n	Displacement V_D (in^3)	Compression Ratio r	Fuel Performance Numbers P.N.	Take Off Horsepower BHP	Take Off Engine Speed N (rev/min)	Take Off Brake Mean Effective Pressure BMEP (psi)	Take Off Piston Speed S (ft/min)
Sleeve Valve	**Bristol Hercules 815**	5.75	6.50	14	2363	7.0	100/130 A.D.I.	2300	2900	266	3142
	Bristol Centaurus 873	5.75	7.00	18	3272	7.2	100/130 A.D.I.	3150	2800	272	3267
Poppet Valve	**Pratt & Whitney R-2800 CB17**	5.75	6.00	18	2804	6.75	108/135 A.D.I.	2500	2800	252	2800
	Wright R-3350	6.125	6.3125	18	3348	6.5	115/145	2800	2900	228	3051

A.D.I. = Anti Detonation Injection

The ratings of commercial aircraft engines in the post World War II period are assumed by the author to be fairly representative of what they were actually asked to do in an aircraft. This allows comparing them on a reasonably equal basis, despite differences in their country of origin and manufacturer. Military engine ratings are more problematical, since the rating systems are likely to vary significantly and differing standards of service life and probability of failure are likely to apply, depending on the country of origin.

3. Sources and Acknowledgements

Unless otherwise noted the horsepower, weight, and dimensions of engines in what follows were obtained from *Jane's, All theWorld's Aircraft* for the appropriate year.

The author is grateful to the Archives of the Massachusetts Institute of Technology for permission to use M.I.T. thesis material and information contained in Professor C.F. Taylor's files, and to Ricardo UK for its permission to use Figures 4 and 5. Specific references to this material are made in the text and each source is listed in the References section.

4. Sleeve-valves

Figure 1 shows the internal components of the Bristol Hercules sleeve-valve aircraft engine. In all other respects, it was very similar to a poppet-valve engine, with two rows of air-cooled cylinders, one-piece master rods and a three-piece built-up crankshaft. Two of the fourteen sleeves are shown in Figure 1 along with their ball-crank operating mechanism. As the name implies, the sleeve was ported to allow passage of mixture into the cylinder and combustion products out through passages in the stationary cylinder barrel wall. The sleeves for the Bristol Hercules, which had a bore of 5.75", had a wall thickness of 0.139" and were 14" long[6]. They were made from alloy steel forgings and weighed about 18% of the piston assembly weight (author's estimate).

Figure 2 is a developed view of the porting sequence of the sleeve-valve. The sleeve reciprocated and oscillated in the cylinder barrel in a simple sinusoidal fashion under the action of the ball-crank mechanism so that the path of any point on the sleeve was an ellipse. It should be noted that the sleeve was always in motion relative to the piston and cylinder barrel, unlike the situation in a conventional poppet-valve engine where the piston rings have zero velocity relative to the cylinder barrel at both top and bottom dead center. This has implications regarding engine friction which will be discussed further along in this paper.

The porting arrangement in Figure 2, which shows three intake ports and two exhaust ports in the stationary cylinder barrel and four ports in the sleeve with the triangular port serving both intake and exhaust, was typical of the arrangements in all of the Bristol, Napier, and Rolls-Royce sleeve-valve aircraft engines. It is interesting that they all selected this arrangement, since there were many alternatives with regard to the size and number of ports. There were also a number of constraints, chief among them being:

- The larger the individual port, the thicker the sleeve wall must be so that it does not extrude through the port when the cylinder is under high pressure.
- A large number of small ports presents manifolding problems, particularly in air-cooled engines.
- The ports cannot occupy so much of the circumference of the cylinder that the stationary cylinder barrel is unable to carry the axial firing load down to the crankcase.

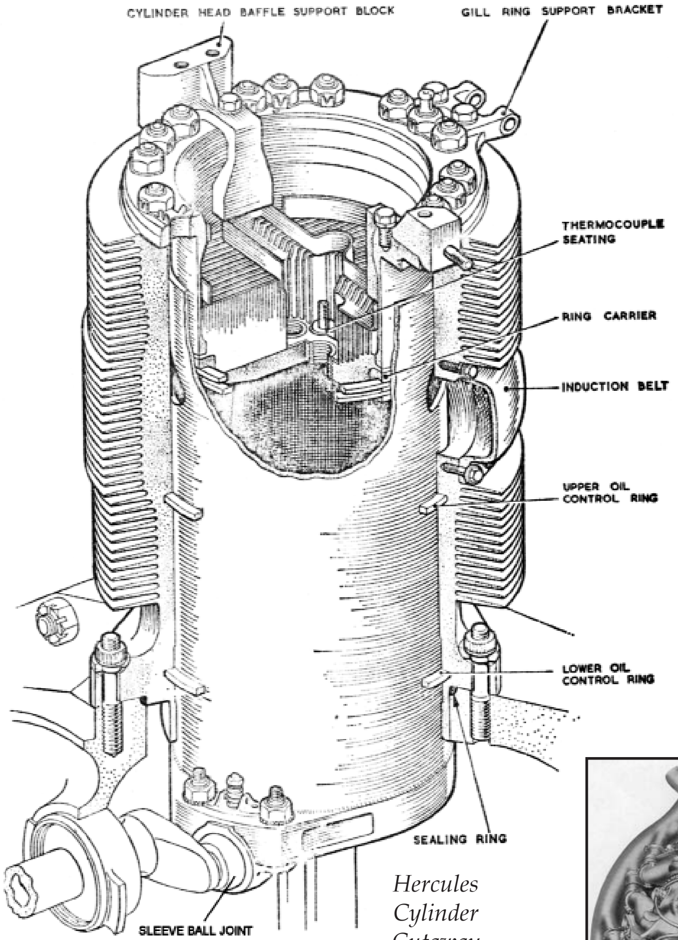
The ratio of bore to sleeve stroke was roughly two for both the Centaurus and Sabre engines. The Bristol Hercules and Centaurus engines differed only in the number of cylinders and piston stroke. Pertinent dimensions of these two engines as well as two poppet-valve engines are given in Table 1. The internal arrangement of the Hercules, shown in Figure 1, differed from the Centaurus only in having two fewer cylinders per row and in driving both rows of sleeves from the front side of the engine. The tightening up of the space between cylinders with nine per row in the Centaurus, apparently dictated that the rear row of sleeves be driven from a separate gear train at the rear of the engine.

Figure 3 depicts details of Bristol cylinders. Since the portion of the sleeve with the ports must be out of the combustion chamber during the compression and expansion strokes, the cylinder head was deeply recessed into the cylinder barrel with an annulus which allowed the sleeve travel space and piston rings for sealing off the combustion space. This implies that the depth of the cylinder head recession was the sleeve stroke plus the space required for two piston rings and their associated ring lands. The problems associated with cooling the cylinder head was one of the major development efforts in air-cooled sleeve-valve engines. Figure 3 gives some indication of the baffling and finning required to remove heat from the deeply recessed face of the combustion chamber.

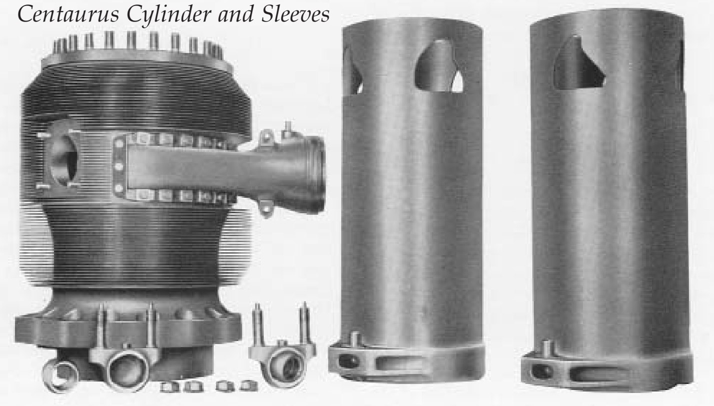
One characteristic of the sleeve-valve which gets little attention in the literature is the passage of the intake and exhaust ports over the stationary piston rings in the cylinder head. This would have created a momentary short circuit around the piston rings allowing gas in the cylinder to by-pass the rings and leak into the annulus above the sleeve and circumferentially to the intake or exhaust ports. This happened twice per cycle just before the exhaust ports opened on the power stroke and again just after the intake ports closed on the compression stroke. It would seem that the movement of hot, high velocity gas over the rings and cylinder head during this period would have added considerably to the thermal loading on the cylinder head.

A brief summary of the requirements of the sleeve-valve are:

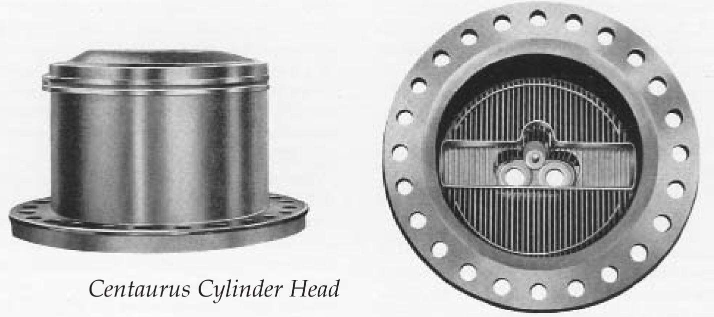
1) Since the sleeve and the oil film on its outer surface represent an additional thermal barrier to the removal of heat from the piston, the sleeve should have been as thin as possible and have had high thermal conductivity.
2) The coefficient of expansion of the sleeve material had to be a reasonable match to that of the cylinder barrel.
3) The sleeve material had to be compatible as a bearing surface with the piston, rings and cylinder barrel with no tendency to scuff or exchange materials under marginal oil film conditions.



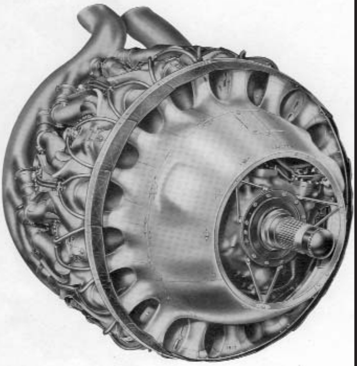
Hercules Cylinder Cutaway

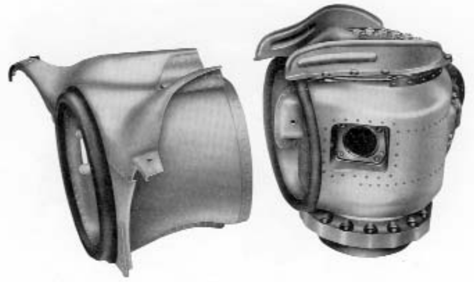


Centaurus Cylinder and Sleeves

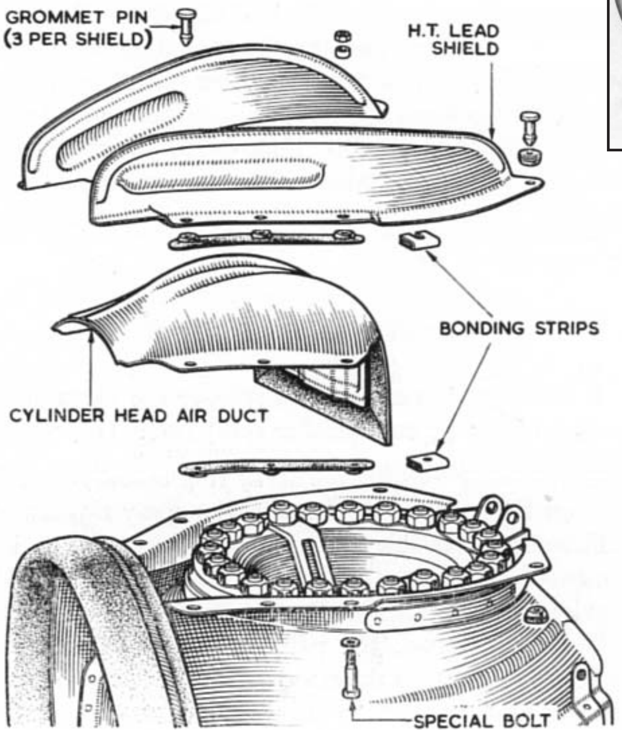


Centaurus Cylinder Head

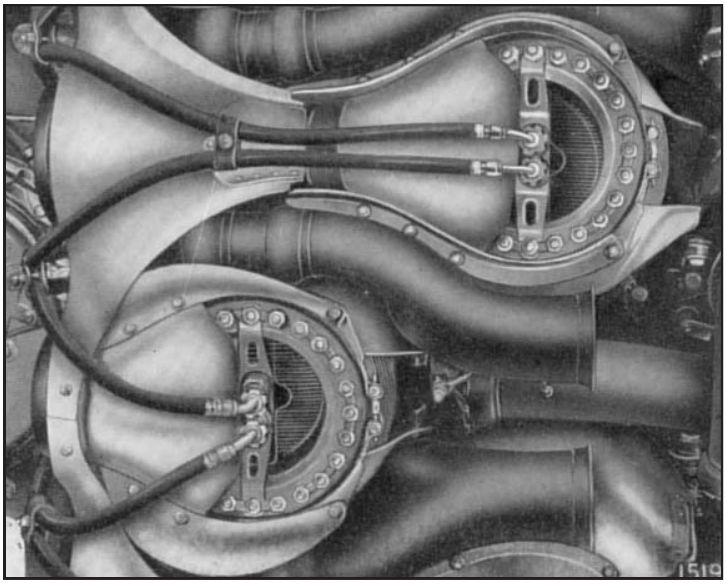




Left: Centaurus in Airspeed Ambassador
Above: Intermediate Duct and Cylinder Baffle



Centaurus Cylinder Head Baffling Detail



Top View of Centaurus Cylinder Head Cooling Ducts

Fig. 3. Bristol Sleeve-Valve Cylinder Detail

4) Techniques for fabricating the sleeve had to be developed which allowed maintaining sleeve out-of-roundness to very tight tolerances. Apparently Bristol was able to maintain out of roundness to less than 0.0002″ in the manufacture of their sleeves[6].

Some of these requirements presented conflicts or compromises in the choice of sleeve material, while the minimum wall thickness of the sleeve is limited by the port extrusion problem already mentioned. As late as 1944 and after he had left Bristol, Fedden was calling for increased research to develop a sleeve material with higher thermal conductivity so as to reduce piston temperature to the level of comparably rated poppet-valve engines[8] Both Fedden and Hives of Rolls-Royce mention a figure of 50°C as the temperature difference, but it is unclear if they are referring to the same test and if the engines referred to are liquid or air-cooled[9]. A 50°C temperature difference in an aluminum piston is very significant at high specific power ratings and should have caused either a relative de-rating or durability problems.

Another characteristic of the sleeve-valve which it is important to emphasize was its inherent ability to produce swirl in the incoming charge. This is illustrated in Figure 4. It should be noted that the inlet passages leading to the ports could be easily modified to enhance the swirl rate beyond that attainable with the symmetric arrangement shown in Figure 4. The effect of swirl rate on flame speed and cycle-to-cycle peak pressure variation is now well understood as are the effects of these two variables, both of which increase an engine's resistance to detonation.

Figure 5 shows a partial section of a liquid-cooled sleeve-valve engine, in this case the Napier Sabre. The bore and stroke of this engine were 5.000″ and 4.750″ with 24 cylinders arranged in an H configuration, namely two horizontally-opposed 12-cylinder engines with two crankshafts one above the other and geared together at the propeller end. Note that the sleeve drive mechanism was very similar to that used by Bristol (Figure 1). Figure 5 illustrates the relative ease in cooling the cylinder head as compared to the air-cooled engine.

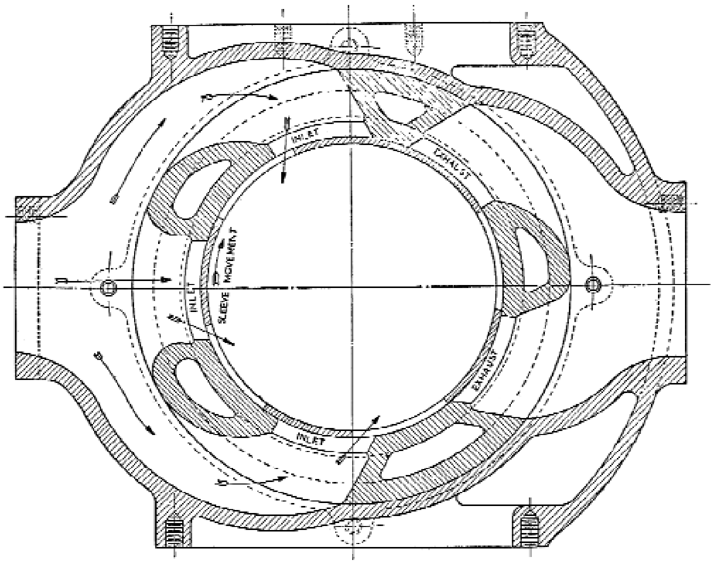


Fig. 4. Section through the Ports of a Single-Cylinder Sleeve-Valve Engine Showing Induced Swirl (Ricardo [1])

The foregoing description of the sleeve-valve and its method of incorporation into an engine raises immediate questions as to its impact on size, weight, specific power output, and efficiency.

Was the resulting engine physically larger or smaller than its poppet-valve counterpart?

Was it heavier or lighter?

How was the power output and efficiency influenced by the effects of:

- intake port area and flow characteristics on volumetric efficiency,
- the sleeve and its drive mechanism on engine friction,
- the air flow pattern in the cylinder on detonation,
- combustion zone surface temperatures on detonation?

In addition, the question of out of balance forces and moments due to the sleeve cannot be ignored and the impact of the lubrication requirements of the sleeve on lube oil consumption is of interest.

The remainder of this paper, after a brief look at poppet-valves for aircraft engines, will be an attempt to answer these questions in a quantitative manner.

5. Poppet Valves

It is useful to bear in mind that the development of the sleeve-valve was proceeding (1920-1940) against a rapidly changing poppet-valve technology[10]. The most important developments impacting the durability of the exhaust valve were:

- Compression ratios were increasing with the development of higher octane fuels thereby dropping exhaust temperatures.
- Sodium cooled valves were developed and forging techniques allowed the entire valve head to be cooled in the larger valves used in air-cooled engines.
- The metallurgy of valves and seats was improving rapidly.
- Valve spring metallurgy and design had advanced to the point by the early 1930s that springs could be enclosed from the cooling air and still be durable.
- Valve train and cam dynamics were better understood so that higher engine speeds were attainable.

The introduction of tetraethyl lead as a fuel additive had a negative impact on exhaust valve durability due to deposits of lead oxide on the head of the valve. This problem was gradually understood and overcome[9, 10].

Figure 6 shows a typical air-cooled cylinder with poppet-valves. The exhaust valve is shown in section. The cavity in the valve would have contained about 40% by volume of sodium. The movement of sodium induced by valve motion enhanced heat transfer from head to stem and out through the valve guide, reducing the maximum valve temperature significantly. Inclining the valves at an angle relative to the cylinder axis allows for larger valve diameters and consequently higher air flow. Increasing the number of valves as well as inclining them can increase the flow area even more, but aside from the Bristol poppet-valve engines, all high output air-cooled engines had two valves per cylinder.

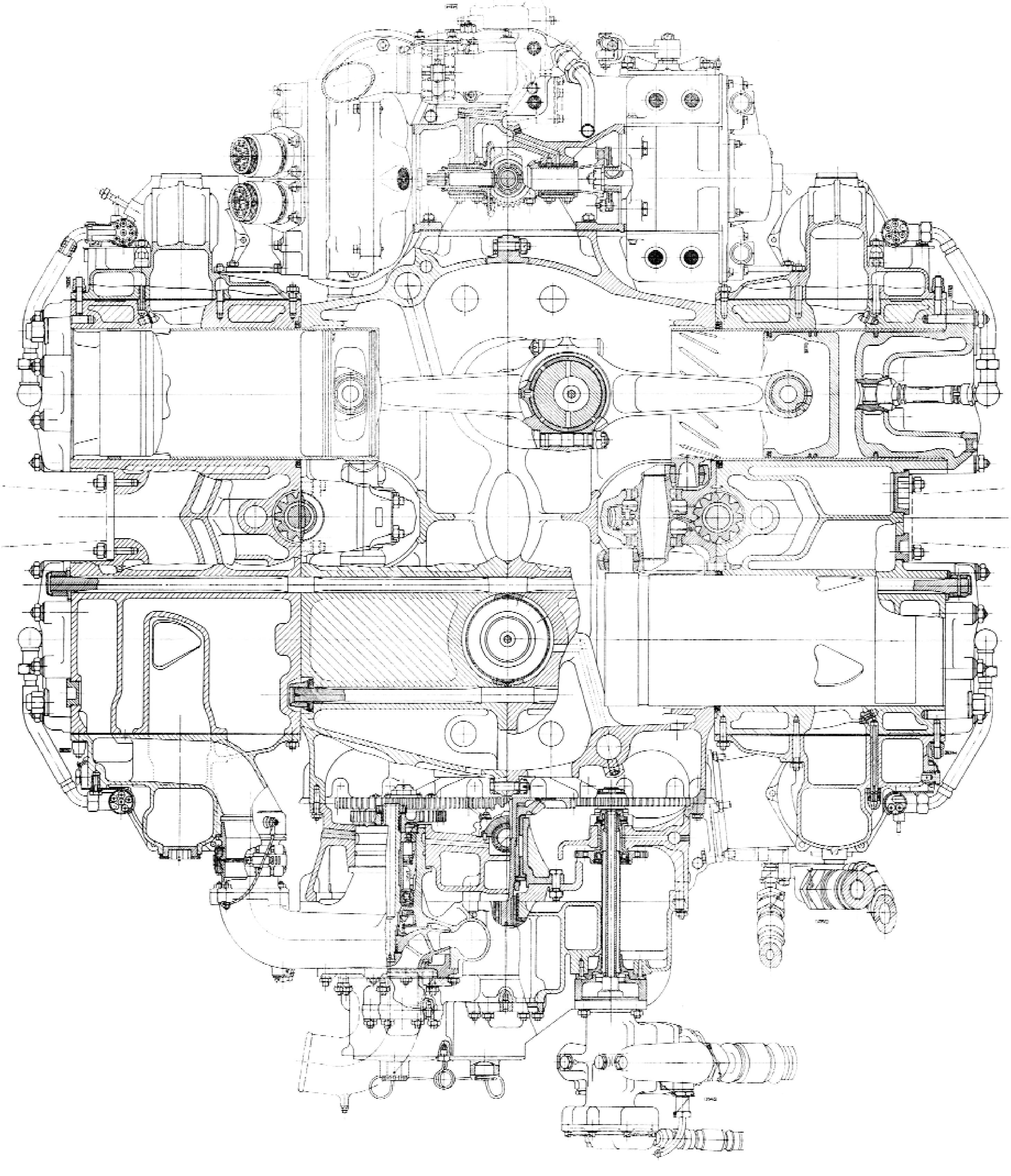


Fig. 5. Cross Section of the Napier Sabre Engine (Ricardo, [1])

Liquid-cooled engines typically had four valves, two inlet and two exhaust, with the valves inclined in some, and parallel to the cylinder axis in others.

The construction of the poppet-valve air-cooled cylinder/head assembly was significantly different than the sleeve-valve cylinder assembly, as Figures 3 and 6 demonstrate. In the poppet-valve arrangement the cylinder head was threaded and shrunk to a steel cylinder barrel; this joint, then, carried the firing pressure loads to the crankcase, eliminating the studs and nuts of the sleeve-valve arrangement which hold its cylinder head in place. These nuts occupied space which could otherwise have been finned, as can be seen in Figures 3 and 7.

The poppet-valve cylinder head was an aluminum forging with machined fins, a technique first developed at Bristol to replace cast aluminum. In many U.S. engines, as in Figure 6, the fins on the cylinder barrel were aluminum and swaged to the steel liner. The sleeve-valve cylinder head was aluminum in early Hercules and Centaurus engines but evolved over the production life of the engines to a copper and steel composite in order to handle the increasing thermal loads induced by ever higher ratings.

The exhaust valve in poppet-valve engines remained a major developmental effort throughout the era. Technical papers from the 1950s contain many examples of improvements in valves, valve guides, and seats[12, 13]. The larger valves of the two valve head were more flexible, particularly the hollow headed exhaust valve, and therefore better able to accommodate themselves to any thermal distortion of the cylinder head valve seat.

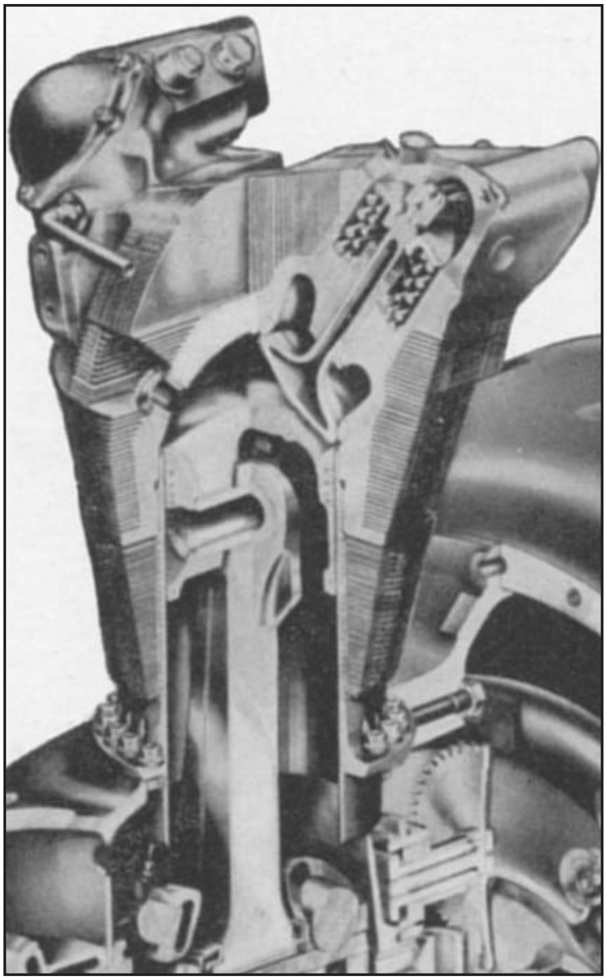


Fig. 6. View of a Sectioned High-Output Poppet-Valve Engine Cylinder Circa 1948 - Curtiss-Wright TC18 (R-3350)

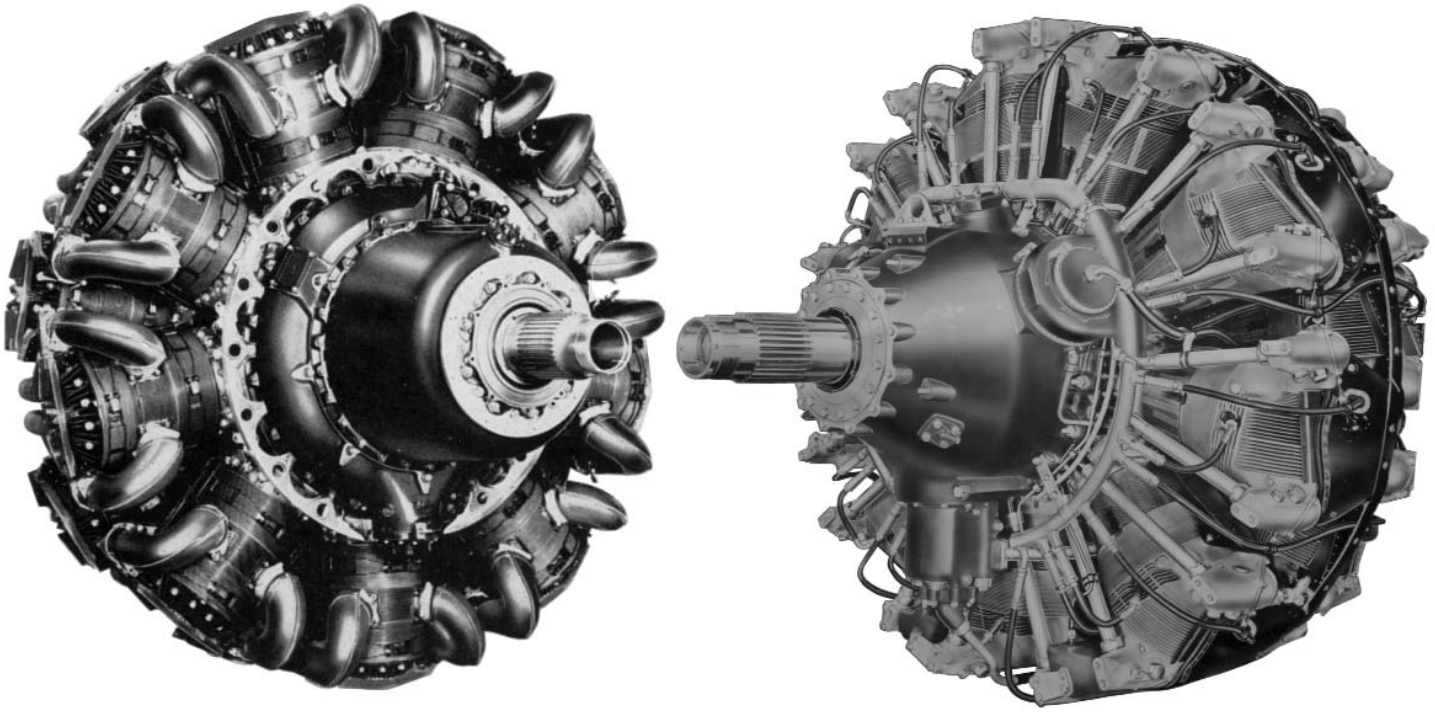


Fig. 7. Eighteen Cylinder Sleeve and Poppet-Valve Engines - Bristol Centaurus, Curtiss-Wright C18CA (R-3350CA)

Figure 7 shows two radial air-cooled engines, one sleeve-valve and one poppet-valve. Note that in the sleeve-valve engine the two exhaust ports opened forward while in the poppet-valve both intake and exhaust ports faced to the rear. It would appear that the sleeve-valve arrangement would have aggravated the problem of getting a uniform cooling air flow around the cylinder barrel.

Figure 8 shows the Allison V-1710 engine in transverse section, with inclined valves and overhead camshaft. This arrangement was typical of in-line, liquid-cooled engines of the WWII era, except that neither Rolls-Royce nor Daimler-Benz used inclined valves.

6. Sleeve Valve versus Poppet Valve – Historical Claims

Mention of the early work by Ricardo & Co. has already been made. The claims made for the sleeve valve by Sir Harry Ricardo appear to be the source of much of what has been repeated in the writing which has appeared on the subject since the end of the high output piston engine era. These claims were first made around 1920 to encourage the British Air Ministry to sponsor research on sleeve-valves. In the 1968 edition of his book[1], these arguments are repeated at the beginning of an entire chapter devoted to sleeve-valve engines, which by that time were history. (In the preface to that edition Ricardo refers to the book as "an idiosyncratic one"). These arguments were stated as follows:

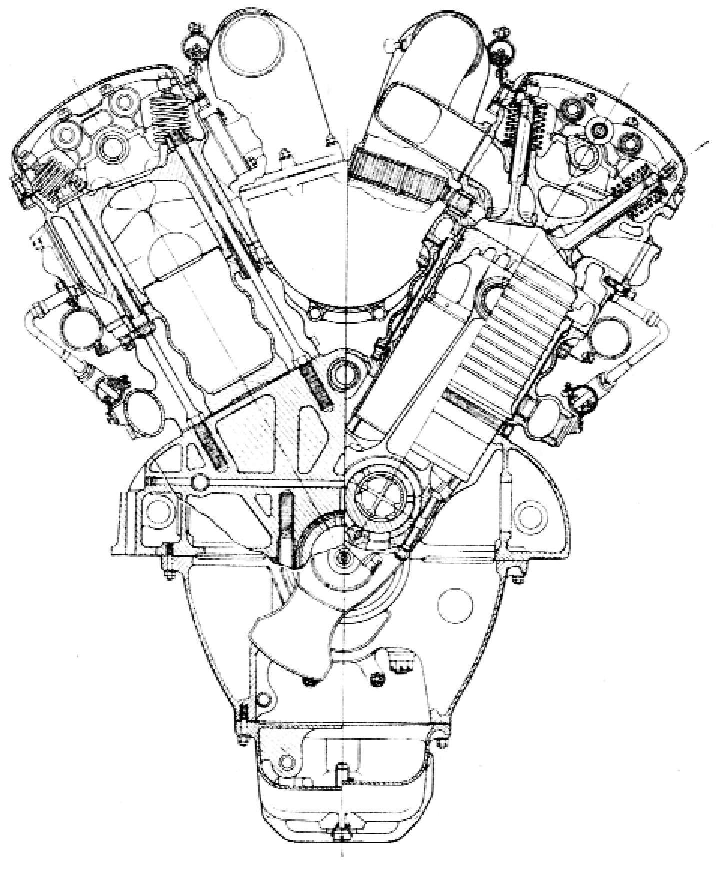


Fig. 8. Allison V-1710 Liquid-Cooled Poppet-Valve Engine

1) The sparking plug could be placed in the centre of a circular combustion space; thus the length of flame travel would be little more than the radius of the piston, and would be the same in all directions.
2) The exhaust valve which, in those days of low compression ratios and therefore high exhaust temperatures, was always the weak link, would be eliminated entirely.
3) The absence from the combustion chamber of a highly heated exhaust-valve head should reduce considerably the tendency to both detonation and pre-ignition.
4) Since the inlet ports opened directly into the cylinder and with probably a high orifice coefficient, there should be ample initial turbulence available.
5) The breathing capacity available should be at least equal to that of any poppet-valve arrangement that could be accommodated.
6) The whole engine could be made more compact and its frontal area less than that of an overhead poppet-valve engine.

Along with these claims, Ricardo lists only two "misgivings" with respect to the sleeve-valve; these were the additional thermal barrier presented by the sleeve and an extra oil film, and the friction losses associated with the sleeve and its drive mechanism. All the work that followed at Ricardo & Co. apparently justified the claims and dispelled the two "misgivings". It was, in fact, an admirable piece of research and development which laid the ground work for Bristol, Napier, and Rolls-Royce. This work showed that, in naturally aspirated engines, the sleeve-valve engine could operate at one compression ratio higher than its poppet-valve equivalent. It should be noted that the poppet-valve equivalent had four valves whose axes were parallel to the bore, not the optimum arrangement, but probably not very significant with respect to detonation.

The curious thing is that Ricardo was well aware of the effect of the sleeve on swirl and hence on combustion rate, but he never attributes any of the higher detonation limit of the sleeve-valve to this phenomenon rather than to the "highly heated exhaust valve" of claim 3. Ricardo's findings with regard to friction losses were carried out in comparative motoring tests of single cylinder engines and the results apparently came as a pleasant surprise—there was little difference. The effect of the additional thermal barrier presented by the sleeve and extra oil film was evaluated in liquid-cooled poppet and sleeve-valve engines using fusible plugs in the piston. These tests showed that the sleeve-valve engine's piston ran slightly cooler at the same output. The reason given for this result was that the moving sleeve distributed the heat flow over the length of the cylinder more effectively than would the piston alone. No mention is made by Ricardo in reference 1 to the higher piston temperatures in sleeve-valve aircraft engines mentioned by Fedden & Hives.[8, 9]

The other primary source of claims made for the sleeve-valve is a 1938 SAE paper by Fedden[3] of the Bristol Aeroplane Co. This paper summarized the development of their sleeve-valve engines from 1926 and described the recently introduced Perseus, a single row nine cylinder radial, and listed nineteen "inherent advantages" of the sleeve-valve engine. Included were all of those listed by

Ricardo with the significant exception of number 6, that the engine would be more compact. And despite claims of fewer parts, there was no claim that sleeve-valve engines would be lighter per unit displacement. By this time, as we shall see, Fedden already knew the answer to both these questions.

Fedden amplified considerably on Ricardo's fourth claim ("initial turbulence available") by stating in his tenth "inherent advantage" that "any desired control of cylinder turbulence" was possible. He never used the term swirl nor did he attribute any of the sleeve-valve's advantage with respect to detonation to this phenomenon. Rather, he emphasized the potential for running lean mixtures and for stratified charge with fuel injection.

Neither of Ricardo's two "misgivings" (thermal barrier and friction) were discussed by Fedden. At about the same time as the SAE paper, Judge published a book on aircraft engines[14] with a chapter on sleeve-valve engines which contained a statement referring to motoring tests on the Bristol Mercury (poppet-valve) and Perseus (sleeve-valve) engines: "… there is no measurable difference in mechanical efficiency up to the highest speeds at which the engines can be motored". No source for this statement was given by Judge and, of course, it assumed that the effect of IMEP on mechanical friction was the same in a sleeve-valve engine as in one equipped with poppet-valves. Judge also repeated Ricardo's claim number 6 for smaller engine size with sleeve-valves.

The remainder of Fedden's "inherent advantages" were either elaborations of the claims in common with Ricardo (e.g. "cooler exhaust" was an obvious result of higher compression ratio), claims for lower maintenance and higher reliability due to the absence of the poppet valve's shortcomings, a fully enclosed valve gear (only compared to Bristol's poppet-valve gear), and, somewhat ludicrously for an aircraft engine, that they gave "more silent operation".

We can summarize the major technical claims as follows:

- Sleeve-valve engines should have been somewhat smaller (No claims are made for the overall weight).
- They should have had higher volumetric efficiency due to larger port area and "higher orifice coefficient".
- They should have had higher indicated thermal efficiency due to the ability to run at a higher compression ratio.
- In a supercharged sleeve-valve engine running at the same compression ratio as a poppet-valve engine (to limit firing pressure) the sleeve-valve engine should have been capable of higher detonation limited IMEP's.
- There should have been no significant difference in the friction of a sleeve-valve engine.
- The sleeve and its associated oil film should not have caused the piston to operate at significantly higher temperatures than in a poppet-valve engine.

It should be noted that there were nay-sayers on both sides of the Atlantic. Technical papers related to general developments in aircraft engines which appeared in the year or so after Fedden's 1938 paper contained comments specifically aimed at Fedden's claims[9, 15, 16]. These did not, in general, attack the claims made for the sleeve-valve but, rather, defended the poppet valve, citing the recent advances made in that technology.

One exception to this was the paper by Hives of Rolls-Royce[9]. Writing in 1940, he cites design studies on in-line engines which indicated the sleeve-valve would cause the engine to be longer than a poppet-valve equivalent. He also mentioned the 50°C hotter piston test already mentioned in this paper. He went on to state that Rolls-Royce had test results indicating "that pistons give trouble in shorter running periods with sleeves than with poppets under high performance conditions". Presumably the "trouble" Hives refers to here is piston ring sticking due to excessive temperature in the ring groove area. Banks[16] also claimed ring sticking as the limiting factor in engine service period rather than the poppet valve. It would be interesting to

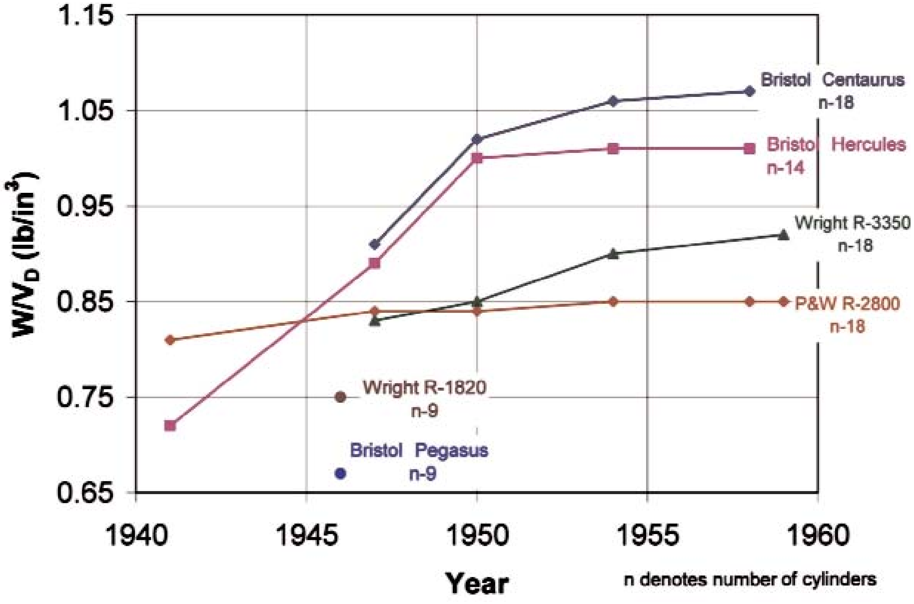


Fig. 9. Weight per Unit of Engine Displacement versus Time: Various Sleeve-Valve and Poppet-Valve Air-Cooled Radial Engines

know what prompted Rolls-Royce to go on and develop the sleeve-valve Eagle engine given Hives' rather negative tone in early 1940.

The remainder of this paper will examine these claims in some detail, along with a look at the effect of the sleeve on engine balance and oil consumption.

7. Weight and Size – Air-cooled Engines

The weight and size, especially with regard to frontal area, are the two most important physical characteristics of an aircraft engine. The weight of the engine limits the payload the aircraft can carry. Some weight penalty can be tolerated if an engine has a significantly higher efficiency than its competitor, sufficient to compensate for increased engine weight with reduced fuel weight for a given time in the air. The frontal area has a direct impact on aerodynamic drag and hence top air speed and fuel consumption at cruise. The usual figure of merit for an aircraft engine is its weight per unit of take-off horsepower. It is instructive in comparing two different types of construction, as we are here, to begin by comparing the sleeve-valve and poppet-valve engines on the basis of weight per unit of engine displacement. Thus any engine which is heavier on this basis must run at higher BMEP and/or engine speed to get a competitive value of weight per unit of take-off power.

We begin the comparison by looking at air-cooled engines in the (mainly) post World War II era. We do this as a function of time because it shows interesting trends in the specific weight of engines not evident with liquid-cooled engines. The air-cooled engines were competing for the commercial aircraft business in this time frame while the liquid-cooled engines were intended primarily for military aircraft and did not outlive the war by very much, especially the sleeve-valve engines. Rolls-Royce made some attempt at the commercial market with the Merlin-powered Canadair DC-4M North Star, but their Griffon was the only high output liquid-cooled engine to see much application beyond the war, and this was mainly in military applications.

Figure 9 shows the weight per unit of engine displacement versus time for a number of air-cooled engines. The engines are chosen so as to be similarly equipped with regard to options such as superchargers, reversible pitch propellers, etc. All of the engines shown have single stage, two speed superchargers and the figures for the Wright R-3350 are for the non turbo-compounded model. It should be noted that both the P&W R-2800 and the Wright R-3350 had second-order balancers to eliminate a twice engine speed unbalanced couple caused by the master/articulated connecting rod geometry. This would have added considerable weight and was never adopted by Bristol. The R-3350 was equipped with cylinder fuel injection from 1950 onwards; the remaining engines were equipped with injection carburetors.

Two things are striking about Figure 9. The first is the relative lightness of the Bristol Pegasus, the last, together with their Mercury, of their large poppet-valve engines. This explains why Fedden made no claims for lightness for sleeve-valve engines. The Pegasus and the Wright R-1820 had about the same displacement and were both single-row, nine-cylinder radials. But by 1946 the R-1820 ratings were such that, on a per horsepower basis, it was lighter than the Pegasus (Fig. 10).

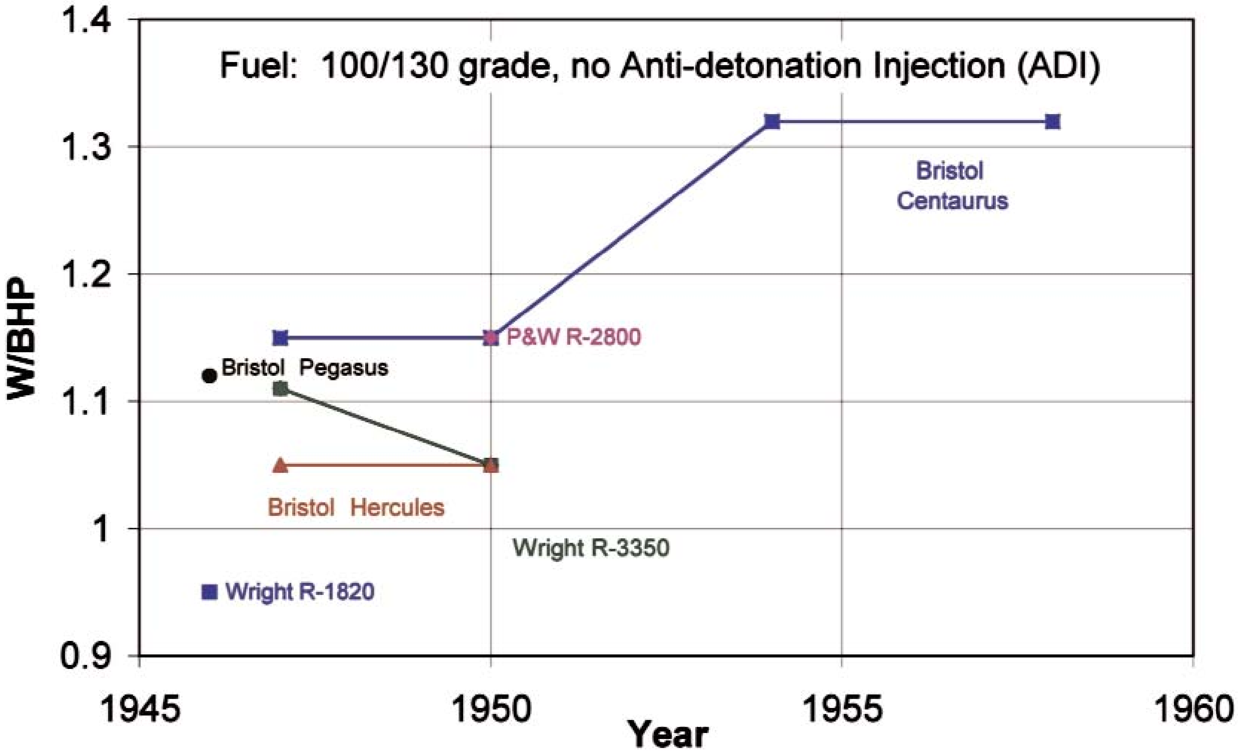


Fig. 10. Weight per Unit of Takeoff Horsepower versus Time: Various Sleeve-Valve and Poppet-Valve Air-Cooled Radial Engines

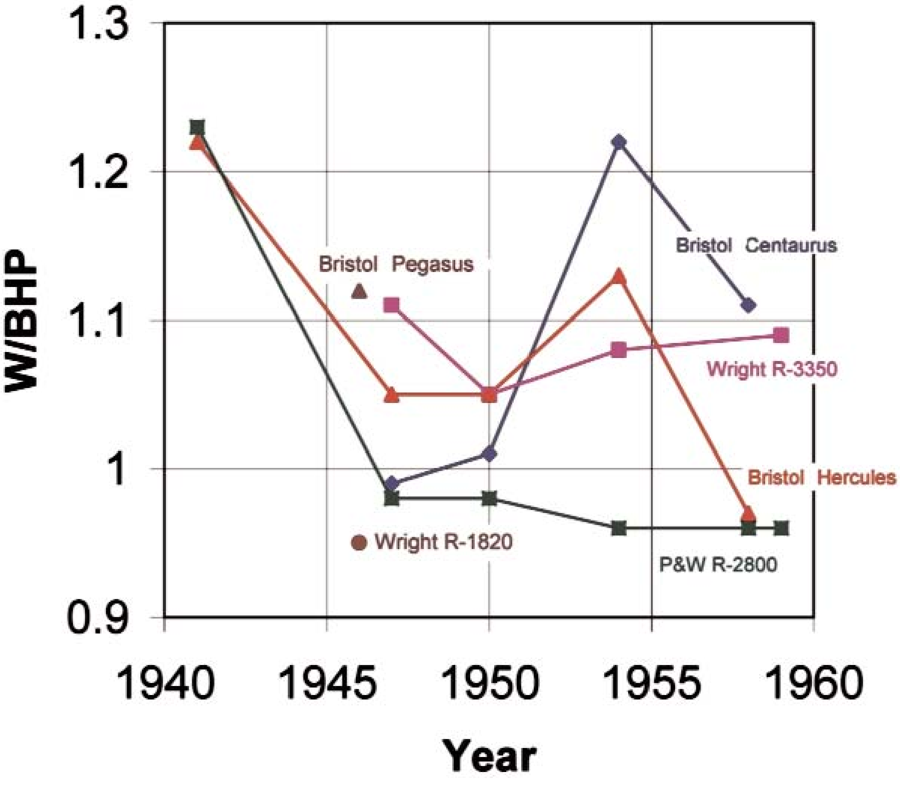
The second interesting thing about Figure 9 is the dramatic weight increase of the two sleeve-valve engines over their production life. The Hercules in 1940 was lighter than all of the American poppet-valve engines shown but by 1950 was considerably heavier. The Centaurus shows a similar trend in weight growth. By comparison, the P&W R-2800 had a very modest weight gain and the Wright R-3350 somewhat more, but nothing like the sleeve-valve engines.

The most dramatic weight increases of the Bristol sleeve-valve engines came in the earlier stages of their development and were due to increased finning, an increase in the number of cylinder hold down bolts, an increase in the size of the crankshaft journals, and a switch from aluminum to copper and steel in the cylinder heads[7] among a number of improvements. The crankpin diameter of the Bristol Centaurus was 3.783″[17] while that of the R-2800 was only 3.500″[18]; both had a 5.750″ bore. The crankshaft is the single heaviest component in an air-cooled radial engine.

Both the Wright and P&W engines had extensive design changes to almost every component over their production lives, indeed it could be argued that the R-2800 had the most exhaustive development program of any high output aircraft engine[19], yet its weight only increased about 5%. The differences in pre-war design practice between the U.S. and Britain are apparent in the weights of the Pegasus and R-1820 engines. Both of these engines had their origins in design practices of the late 1920s, when U.S. practice was considerably more conservative than that of Britain and the European continent. Bristol's pistons, for instance, had far less skirt area and were shorter and lighter (for the same bore) than American practice[20]. This was probably due to the differences in duty cycle and service requirements of British versus American applications as well as manufacturing cost. U.S. engines tended to have fewer machined surfaces than British engines. The more robust construction of the American engines apparently paid off when higher octane fuels made higher ratings possible. The fact that Bristol had to increase substantially the weight of their engines to get the desired ratings indicates they were certainly no heavier than they had to be at the end of their production lives.

The foregoing arguments indicate that, in air-cooled engines, the sleeve-valve mechanism led to an inherently heavier design. Bristol certainly were very experienced at producing the lightest possible engines so one can only conclude that it was the characteristics of the sleeve-valve which led to this situation.

Figure 10 shows the specific weight (weight per unit of take-off horsepower) for the engines of Figure 9 versus time for 100/130 Performance Number fuel and no anti-detonation injection (ADI). Most of the engines shown were not rated for take-off with this fuel after 1950. It is interesting that the Bristol Pegasus (their final poppet-valve engine) was now heavier on a per take-off horsepower basis than all of the other poppet-valve engines, while the sleeve-valve Hercules was as light as the R-3350 and considerably lighter than the R-2800 in 1950. To achieve the same specific weight the R-3350 ran at a BMEP of 220 psi and 2,900 rpm while the Hercules ran at 244 psi and 2,800 rpm. The piston speeds were practically the same at slightly over 3,000 ft/min.



Fuel

Various grades as noted with performance numbers (P. N.) and with or without Anti-Detonation Injection (ADI). Final Values of W/BHP Circa. 1958-59 were with fuels as follows:

Bristol Centaurus - 100/130, ADI
Bristol Hercules - 100/130, ADI
P&W R-2800 - 108/135, ADI
Wright R-3350 - 115/145
All others - 100/130

Fig. 11. Weight per Unit of Takeoff Horsepower versus Time: Various Sleeve-Valve and Poppet-Valve Air Cooled, Radial Engines

Figure 11 shows the same variable with various Performance Number fuels from 1940 until the end of the high output piston engine era in the late 1950s. On this figure, the R-2800 shows up as having been somewhat lighter than the Hercules in 1950 because it was rated with 100/130 fuel and ADI. It is clear from the final ratings, circa 1958, who was competing with whom; the Bristol Centaurus versus the Wright R-3350, and the Bristol Hercules versus the P&W R-2800. The two engines in each pair approached the same specific weights, with the R-2800 and Hercules significantly lower than the Centaurus and R-3350. The Centaurus developed more take-off power than the R-3350 (3,150 BHP versus 2,800) with slightly less displacement while the Hercules developed slightly less take-off power (2,300 BHP versus 2,500) with significantly less displacement. Table 1 give the dimensions of these four engines and the ratings for the four data points circa 1958 shown in Figure 11.

It is of interest to note that the turbo-compounded version of the R-3350 gave 3,440 BHP on 115/145 fuel and, although 600 lb heavier, maintained a specific weight of 1.07 lb/BHP thereby besting the Centaurus in both categories.

We have seen that the sleeve-valve air-cooled engines were significantly heavier on a weight per displacement basis but were able to match the poppet-valve engines on a weight per take-off horsepower basis on a lower performance number fuel. This was due to their ability to run at higher BMEP and/or RPM on these fuels. This will be taken up further along when we discuss detonation limits, one of the chief claims in favor of sleeve-valve engines.

Let's turn our attention to the size of the sleeve-valve air-cooled engines versus their poppet-valve counterparts. Here the important dimension is the diameter of the engine since it defines the frontal area of the aircraft (or engine nacelle in the case of multi-engine aircraft). In comparing engines it is convenient to use a dimensionless diameter so as to eliminate the effect of engine displacement on diameter. This procedure will use the value defined as the engine diameter divided by the cube root of the displacement of the cylinders per row as the dimensionless diameter. With this definition, and assumptions governing the relationships between internal engine dimensions, a single valued expression can be derived for the dimensionless diameter, K. Figure 12 gives a plot of K versus stroke/bore ratio for radial engines of seven and nine cylinders per row. The solid lines on this figure represent a hypothetical engine with the dimensions shown in Figure 13. This method of presentation was first used by E.S. Taylor[21] in the early 1930s. His relationships were re-derived by the author and more modern engine proportions used for Figure 13. The piston and cylinder proportions shown for the hypothetical engine of Figures 12 and 13 are an average of four U.S., one British and one French poppet-valve engine circa 1944. The cylinder head dimensions (1.35 B and 1.70 B) in Figure 13 are averages of four American poppet-valve engines.

In Figure 12, the solid lines for seven and nine cylinders per row were both based on a ratio of master rod length to stroke of 2. This assumption determines the point of discontinuity, or minimum value of K, and the choice of shorter master rod for the seven cylinder lines would move this point to the right where it might have better agreed with the actual engine data points. The relationship between master rod length and stoke/bore ratio is shown in Figure 13 for seven and nine cylinders per row. Also shown is a sketch of the radial engine configuration used to derive the

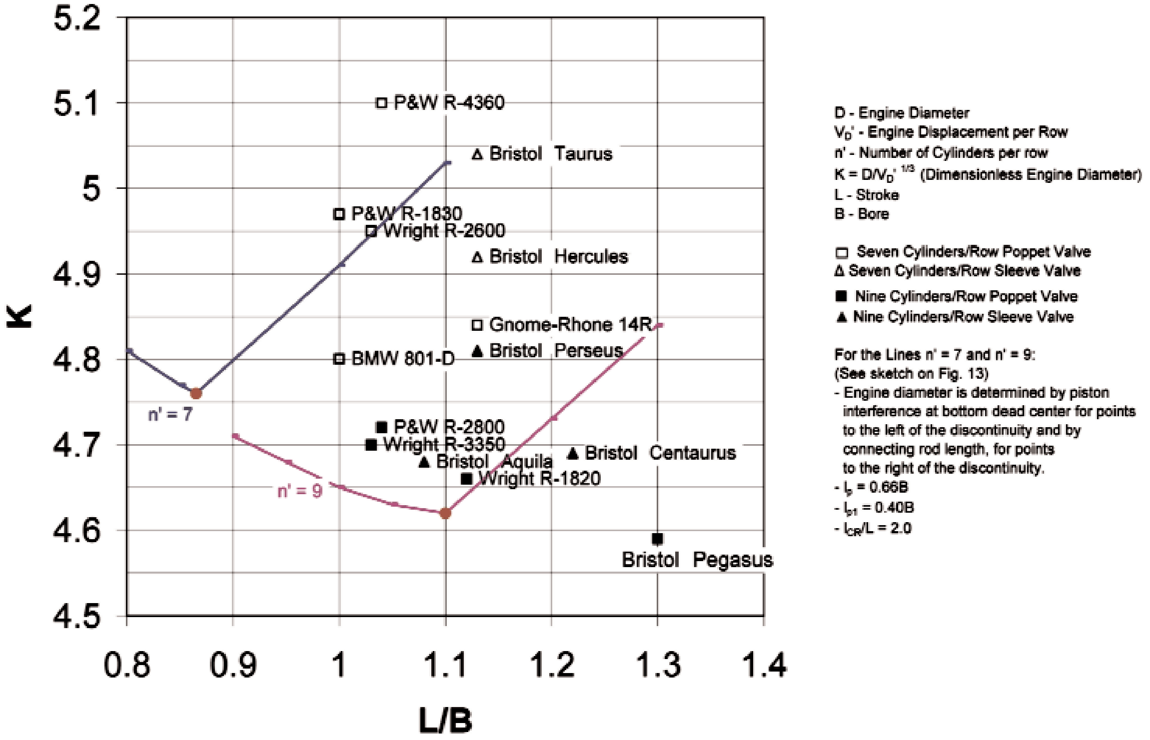


Fig. 12. Dimensionless Engine Diameter versus Stroke/Bore Ratio, Circa 1946

relationships shown as solid lines in Figure 12. The portion of the curves in Figure 12 to the left of the minimum point is based on the assumption that the piston skirts of adjacent cylinders touch when they are at their bottom dead center positions. This assumption allows for a little clearance since the pistons are not at bottom dead center at the same time.

Figure 12 clearly indicates the sleeve-valve engines were no smaller than their poppet-valve counterparts and in neither the seven or nine cylinders per row configuration were they the smallest. It is interesting that the Bristol Pegasus was smaller than the other poppet-valve engines. This was due to its much shorter piston and the four valve cylinder head which had proportionately shorter valve stems and springs due to the smaller diameter of the individual valves. The dimensionless diameter, K, of Figure 12 is at a fairly fine scale so that the difference between the Bristol Centaurus and the smallest single poppet-valve nine cylinder per row engine (the R-1820) is less than 1%. Similarly, the difference between the seven cylinder per row Hercules and the smallest in that category (the BMW 801-D) is a little over 2%.

To explain fully the differences in weight per unit displacement and the similarity in diameter despite the very significant differences in construction between the sleeve and poppet-valve air-cooled radial engine is beyond our scope here. It would require a detailed weight analysis, an almost part by part comparison, as well as a look at the layout drawings of both types of engines. As to the diameter, however, it would appear that the sleeves did not dictate a significantly longer master connecting rod so as to prevent them touching as they pass through their bottom dead center positions or to prevent their operating crank mechanisms from touching the counterweights (see Figure 1). The Centaurus master rod length to stroke ratio was 2.12 while that of the R-3350 was 2.21. The relatively short sleeve-valve engine pistons would have given a smaller diameter engine, but this must have been more than compensated for by the depth of the cylinder head and air deflectors to get air down to its base (see Figure 3). This all resulted in a wash between sleeve and poppet-valve mechanism as regards engine diameter.

8. Weight and Size - Liquid-cooled Engines

As already mentioned, the history of liquid-cooled engines post WWII is too limited to warrant a plot like Figure 9. Only two liquid-cooled sleeve-valve engines received much development effort and only one, the Napier Sabre, saw any significant production volume. Table 2 gives pertinent dimensional and weight information comparing sleeve and poppet-valve engines. The sketch of a crankshaft in the upper right corner and the Table 2 shows that the cylinder spacing of the poppet-valve engines was much tighter than that of the sleeve-valve Sabre (the author has not found the corresponding dimensions for the Rolls-Royce Eagle). The Rolls-Royce design study indicated in Table 2 shows a similar difference. A glance at Figure 4 gives the probable cause for the wider cylinder spacing. In order to get adequate flow area to the two intake ports furthest from the intake plenum a significant amount of space would have been required, which would have forced the cylinders apart. Normally, in a poppet-valve engine with the wet cylinder liner typical of an aircraft engine, cylinder spacing is limited by water jacket and sealing considerations. This particular problem does not present itself in radial engines because the

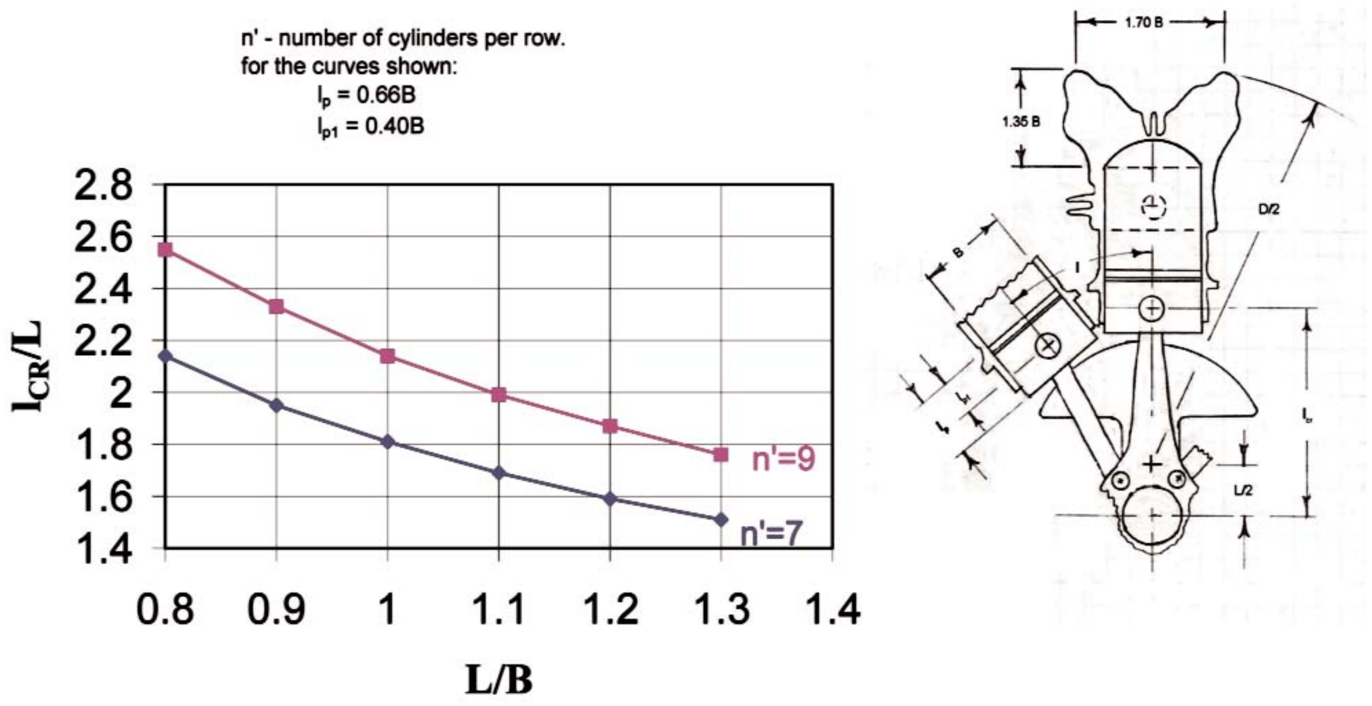


Fig. 13. Maximum Connecting Rod Length versus Stroke/Bore Ratio When Piston Interference Determines Engine Diameter

cylinders are like spokes on a wheel and the intake ports are well away from those on adjacent cylinders.

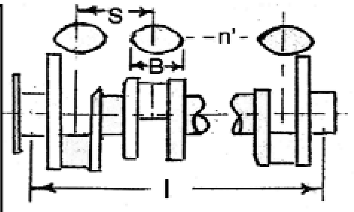
The increased cylinder spacing implies a longer crankshaft, one of the heaviest components in an engine, as well as longer cylinder blocks and crankcases. The sleeve-valve configuration with deeply re-entrant cylinder heads to accommodate the sleeve at top dead center required that the cylinder heads must be individual for each cylinder rather than one continuous casting for an entire bank as in liquid-cooled poppet-valve engines. This would undoubtedly have caused increased weight due to a larger number of hold down studs and nuts.

The Sabre and Eagle sleeve-valve engines were very significantly heavier, on a weight per cubic inch of displacement basis, than their poppet-valve counterparts. To show this it is important to compare comparably equipped engines. In Table 2, the Napier Sabre VII should be compared to the Merlin-24, as both had one stage, two speed, superchargers. The Sabre was 28% heavier than the Merlin-24. Even more dramatic is the weight difference between the Sabre and the Rolls-Royce Griffon VI. These engines had the same displacement but the sleeve-valve Sabre was almost 42% heavier than the Griffon. The Rolls-Royce Eagle should be compared to the Griffon-130 since they were both equipped with two stage superchargers and aftercoolers, as well as the gears and co-axial propeller shafts required for contra-rotating propellers. Again, the sleeve-valve Eagle was 42% heavier than the poppet-valve Griffon-130.

Table 3 shows the weight per brake horsepower at the maximum power ratings for the comparable sleeve and poppet-valve engines of Table 2. The Napier Sabre VA performance is shown in Table 3, and at these ratings its weight per horsepower was quite high compared to the Merlin. The later model, Sabre VII, at a rating of 3,055 BHP gave a much more competitive number of 0.83 pounds per brake horsepower. The Eagle's performance relative to the Griffon was not impressive and despite the theoretical possibility based on estimated detonation limits, it was apparently never rated above 3,500 BHP.

The remaining three columns in Table 3 are concerned with estimated performance based on the higher detonation limited IMEP of the air-cooled sleeve-valve engines and will be discussed at that point in this paper.

Table 2. Weight and Cylinder Spacing Characteristics of Sleeve-Valve and Poppet-Valve Liquid-Cooled Aircraft Engines Circa 1946



n' - no. of cyl's per bank

		Configuration	n Number of Cylinders	B Bore (in)	L Stroke (in)	V_D Displacement $(in)^3$	W Weight (lbs)	W/V_D Weight Density (lbs/in^3)	A_f Frontal Area (ft^2)	Dimensionless Frontal Area $A_f/V'^{2/3}_D$	S (in)	l (in)	S/B	l/n'B	Comments
Poppet Valve Engines	Rolls-Royce Merlin -24	60° V	12	5.40	6.00	1649	1450	0.88	7.5	25.6	6.10	36.5	1.13	1.13	One stage, two speed supercharger
	Rolls-Royce Merlin -130	60° V	12	5.40	6.00	1649	1715	1.04	7.5	25.6	6.10	36.5	1.13	1.13	Two stage, two speed supercharger & aftercooler
	Rolls-Royce Griffon -VI	60° V	12	6.00	6.60	2239	1790	0.80	7.9	22					One stage, two speed supercharger
	Rolls-Royce Griffon -130	60° V	12	6.00	6.60	2239	2165	0.97	7.9	22					Two stage, three speed supercharger & aftercooler; two co-axial contra-rotating prop shafts
	Allison V-1710-G	60° V	12	5.50	6.00	1711	1475	0.86	6.2	20.6	6.30	38.3	1.15	1.16	One stage, two speed supercharger
	Allison V-3420	4 bank version of V-1750	24	5.50	6.00	3421	2600	0.76	11.6	24.3	6.30	38.3	1.15	1.16	One stage,two speed supercharger. Utilizes two crank shafts
	Rolls-Royce Design Study	60° V	12	5.25	—	—	—	—	—	—	5.90	—	1.12	—	Liquid cooled mono bloc construction From Reference 9
Sleeve Valve Engines	Rolls-Royce Design Study	60° V	12	5.25	—	—	—	—	—	—	7.00	—	1.33	—	
	Napier Sabre VII	H	24	5.00	4.75	2238	2540	1.13	8.8	24.5	6.50		1.30		One stage, two speed supercharger, two crankshafts
	Rolls-Royce Eagle	H	24	5.40	5.125	2817	3900	1.38	10.6	25.3					Two stage, two speed supercharger; aftercooler; two cranks contra-rotating props

V'_D = Total Engine Displacement Facing Air Stream

With regard to frontal area, the liquid-cooled sleeve-valve engines appear to have been somewhat larger. The Rolls-Royce Griffon engine, with almost exactly the same displacement as the Napier Sabre, had 10% less frontal area. Table 2 gives a dimensionless frontal area defined as the frontal area divided by the cylinder displacement facing the air stream raised to the two-thirds power. (The "V" engines have two cylinders facing forward while the "H" configured sleeve-valve engines have four cylinders facing forward). Unfortunately, we have no H configured liquid-cooled poppet-valve engines to compare with the sleeve-valve engines so there is some uncertainty as to how much the difference was due to the sleeve-valve and how much was due to the configuration. The Allison V-3420 (Table 2) had four cylinders facing forward in an "X" configuration and its dimensionless area was less than both sleeve-valve engines.

9. Air Capacity

The power output of an engine is determined by its ability to breathe fresh air. This ability is, in turn, influenced by the speed of the engine and the restrictions posed by the intake system. We have seen that proponents of the sleeve-valve had claimed an advantage over the poppet-valve in this regard, but hard data where comparable measurements of volumetric efficiency were taken has not been discovered. There is some anecdotal comment in the literature on this subject but no hard references have so far been identified.

In a supercharged engine, as all of the high output piston engines both sleeve and poppet were, the air flow can be increased by raising the manifold pressure with the supercharger to compensate for a higher intake restriction. This, however, increases the power required by the supercharger and results in higher manifold temperatures which will lead to a lower detonation limited IMEP. So the supercharger is not an effective way to compensate for a restrictive intake system design. In a supercharged engine the volumetric efficiency must be defined on the basis of intake manifold conditions, otherwise the supercharger performance becomes involved in the definition in a complex way and masks the effect of intake system restrictions on breathing. This situation is further complicated by the lack of steady state thermodynamic conditions in the intake manifold, due primarily to fuel evaporation.

We will approach the analysis of the relative restriction of the two valving systems using techniques developed by C.F. Taylor[22]. By using dimensional analysis techniques, Taylor showed experimentally that the volumetric efficiency of an engine could be characterized by various dimensionless groups, such as the ratio of exhaust to intake manifold pressure, and valve timing, metal temperatures inside the working cylinder, etc. The dimensionless variable that characterizes the relative restriction of the intake system is a kind of Mach number where the characteristic velocity is defined as a mean air speed based on the mean piston speed and the effective area of the intake valve; and the speed of sound is calculated for the intake manifold charge temperature. This "Mach number" is represented by the letter Z and is defined in Table 4. It is clear that this is not strictly a true Mach number because the velocity is not based on the actual mass flow through the valve. A more accurate relationship is easily derived but is less convenient

Table 3. Specific Output Comparison of Sleeve and Poppet-Valve Liquid-Cooled Engines

	Compression Ratio r	Maximum Power Ratings				Weight per Brake Horsepower (lb/bhp)	Estimated Max. Brahe Mean Effective BMEP (psi)	Estimated Max Brake Horsepower BHP	Estimated Min. Weight per Brake Horsepower (lb/bhp)	Comments
		Brake Horsepower BHP	Engine Speed N (rev/min)	Brake Mean Effective Pressure BMEP (psi)	Fuel P.N.					
Napier Sabre V A (Sleeve)	7	2300	3850	211	100/130	1.09	275	2992	0.84	A later model, the Sabre VII, had a max. military rating of 3055 BHP @3850 rpm with 100/130 fuel
Rolls-Royce Merlin - 24 (Poppet)	6	1610	3000	258	100/130	0.90	—	—	—	
Rolls-Royce Eagle 46H-22 (Sleeve)	7	3500	3500	281	115/150	1.11	348	4332	0.90	
Rolls-Royce Griffon - 130 (Poppet)	6	2420	2750	311	115/150	0.89	—	—	—	

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* It is assumed that the ratio of knock limited IMEP of the sleeve valve to poppet valve engines is the same as estimated for air cooled engines; See Table 5. Corrections for compression ratio and bore size are included

because volumetric efficiency ends up in the term in the right hand side of the equation which limits its usefulness.

Taylor's work shows that the definition given in Table 4 is very useful in establishing a limiting value of Z, above which volumetric efficiency falls off very rapidly, and below which it is relatively constant. The key to making this correlation consistent is in establishing an average steady state flow coefficient for the intake valve system over the entire valve opening period. The simple experimental technique for accomplishing this is given by Taylor in reference 22. As noted in Table 4, the reference area for the poppet-valve is simply the area defined by the outer diameter of the valve. This means that the flow coefficient will vary from zero to a maximum near maximum valve lift. The coefficient could as easily be based on the actual flow area at any valve lift but the average effective valve area, or product of flow coefficient and area, averaged over the valve opening and closing cycle, would be the same. With the average effective flow area defined in this way and using the mean piston speed to get the characteristic valve velocity, the limiting value of Z for many different intake system designs was found by Taylor to be Z=0.5.

A look at the values of piston speed to get Z=0.5 and comparing these with the take-off piston speeds of a number of aircraft engines is given in Table 4, in the last two numerical columns. These numbers indicate that all of the engines operated close to Z=0.5 at take-off with the R-2800, at 10% lower than this value, representing the largest difference. The last row in Table 4 is a hypothetical engine with the physical dimensions of the R-2800 but an intake passage/valve design yielding a 0.38 flow coefficient. This was the highest flow coefficient for an air-cooled cylinder found in the literature[25], and yields a piston speed at Z=0.5 close to 3,700 ft/min. This would indicate that the take-off piston speed was limited by bearing loads rather than air flow, particularly for the radial engines.

It is worth noting that the measurements to get the effective valve area were carried out at the Sloan Laboratory for Automotive and Aircraft Engines at M.I.T. or at the NACA Laboratories, which used basically the same techniques as M.I.T. The author's estimates are based on data taken at M.I.T.; for instance the higher value of flow coefficient attributed to the Merlin relative to the Allison is based on the effect of the ratio of valve lift to diameter which was somewhat higher for the Merlin. The values for the sleeve-valve engine were also obtained from a Hercules cylinder tested at the Sloan Laboratory[23].

What Table 4 indicates for the sleeve-valve versus poppet-valve question is that, everything else being equal, the sleeve as represented by the two Bristol engines had no

Table 4. Intake Valve and Port Characteristics of Selected Poppet and Sleeve-Valve Engines

		Bore	Stroke	Rated Speed at Takeoff	Max. Valve Diameter	Max Valve Lift	Ratio: Valve Lift to Diameter	Valve Flow Coefficient	Valve Reference Area *	Effective Valve Area	Ratio: Effective Valve Area to Piston Area	Piston Speed at Z=0.5	Piston Speed at takeoff	
		B (in)	L (in)	N (rev/min)	D_v (in)	L_v (in)	L_v/D_v	C	A_v (in^2)	CA_v (in^2)	$(CA_v)/A_p$	$S_{Z=0.5}$ (ft/min)	$S_{t.o.}$ (ft/min)	Comments
Sleeve Valve	Bristol Hercules XVI	5.75	6.50	2800	N/A	N/A	N/A	0.35	6.00	2.12	0.082	2977	3033	Value of CA_v from ref. 23
	Bristol Centaurus	5.75	7.00	2800	N/A	N/A	N/A	0.35	6.65	2.35	0.09	3267	3267	Assumes same C as for Hercules
Poppet Valves	Wright R-1820	6.125	6.875	2800	3.10	0.625	0.20	0.32	7.55	2.42	0.082	2977	3208	Flow coefficient from ref. 10
	Pratt & Whitney R-2800	5.75	6.00	2800	2.97	0.70	0.24	0.32	6.93	2.22	0.085	3103	2800	Flow coefficient is author's estimate
	Allison V-1710	5.50	6.00	3000	2.00 **	0.534	0.27	0.32	6.28	2.01	0.085	3086	3000	Flow coefficient from ref. 24
	Rolls-Royce Merlin	5.4	6.00	3000	1.88 **	0.58	0.31	0.35	5.55	1.94	0.085	3086	3000	Flow coefficient is author's estimate
	Engine based on R-2800 but with higher intake valve flow coefficient	5.75	6.00	N/A	2.97	0.70	0.24	0.38	6.93	2.63	0.101	3666	N/A	Flow coefficient is the best found for an air cooled cylinder head ref. 25

$Z = (A_P/CA_v)(S/a)$, $A_p = \pi B^2/4$, $S=2LN$, $a = 1210$ ft/sec (sound velocity at assumed manifold temperature of 150°F)

* Valve Reference Area is Maximum Port Area for Sleeve Valve Engines and $\pi D_v^2/4$ for Poppet Valve Engines, therefore the values of flow coefficient for poppet and sleeve valves shown are not directly comparable. See Section 9.

** Two valves

advantage over the poppet with regard to volumetric efficiency. But everything else was apparently not equal. We have already seen that the piston in a sleeve-valve engine ran considerably hotter (50°C) than in a conventional engine. The inner surface of the sleeve is also very likely to have run much hotter than the bore of a conventional air-cooled or water cooled engine. And, given the development effort devoted to cooling the air-cooled sleeve-valve cylinder head, it is quite likely that the inner surface of the cylinder head also ran hotter. The only surface in the cylinder of a poppet-valve engine which would have run hotter than those of the sleeve-valve engine would have been the face of the exhaust valve. Combining the effect of higher surface temperatures and the high swirl rate induced by the sleeve-valve, it is very likely that heat transfer during the induction process would have had a negative effect on volumetric efficiency.

Heat transfer to its surroundings from the charge in an engine cylinder has two major effects. The first, due to heat transfer while the intake port is still open, influences the quantity of charge trapped when the valve closes and hence, volumetric efficiency, and the charge temperature at the beginning of compression. The second effect is due to heat transfer during compression and combustion, and influences the tendency of the last part of the charge to auto-ignite. When we discuss the influence of higher or lower surface temperatures inside the cylinders of sleeve-valve and poppet-valve engines we are, therefore, discussing two separate but interrelated phenomena. Unfortunately, most research on the effect of temperature of internal surfaces on performance has tended to concentrate on the influence on detonation. We will take this up in a following section which discusses the relative detonation limits of sleeve and poppet-valve engines. There is nothing in the data this author has had access to that could shed any light on the relative effects of heat transfer on the volumetric efficiency of sleeve and poppet-valve engines.

One would suspect that the actual average flow coefficient of the sleeve-valve port would be less than that of the poppet-valve since the sleeve port resembles a sharp edged orifice while the poppet-valve and passage are, in well designed examples, more like a nozzle. In Table 4, the reference areas for the two types of valve are different; the sleeve-valve coefficient is based on the maximum port opening (Av in Table 4) while the poppet-valve coefficient is based on the area defined by the outer diameter of the head of the poppet-valve. In a well designed intake passage, circa 1941, the maximum flow area was about 61% of the area defined by the diameter of the valve head. Using this value and the flow coefficient of the Wright cyclone, 0.32, the average flow coefficient becomes 0.52, versus 0.35 for the Bristol Hercules.

Table 5. Detonation-Limited Performance Estimates of a Poppet-Valve and Sleeve-Valve Engine at Two Operating Conditions

		1	2	3	4	5	6	7	8	9	10	11
	Engine Performance (See note 1)											
	Engine	Brake Horsepower BHP	Engine speed N (rev/min)	Piston Speed S (ft/min)	BreaK Mean Effective Pressure Bmep (psi)	Fuel (P.N)	Spark Advance (°BTDC)	Estimated Indicated Mean Effective Pressure IMEP (psi)	Estimated IMEP corrected to 100/130 Fuel IMEP (psi)	Estimated IMEP corrected to a Compression Ratio of 7.0 IMEP (psi)	IMEP Ratio, Sleeve to Poppet Valve	Estimated compression ratio of R-2800 to Give "Hercules" IMEP
Take-Off (Full rich no ADI)	P&W R-2800 CB17	2200	2800	2800	222	108/135	20°	288	277	271	—	5.8
	Bristol Hercules 730	2040	2800	3033	244	100/130	15°	318	—	—	1.17	—
Cruise (lean)	P&W R-2800 CB17	945	1600	1600	167	108/135	35°	189	175	159	—	6.3
	Bristol Hercules 730	860	1600	1733	180	100/130	23°	207	—	—	1.30	—

See Appendix 2 for discussion of assumptions

r = 6.75 for R-2800
r = 7.0 for Hercules

Notes: 1) The engine performance given in this table is based on the following:

- Pratt and Whitney Specification number 8139, revised 6/14/51 for the P&W CB17
- *Latest Bristol Piston Engines*; Flight, 1/8/48; containing performance maps for the Hercules engine

2) For Engine dimensions see Table 1

3) Spark Advance figures for the Hercules are from ref 3, Fig. 22.

Tests performed by NACA on an un-identified 4.500” bore sleeve-valve cylinder[26] are not directly comparable to the results shown in Table 4, but they do point out the necessity of providing ample flow area to the two intake ports not in a direct line with the intake manifold (see Fig. 4). The NACA work reports that the total pressure in the branches supplying these ports was as little as 75% of the total pressure within the manifold entrance. Providing the necessary flow area probably accounts for the increased cylinder spacing of the in-line, liquid-cooled, sleeve-valve engines shown in Table 2.

It seems quite clear that, from the air flow aspect, the sleeve-valve had an important advantage. It could provide very significant amounts of swirl without sacrificing volumetric efficiency. This characteristic, together with the ability to put the combustion chamber in the cylinder head (since there were no valves there), gave the sleeve-valve Diesel engines excellent combustion characteristics and the ability to use single hole fuel injection nozzles with no spring loaded valves[27]. As we shall see in a following section, it was this same characteristic in spark ignition engines that allowed the sleeve-valve aircraft engines to operate at a higher detonation limited IMEP. The data in Table 4 indicates that, with careful intake port and valve design, higher piston speeds were possible with poppet-valve engines if air flow were the limiting factor. Whether or not this would also be the case with sleeve-valve engines has not been shown here. As already discussed the many factors that enter into the size and number of ports makes speculation on this point unproductive.

10. Detonation Limited Performance

We have seen that an increased detonation limit was the major claim which Ricardo made for the sleeve-valve engine. His claim was referenced to an increase in detonation limited compression ratio in naturally aspirated engines. Since we are dealing with supercharged engines we must evaluate the detonation limits in terms of IMEP. This involves estimating the friction, pumping and supercharger work and adding them to the brake output to get the indicated work. The assumptions and method used are given in Appendix 2.

We have chosen the P&W R-2800 and the Bristol Hercules to make this comparison since they are both air-cooled, were rated for commercial applications (and hence were presumably competitive with each other), and had the same bore (the most important engine dimension with regard to detonation). Table 5 shows the two conditions for which the analysis was carried out—take-off, and a cruising condition at minimum specific fuel consumption. These conditions were chosen so as to evaluate the relative detonation limits under full rich (take-off) and lean mixture conditions. It also allows for a check on the method of calculating the IMEP by looking at how accurately the analysis predicts fuel consumption versus that given on the engine performance maps.

Once the IMEP has been estimated, as shown in Table 5, column 7, it must be corrected for the different fuels used and the different compression ratios of the two engines. The correction for fuel difference is simply made by the ratio of the performance number (P.N.) at the rich (130/135) and lean (100/108) conditions to give the values for the R-2800 in column 8. Data from [43] was used to correct the R-2800 to the same compression ratio as the Hercules. This data was obtained on a P&W engine at values of IMEP in the range of those given in Table 5. Knock limited IMEP was measured versus compression ratio at three values of fuel/air ratio; full rich takeoff, best power and lean (best economy). The full rich curve was used to correct the compression ratio at takeoff and the lean curve for the cruise condition. These corrections are somewhat subjective since extrapolations are involved (The lowest compression ratio tested was 6.7 and the highest was 8.00.) and the spark advance is not specified.

Column 10 shows the Hercules to have a 17% higher detonation limited IMEP at rich mixture and 30% higher at lean mixtures. Column 11 gives an estimated compression ratio that would have allowed the R-2800 to run at the same detonation limited IMEP as the Hercules. The difference between compression ratios at the same detonation limit is 1.2 for the rich mixture and 0.7 for the lean mixture. Knock limited IMEP is a much weaker function of compression ratio at rich mixtures than at lean. Ricardo’s claim for a one compression ratio advantage for the sleeve-valve was probably for a rich mixture (best power) which would indicate that his claim was justified for the supercharged aircraft engine.

We have already discussed what the likely source of this sleeve-valve advantage was. It had little or nothing to do with the absence of a hot exhaust valve. Experiments carried out with externally cooled exhaust valves[28, 29] have shown little effect on detonation. Conversely, experiments with temperature controlled pistons have shown a marked increase in the tendency to detonate with higher piston temperatures[30[. And, as we have seen, piston temperatures with at least some sleeve-valve engines were higher than in poppet-valve engines.

We have seen that the sleeve-valve had an inherent tendency to produce swirl in the incoming charge and that this could be enhanced by suitable arrangement of the ports. Figure 14 shows the influence of air motion on detonation limited compression ratio. This data, taken from Hurley and Cook[31], shows that an increase of two compression ratios was possible in a sleeve-valve engine simply by manipulating the porting with a concomitant reduction in best power spark advance, due to higher flame speed.

Increases in detonation limited IMEP have also been demonstrated in poppet-valve engines by using shrouded valves to induce swirl[28]. While not as pronounced as the improvements shown in Figure 14, they are sufficient to account for the differences shown in Table 5. However, none of the aircraft poppet-valve engines considered here utilized shrouded valves or an intake port designed to produce a significant amount of swirl.

Another benefit of high swirl is to reduce the cycle-to-cycle variation in peak firing pressure[32[. This has the effect of reducing the number of cycles which detonate heavily if the average cycle is at incipient detonation. Therefore, an engine with lower cycle-to-cycle variation can be operated at a higher detonation limited IMEP for the same detonation intensity.

The procedure just described for the air-cooled engines was applied to the liquid-cooled engines of Table 3 in order to estimate the maximum detonation limited performance of the two sleeve-valve engines. The analysis indicated that the Sabre VA rating was not limited by detonation, and that it should have been capable of about 3,000 BHP. In fact a later model, the Sabre VII, was rated at 3,055 BHP. The analysis for the Eagle indicates it should have been capable of about 4,300 BHP on 115/150 fuel. This rating would have made it competitive with the Rolls-Royce Griffon 130 on a weight per horsepower basis, but it apparently was never rated at that horsepower. It also would have been the most powerful aircraft piston engine by a good margin.

11. Friction

In this section we will look at the claim for equal mechanical losses between the sleeve-valve and poppet-valve engines. While comparable motoring tests are referred to in the literature on the subject, your author has not found published details of these tests. In order to examine this claim, therefore, we will attempt a detailed look at the influence on mechanical FMEP of the presence of the sleeve.

This procedure utilizes the approach taken by Bishop[33] in his paper published in 1964 where empirical relationships for the mechanical FMEP of the component parts of an engine were developed based on data from a wide variety of engine types. Since all of the data used to develop these expression came from poppet-valve engines it was necessary to modify Bishop's expressions to handle the effect of the sleeve on friction.

Other than the effect of the sleeve on piston and ring friction, we need only consider the friction of the sleeve itself, since the remainder of the engine is the same as a poppet-valve engine. Bishop also provides an expression for the FMEP of the poppet-valve system which allows us to make a comparison as follows:

- Poppet-valve Engine – piston and rings plus valve gear.
- Sleeve-valve Engine – piston and rings as affected by the sleeve motion plus the friction of the sleeve itself.

We will use the Bristol Centaurus as the basis for comparison and, for the poppet-valve case, assume it would have had the same size valves as the P&W R-2800 since they had the same bore.

Figure 15 gives relevant data for the sleeve and piston of the Centaurus engine, i.e. sleeve stroke and angular travel. It should be recalled that the sleeve motion is both axial (in the direction of the cylinder bore) and tangential, under the influence of its simple crank mechanism. Figure 15 also shows the piston velocity as a function of crank angle at an engine speed of 2,400 RPM. Also shown is the axial component of velocity and the total velocity of any point on the sleeve, also as a function of crank angle. These plots show that the velocity of the sleeve relative to the piston is significant (700 ft/min) when the piston is at top and bottom dead center. They also show that the axial movement of the sleeve is in the same direction as the piston on the expansion and compression strokes, thereby reducing the relative piston speed, and in the opposite direction on the exhaust and intake strokes.

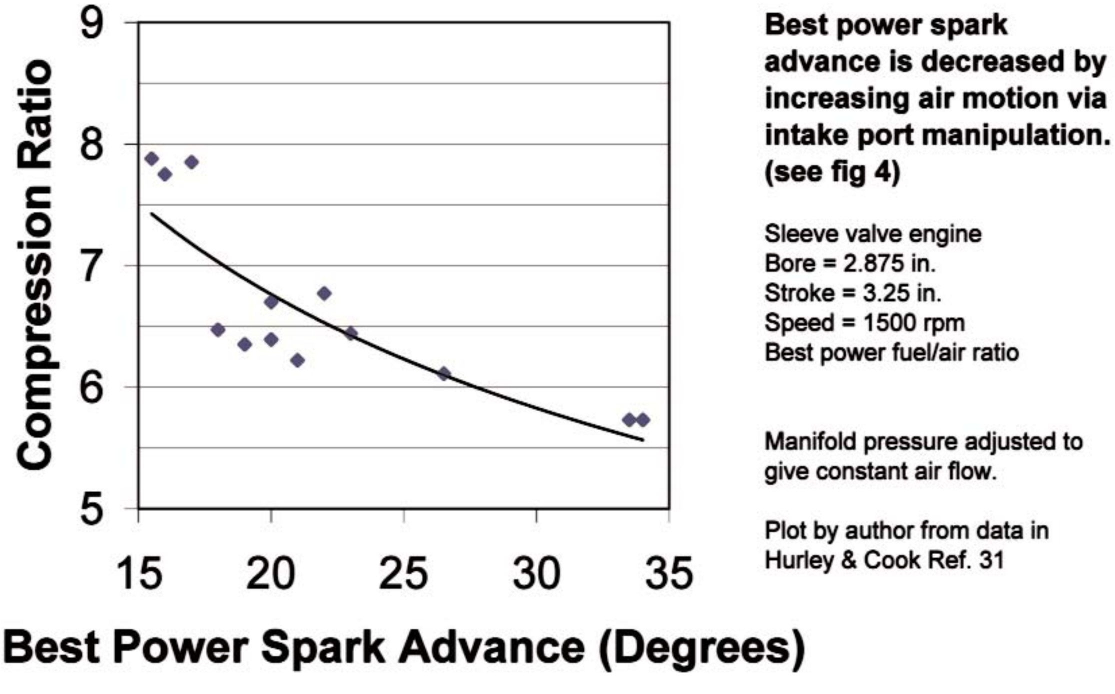

Fig. 14. Influence of Air Motion and Turbulence on Detonation-Limited Compression Ratio

Bishop's analysis of piston and ring friction indicates a strong influence from coulomb friction, i.e., friction forces independent of piston velocity. Bishop breaks down the ring and piston friction into three terms: ring tension, gas pressure behind the piston rings, and viscous friction of piston and rings. The last term is the only one where piston velocity is important and represents that portion of the piston stroke where hydrodynamic lubrication is occurring. It would seem clear that the motion of the sleeve relative to the piston and rings would alter the relative importance of these three components of piston and ring friction. It has been well established in experimental engines, where axial forces on the cylinder wall have been measured, that these forces are relatively high when there is little or no relative motion between piston and cylinder. These high forces are due to boundary lubrication and are a weak function of speed but a strong function of MEP.

We will estimate the friction of the sleeve-valve configuration, which will, of course, include the coulomb friction term. In addition to the piston velocity, compression ratio, and number of rings, the analysis requires an effective skirt length, M, defined as the projected area of the piston skirt divided by the bore. Data derived from reference 20 gives a value of M for the Centaurus of 0.85". This is a very low value but plausible given the very short Bristol piston design. Equivalent values for the Allison V-1710 and Wright R-1820 were 1.6" and 2.0", respectively. Automotive practice of the early 1960s, when Bishop's work was carried out, was for M values of about 2.0".

In evaluating the sleeve, the friction of its inner diameter is computed based on an effective piston length of 0.85", since the piston is the primary rubbing surface (the two cylinder head rings are added to the piston ring total) while the effective length on the outer diameter is taken as the engine stroke plus the sleeve stroke less the port area divided by the bore, giving a value of M=8.0". It is assumed that there are no rings on the outer diameter of the sleeve, so all of the friction is viscous piston.

With appropriate modifications to Bishop's relationships for the shorter stroke and half speed of the sleeve, the friction analysis indicates the following for the condition shown in Figure 15 and atmospheric manifold pressure.

Poppet-valve Centaurus

Wall tension of rings	1.8 psi
Gas pressure behind rings	1.0 psi
Viscous piston	1.3 psi
Total, rings and piston	4.1 psi
Valve train	0.6 psi
Total	4.7 psi

Sleeve-valve Centaurus (with coulomb friction)

Total, rings and piston	4.1 psi
Inner surface of sleeve	0.2 psi
Outer surface of sleeve	1.4 psi
Total	5.7 psi

Sleeve-valve Centaurus (without coulomb friction)

Total, rings and piston	1.3 psi
Inner surface of sleeve	0.0 psi
Outer surface of sleeve	1.4 psi
Total	l2.7 psi

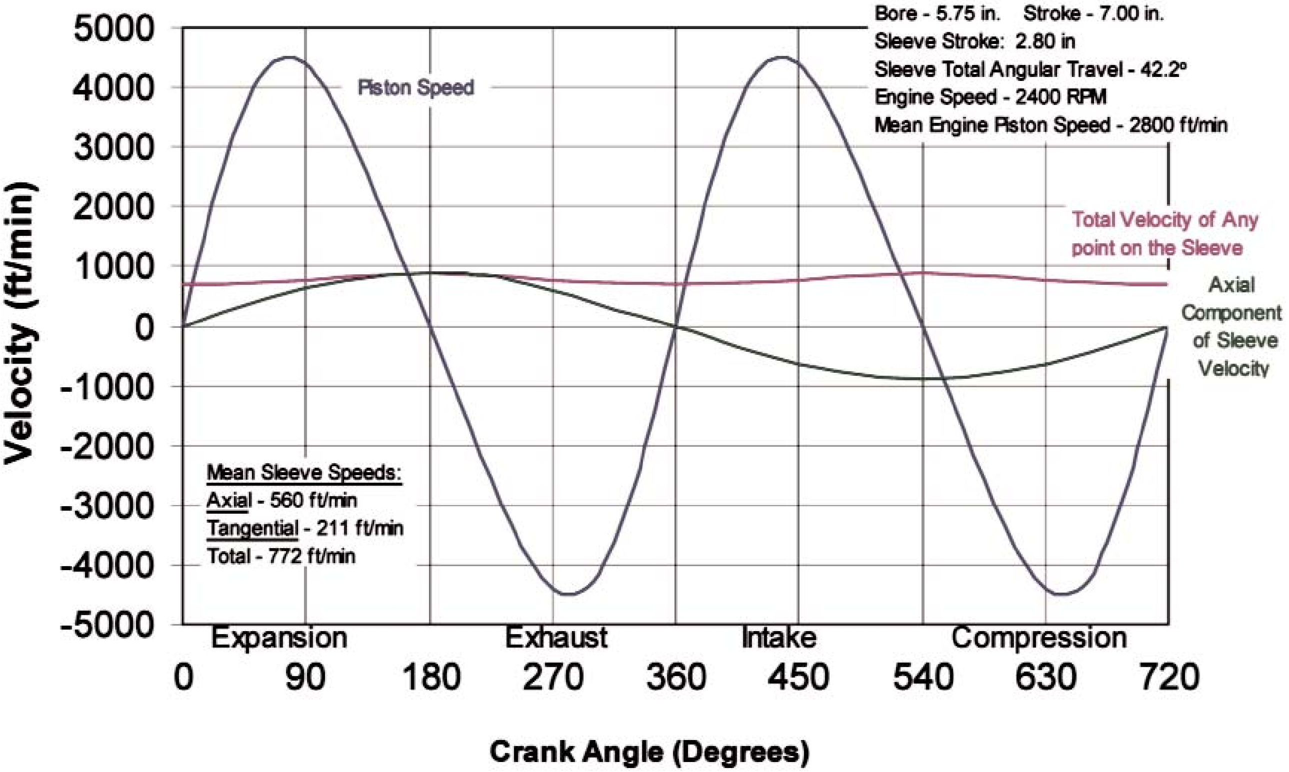

Fig. 15. Piston and Sleeve Velocities versus Crank Angle: Bristol Centaurus

This analysis indicates a range of variation of sleeve-valve friction of about +1 psi assuming the sleeve has no effect on coulomb friction, and -2.0 psi assuming no coulomb friction. In short, the analysis says that the claims are probably correct; i.e. the sleeve-valve engine's mechanical friction was about the same as that of poppet-valve engines.

The relatively low value of effective piston length for the Bristol engines may explain their low fuel consumption relative to some poppet-valve engines. Differences in compression ratio and ability to run leaner mixtures do not completely account for differences in fuel consumption under rich and lean conditions.

12. Oil Consumption

Perhaps the most difficult aspect of sleeve-valve engine performance to rationalize is the oil consumption claims. Published information in the post WWII era give oil consumption figures on a weight per horsepower-hour basis at about half for the Bristol sleeve-valve engines than comparable American poppet-valve engines (P&W and Wright). The specific oil consumption at cruise conditions for the Bristol Hercules and Centaurus was given as 0.008 lb/HP/hr versus 0.015 for the P&W R-2800[34]. That this seems counter-intuitive is based on the following characteristics of the sleeve-valve design: (See Figure 3).

- A continuous oil film is required between the outside surface of the sleeve and the cylinder barrel. The cylinder barrel contains the intake and exhaust ports and the sleeve ports themselves are oscillating in the oil film and communicating with the cylinder ports. This would seem to ensure a loss of oil both into the exhaust port and into the combustion space.
- Sufficient oil must arrive at the stationary cylinder head rings to provide a hydrodynamic film. Some of this oil must be consumed in the process of getting to these rings.

Poppet-valve engines do have another path to oil consumption not present in sleeve-valve engines, namely the clearance between the valve stems and guides. This seems an unlikely source of the difference between the two types, especially when manifold pressure is higher than atmospheric pressure.

The controlling factor in oil consumption in a conventional poppet-valve engine is the quantity of oil deposited on the cylinder wall and the resulting average film thickness after the piston and rings have completed a cycle. The design of the piston ring pack is carefully adjusted to provide sufficient oil film to handle the following situations:

- The top ring must have sufficient lubricating oil, fairly evenly distributed around its circumference, to provide squeeze film lubrication when the ring is stationary at firing top dead center.
- The piston skirt must have sufficient oil, again well distributed over its bearing surface, to form a hydrodynamic film when the piston is moving with significant velocity. This problem is aggravated by the fact that the piston skirt may not bear uniformly on the bore, but may, under some operating conditions, make line contact with the bore in the direction of motion, thus making the development of a hydrodynamic film very difficult.
- The quantity of oil deposited on the cylinder must be sufficient to resist dilution by raw fuel under start-up and extremely rich running conditions as existed at take-off in aircraft engines. Such dilution could lead to piston and ring scuffing.

It can be reasoned that the sleeve-valve could mitigate the above conditions, particularly the first two. The sleeve motion acts to spread any oil around the circumference of the rings and piston. If there is an area where the oil film is marginal, the only mechanism for alleviating the situation in a conventional engine is to adjust the ring pack to allow more oil to stay on the bore and hope that the starved areas are replenished. The motion of the sleeve could have made this a more efficient process, allowing the sleeve-valve engine ring pack to remove more oil than in a conventional engine.

The effectiveness of the piston ring assembly in controlling oil consumption may be compromised by cylinder bores that go out of round during operation due to thermal effects. Ricardo[1] showed that the sleeve in liquid-cooled engines acted to distribute the heat losses more uniformly around the bore. One could speculate that the same effect in the air-cooled engines might also have acted to keep the bores more round than in poppet-valve engines.

The Napier Sabre engine's sleeves had inclined grooves on their inner diameters (see Figure 5) which contained holes. These grooves overlapped each other circumferentially and acted to wipe excess oil off the piston and allow it to pass through to the crankcase. This could have been a more effective way of controlling oil consumption than the conventional scraper ring with passages through the piston.

It should be noted that the oil consumption of these high output aircraft engines was extremely high by modern standards, almost two orders of magnitude higher than current automotive gasoline engine practice and about one order of magnitude higher than modern Diesel engines. There is little doubt high oil consumption was necessary to give acceptable ring and cylinder durability in these engines, but it does show that, if the sleeve-valve could handle less oil consumption, the ability to adjust the ring pack to achieve this result was most certainly possible.

13. Balance Considerations

The piston reciprocating mechanism of the sleeve-valve engines was identical to conventional poppet-valve piston engines. The radial air-cooled engines used the master/articulated connecting rod while the in-line liquid-cooled engines used the fork and blade connecting rod arrangement. From the point of view of unbalanced forces and moments due to piston motion, there was no difference between sleeve and poppet-valve engines. Both the P&W and Wright 18-cylinder engines were equipped with second order (twice engine speed) balancers, which consisted of counterweights concentric with the crankshaft acting to cancel an unbalanced moment due to the geometry of the master/articulated connecting rod arrangement and the mass of the pistons. Bristol never adopted this arrangement. The reason is not known to the author; perhaps the lower piston mass of the Bristol engines reduced the problem to manageable proportions for the airframe manufacturers. It also could be that the complex of gears required to drive the sleeves made it too difficult to incorporate a second order balancer. Another factor may have been, as we have seen, the relative weight disadvantage under which the sleeve-valve engines were already laboring.

Unbalanced forces and moments due to the sleeves also require our consideration since the sleeves had significant weight. For the radial engines, an investigation of both seven and nine cylinders per row shows that all reciprocating forces due to the sleeve at half engine speed are balanced (author's analysis). Since the motion of the sleeve (unlike the pistons) is purely sinusoidal, there are no higher orders.

For the in-line sleeve-valve engine, however, all firing orders for a standard six-cylinder symmetrical crank result in unbalanced moments but no unbalanced forces at half engine speed[35]. Both the Napier Sabre and Rolls-Royce Eagle employed a conventional six-cylinder crank. The firing order chosen for the Sabre minimized the unbalanced moment for six of the twelve cylinders horizontally opposed on a single crank. The additional six cylinders reduced this moment but did not eliminate it. The second crank with its twelve cylinders (see Figure 5) was timed 180° out of phase, thereby allowing its unbalanced moment to cancel that of the other crank. This allowed the Sabre and Eagle to be inherently balanced and therefore, in this respect, on a par with the V-12 liquid-cooled poppet-valve engines.

14. Conclusions

14.1. Weight and Size

Both air and liquid-cooled sleeve-valve engines were heavier per unit of displacement than their poppet-valve counterparts. The Bristol air-cooled engines were competitive on a weight per take-off horsepower basis while only the Napier Sabre in its VII A version was competitive with the liquid-cooled poppet-valve engines on the same basis.

The frontal area of the radial sleeve-valve engine was comparable to the poppet-valve radials, while the liquid-cooled sleeve-valve engines were somewhat larger than the poppet-valve engines. The latter comparison is somewhat subjective since both of the liquid-cooled sleeve-valve engines were of an H configuration while the poppet-valve engines were all V-12s. There were no poppet-valve H configurations with which to compare the sleeve-valve engines, so one cannot state definitively that the difference in the frontal area was due solely to the presence of the sleeve-valve.

14.2. Detonation

For the two engines examined the air-cooled sleeve-valve engine had a significant advantage over the poppet-valve engine in detonation limited IMEP at both rich and lean mixtures. This translated into roughly one compression ratio at rich mixtures if the engines were operated at the same IMEP; a value close to the value Ricardo claimed for the advantage of the sleeve.

This improvement for the sleeve-valve was very likely due to the following:

- Higher flame speed due to air motion (swirl) inherent in the sleeve-valve design, and
- Lower cycle-to-cycle variation in peak firing pressure due to port induced swirl.

Any differences in internal surface temperatures probably worked to the sleeve-valve's disadvantage. Exhaust valve surface temperature was not a factor.

The liquid-cooled Rolls-Royce Eagle was apparently never developed to the point that it could take advantage of the higher detonation limit that its sleeve-valve should have given it.

14.3. Air Flow

As configured in the Bristol engines, the sleeve-valve did not provide the potential for higher volumetric efficiencies than in poppet-valve engines. From the point of view of air flow, its main advantage was its swirl inducing characteristic and its consequent effect on detonation. Higher surface temperatures in sleeve-valve cylinders due to the additional thermal barrier introduced by the sleeve and its oil film as well as difficulties in cooling the cylinder head in the air-cooled sleeve-valve engines would have had a negative effect on volumetric efficiency.

14.4. Friction

The claims made for sleeve-valve engine friction are most likely justified. Even without the assumption that relative motion between the sleeve and piston reduced or eliminated the coulomb friction component of total friction, the sleeve did not contribute all that much more to the friction as compared to the valve gear of a poppet-valve engine. Most of the incremental friction from the sleeve would appear to have come from its outer surface, where the rubbing area is quite high. Neglecting coulomb friction, the FMEP of the outer surface of the sleeve is higher than the viscous piston friction, despite its shorter stroke and slower speed.

15. Summary

These conclusions testify to a remarkable effort by some very talented engineers. Anyone with experience in the development of complex mechanical devices can appreciate how much time, effort, and tenacity it surely took to bring these engines to the performance level they ultimately achieved. Starting somewhat later than Bristol, both Napier and Rolls-Royce had difficulty in achieving the full potential of the Sabre and Eagle, despite their extensive experience with poppet-valve engines and not having to deal with the cylinder head cooling issue. As Table 3 indicates, the Eagle was probably never rated at its full potential. The many references in the literature (mostly anecdotal) to the "high manifold pressure" required to get the desired output indicates the engine was probably some way from being fully developed.

One should also bear in mind that in the time frame we are considering, the production of poppet-valves had become a specialty of a few large firms who worked with engine manufacturers to solve their particular developmental problems. This spread the cost of valves, valve guides and seats over the entire engine industry, including industrial and automotive. Bristol had no such luxury with their sleeve-valve. They were the experts and even were obliged to help Napier with sleeves at a crucial point in the development of the Sabre.

One could argue that Bristol had an advantage in its support from the British Air Ministry without which, according to Fedden [3], "…it is only fair to say that it is somewhat problematical if the Bristol Co. could have pursued this work to a satisfactory conclusion…". Bristol was not unique in having government support for engine development. The aircraft engine industry was born and came of age during and between two world wars. Though it took different forms in different countries, both the U.S. and the U.K. governments heavily supported engine development[36].

Trying to arrive at a meaningful cost comparison between the air-cooled poppet and sleeve-valve engines is far beyond the scope of this discussion. To do so would require not only the details surrounding the selling price of the engine, but also a life cycle cost based on very similar duty cycles; i.e. the same number of take-offs between major overhauls and the same cruising power as a percentage of take-off power. While the sleeve-valve engines had a longer time between overhauls as compared to poppet-valve engines, the cost of an overhaul must be included to get a true comparison. Rod Banks[37] was of the opinion that the Wright and P&W engines "were more economical to manufacture than any of the equivalent Bristol sleeve-valve types." As director of engine production for the British government during World War II, he was in a position to make that judgment. He stated in the same source that during the war, the Bristol Hercules cost twice as much in time and material (no developmental costs) to produce on a per horsepower basis as the Merlin.

This leaves us with the question as to whether or not the sleeve-valve engine was worth the developmental effort. With the invention, development, and rapid evolution of the aircraft gas turbine well behind us, it is fairly easy to say that the effort was not justified. But from the point of view of the engine designer of the 1930s, the picture is not so clear. A proliferation of design ideas for higher horsepower piston engines were under consideration contemporaneously with the introduction of the gas turbine in aircraft. They had no way of judging accurately how quickly the new device would evolve with regard to reliability, efficiency, and cost. The sleeve-valve engine was still being considered at Rolls-Royce for some of these late designs even though they had already become involved with Whittle's engine. I would argue that the Rolls-Royce Eagle could have been the most powerful piston engine had it been fully developed and that it could have shouldered some of the final military and commercial applications that were left to their Griffon, the P&W R-4360, the turbo-compounded version of the Wright R-3350, and the Bristol Hercules and Centaurus. A few years difference in the rate of evolution of the gas turbine is all it would have taken. With the passage of time, the question of "was it worth it?" will fade away, and these engines will be studied and appreciated for what they are—masterpieces of the art of mechanical engineering.

Appendix I: Definitions

The author has written this paper with the assumption that the reader understands the operating principle of the reciprocating internal combustion engine and is generally aware of mechanical engineering technology. One concept that persons not directly involved in the reciprocating engine field may not be aware of is that of "mean effective pressure". This is defined as that *constant* pressure which, acting over the displacement of the engine, will produce the same work, *per cycle*, as the actual cylinder pressure. The advantage of the concept of mean effective pressure is that it eliminates engine size as a measure of the work being performed per unit time. A further advantage is that it allows all of the power producing and absorbing portions of the engine cycle to be expressed in terms of mean effective pressure as follows:

IMEP: Indicated Mean Effective Pressure

The constant pressure which would give the same net work as the varying pressures occurring during the compression and expansion strokes.

PMEP: Pumping Mean Effective Pressure

The constant pressure which would give the same net work as the varying pressures occurring during the exhaust and intake strokes.

CMEP: Compressor Mean Effective Pressure

The constant pressure which would give the same net work as is given up to drive an engine driven supercharger.

FMEP: Friction Mean Effective Pressure

The constant pressure which would give the same net work as is given up to mechanical friction

BMEP: Brake Mean Effective Pressure

The constant pressure which would give the same net work as obtained at the engine's output shaft.

From the above definitions, it is clear that
BMEP = IMEP – CMEP – FMEP – PMEP

PMEP may be either positive or negative depending on the values of intake and exhaust manifold pressures. The relationship between engine mean effective pressure, horsepower and speed is easily derived, as follows.

From the definition of MEP

MEP = Work per Cycle / Engine Displacement

Since horsepower is work per unit time, and the number of cycles in unit time in a four stroke cycle engine is the speed divided by two, the work per cycle is:

Work per Cycle = (2 * HP) / N
where HP = horsepower
N = engine speed.

The expression for mean effective pressure becomes:

MEP = (2 * HP) / (N * V_D)
where V_D = engine displacement.

In English units with V_D in cubic inches and N in revolutions per minute, this expression becomes:
MEP = (HP * 792,000) / (N * V_D)
where MEP is in pounds per square inch.

The usefulness of the expression for MEP can be illustrated with relation to Figures 9 and 10 of the text. It is easy to show that the expression for MEP gives the following for weight per brake horsepower.
(W / BHP) = (W / V_D) * (792,000 / (BMEP * N))

If an engine is relatively heavy, i.e., if it has a higher value of W / V_D than a competing engine, its product BMEP and N must be higher by the same amount to achieve the desired value of W / BHP.

Appendix II: Estimating Indicated Mean Effective Pressure

This is a brief outline of the approach used to estimate the IMEP of the Bristol Hercules and P&W R-2800 engines in Table 5.

Appendix I has defined MEP and shown that

BMEP = IMEP – CMEP – FMEP – PMEP (equation 1)

The relationship between MEP and power was also shown to be
MEP = (HP * 792,000) / (N * V_D) psi (equation 2)

If it is desired to find the IMEP at a particular operating condition (BHP & N), one calculates the BMEP from (equation 2). Then one guesses the manifold pressure and compressor adiabatic efficiency to get an inlet manifold density, estimates the volumetric efficiency if no measured value is available, estimates the indicated efficiency and fuel/air ratio and calculates the IMEP. Some iteration with the compressor map may be necessary if the air flow calculated causes a shift in the assumed operating point on the map large enough to affect the assumed efficiency. The CMEP may then be calculated based on the assumed intake manifold conditions and a typical compressor map. The FMEP is calculated based on the piston speed and IMEP and the PMEP is calculated based on the intake and exhaust manifold pressure, the intake system Mach index, Z, defined in Table 4, and the ratio of exhaust to intake port area.

With the values of IMEP, CMEP, FMEP and PMEP thus established, the BMEP can be calculated from (equation 1) and compared to the desired value. The procedure is repeated until the values of BMEP match.

The assumptions made and sources are as follows:

IMEP – Requires volumetric efficiency, indicated efficiency and fuel/air ratio.

Volumetric Efficiency – Actual test data where possible, otherwise estimated from valve overlap, Z, and ratio of exhaust to intake manifold pressure. In the case of the R-2800 test data was available[38].

Indicated Efficiency – The fuel/air cycle efficiency was calculated based on the compression ratio and fuel/air ratio using the technique developed by Edson & Taylor[39]. This value was then multiplied by a constant based on experimental data, varying between 0.85 and 0.90, to get the actual indicated cycle efficiency.

Fuel/Air Ratio – Based on aircraft engine practice and characteristics of injection carburetors used on the engines described in Table 5.

CMEP – Requires pressure ratio, total flow of air and fuel, a compressor map for the centrifugal compressor, the gear ratio between engine and supercharger, the diameter of the compressor impeller, and the efficiency of the gear train driving the supercharger.

Pressure Ratio – Since the manifold pressure is an assumed value, the pressure ratio is established by atmospheric pressure and assumed pressure losses in the intake and discharge passages. The tip speed of the compressor establishes whether or not the assumed manifold pressure is possible with a given gear ratio and impeller diameter.

Flow Rate – Established by the engine speed, volumetric efficiency, manifold density, and fuel/air ratio.

Compressor Map – Supercharger compressor characteristics are from Wright Aeronautical circa 1945[40] as arranged by Taylor[22]. This map gives a peak compressor adiabatic efficiency of 81% at a pressure ratio of 2.0 and a dimensionless mass flow of 0.10.

Gear Ratio & Impeller Diameter – *Jane's* and manufacturer's information.

Gear Train Efficiency – Assumed to be 90%. This is a figure used by the NACA in their performance calculations.

FMEP – Very little friction data is available in the open literature for the later model high output aircraft piston engines. Taylor[22] gives data for the Allison V-1710 apparently given to him by the manufacturer. The author has used this data on various liquid-cooled and air-cooled engines with reasonable results. Reasonable, meaning that manifold pressures predicted to give a certain output agree with published values reasonably well and brake thermal efficiencies predicted also agree with manufacturer's claims fairly well.

The NACA used an expression for friction horsepower that, when reduced to a curve of FMEP + PMEP versus piston speed, agrees with the curve given by Taylor to within one psi up to about 2,000 ft/min piston speed and then lags so that at 3,000 ft/min it is about 5.0 psi lower than the Allison curve. The NACA expression assumes PMEP is 0 if the exhaust and intake manifold pressure are equal while the techniques used to calculate the PMEP by the author indicate the PMEP of the Allison engine is about 6.0 psi at a piston speed of 3,000 ft/min.

The NACA used the same expression for friction for both in-line liquid-cooled engines and air-cooled radial engines and claimed it was based on motoring data (unreferenced). In short, I have found no alternative to date other than to use the Allison V-1710 data as presented by Taylor, and to use Taylor's technique to correct the FMEP for IMEP.

The discussion of sleeve-valve engine friction presented in this paper does not indicate that any modification of the technique for predicting FMEP is necessary for the Bristol Hercules engine.

PMEP – The technique used follows Taylor, which is derived from two sources[41, 42]. Valve (or port) areas are required as are flow coefficients (see Table 4). The remaining variables are intake and exhaust manifold pressures and piston speed.

The values of MEP's for the lean condition of Table 5 are given below.

	R-2800	**Hercules**
IMEP	189	207 (psi)
BMEP	167	180 (psi)
CMEP	8	11 (psi)
FMEP	15	16 (psi)
PMEP	-1	0 (psi)
BSFC(predicted)	0.43	0.41 (lb/HP/hr)

These predicted BSFCs are fairly close to the performance map values as are ones calculated for the take-off condition.

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Abbreviations

M.I.T. – Massachusetts Institute of Technology, Cambridge, MA., USA

NACA – National Advisory Committee for Aeronautics, USA

ARR – Advanced Research Reports

TN – Technical Note

TR – Technical Report

SAE – Society of Automotive Engineers, USA

Note to Reader

The author welcomes comments and urges anyone with information missing from Table 2 on the R-R Griffon and Eagle to contact him via the webmaster.

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