TECHNICAL APPENDICES

TECHNICAL APPENDIX A

The Technical Dispute Over Cooling

By Robert Schlaifer

The great controversy over the respective merits of air and liquid cooling continued throughout the period between the two wars and is still alive today in theory, although its practical importance has been greatly reduced by the fact that the only high-power engines being newly undertaken are gas turbines. The reason for going into some detail concerning this controversy here is, however, largely unrelated to its interest as a part of technical history.

First, this is an excellent example of the sort of complex technical question constantly presented to government officials in charge of the award of public funds for the support of research and development. These officials have in general two courses open to them: they may award contracts only on the recommendation of industry, apportioning funds roughly on the basis of the general reputation of the firms suggesting and undertaking the projects, or they may make a technical evaluation of projects proposed by any source and then if necessary use their funds to persuade some firm or firms to carry out the projects which seem technically worth while. Development of liquid-cooled engines in the United States in the 1930's presents one of the most interesting cases of the second solution, where a government agency has believed itself obliged to rely on its own technical evaluation in the award of development funds.

Second, this development is of great interest because of the important role played by research done by a military service itself. The Army's own research on liquid cooling not only affected the decision to support the development of liquid-cooled engines, but very greatly influenced the number of different engines supported by the Army, the design of certain of these engines, and the choice of concerns to which development funds were awarded.

There is one factor in particular which makes exposition of the basic technical problem exceptionally complex. This is the fact that there were really two fundamental controversies involved, not just one, and that these two were sometimes linked and sometimes separate. The first issue is that of cooling per se. The second was that of in-line versus radial cylinder arrangement. Most liquid-cooled engines have used the in-line arrangement, and most air-cooled engines the radial, but this has been far from universally true. Except perhaps for extremely large engines with so many rows and banks that the radial and in-line are indistinguishable,[1] it is true that there is very little to be said for the liquid-cooled radial. It has been tried occasionally, twice in the United States in the 1930's, but it is fair to neglect it as not only unsuccessful (at least since the Salmson of the First World War) but rarely even considered. The in-line air-cooled engine, however, is by no means equally rare. This type has been under development and in production continuously since before the First World War. Since, however, by far the larger part of all effort devoted to the development of air-cooled high-power engines was devoted to the radial type, we shall in general consider the merits of the radial arrangement with those of air cooling per se, and those of the in-line arrangement with those of liquid cooling, leaving the in-line air-cooled engine to be treated as an occasional exception to the rule if the necessity arises.

Weight at Moderate Altitudes

Unquestionably the most important single measure of the performance of an aircraft engine is its specific weight, i.e., the ratio of its weight to its power. If a fair comparison is to be made between liquid- and air-cooled engines, the weight of the cooling system (radiator, piping, and coolant) must be included with the "dry" weight of the liquid-cooled engine itself. It is equally important in principle, moreover, in comparing any two engines of any type or types, to include the weight of fuel and fuel tanks required for the desired length of flight, since one engine may be lighter than another but consume more fuel, so that the airplane with the heavier engine will still carry more payload. In many cases, of course, this will mean that of two engines each with its fuel, one will be lighter for flights up to a certain duration while the other will have the advantage for flights beyond this limit.

The power of all engines tends to decrease with every increase in altitude, but this loss of power can be prevented up to a certain altitude and diminished above that altitude by the use of sufficient supercharging. The altitude to which power loss can be prevented, however, and the extent to which it can be reduced above that altitude, vary not only with the design of the supercharger but with the design of the basic engine itself. Thus an engine which develops more power per pound, i.e., has a lower specific weight, than another at sea level may very well develop less, i.e., have a higher specific weight, above a certain altitude, even if equipped with a

[1]The liquid-cooled Lycoming XR-7755, under development in the latter part of the Second World War, can be equally well considered as having four rows of nine cylinders or nine banks of four cylinders.

supercharger of equally good design. Thus a meaningful comparison of the specific weights of two engines can be made only in terms of some particular altitude. The discussion of specific weights in the present section will be restricted to those altitudes at which most operational flying, both civilian and military, was conducted during the 1930's. The subject of "high-altitude" performance, requiring turbo or two-stage supercharging, is treated in the next section.

At the end of the 1920's the weight of American air-cooled engines per unit of power was very little more than that of liquid-cooled engines without their radiator and coolant,[2] and with water used as the coolant these added about ½ lb per horsepower, or about one-third the "dry" weight of the engine itself. Since additional weight in the power plant required a roughly equal additional weight of airplane structure to support it, liquid cooling subtracted from payload an amount roughly equal to two-thirds of the dry weight of the engine itself.

It was argued throughout the 1930's, however, that with sufficient development the liquid-cooled engine, with the cooling system and coolant included, could be made nearly if not just as light as the air-cooled engine. This was to be accomplished in two ways: by reducing the weight of the radiator and coolant required for a given power output, and by increasing the power obtained from an engine of given "dry" weight.

The weight of the radiator and coolant was to be reduced by using a coolant operating at a higher temperature than the boiling point of water, since if the temperature of the coolant and radiator was increased, heat could be dissipated at the same rate by a smaller and lighter radiator containing a lesser weight of coolant. In 1916 A. H. Gibson of the British Royal Aircraft Factory had made the first trials of a coolant with a boiling point higher than that of water, aniline. In 1923 the American Army, at the suggestion of S. D. Heron, a former colleague of Gibson, began the first development of the use of ethylene glycol, commonly known by the trade name Prestone. The Army converted some Curtiss D-12's and Conquerors to glycol cooling and demonstrated that by the use of glycol at 300°F the weight of radiator and coolant could be reduced to about half of what it was with water. Later American liquid-cooled engines were all developed for this system.[3]

Even if the weight of the cooling system could be much reduced, it could of course never be completely eliminated, so that if over-all

[2]The following data are given in the 1931 issue of *Jane's All the World's Aircraft*. In the category of medium-size engines with direct drive, the water-cooled D-12 weighed 1.5 lb/hp dry, while the air-cooled Wasp weighed 1.6 lb/hp. In the largest size, with geared drive, the water-cooled Conqueror weighed 1.5 lb/hp dry while the air-cooled Cyclone weighed 1.7 lb/hp.

[3]G. W. Frank, "High-Temperature Liquid-Cooling," *SAE Journal* (*Transactions*) 25, 1929, pp. 329-343. The figures for an experimental D-12 installation were 70% less radiator, 30% less coolant by volume (about 27% by weight).

equality with the air-cooled engine was to be achieved the specific weight of the liquid-cooled engine itself would have to be considerably lower than that of the air-cooled engine. This had to be done in spite of the fact that even without its cooling system the in-line type of engine generally used with liquid cooling weighs about 10% more per cubic inch of cylinder capacity than the radial type.[4] The advocates of liquid cooling believed, however, that the power delivered per cubic inch of displacement could be made so much greater in a liquid-cooled engine that its "dry" specific weight would be very much less, and its over-all specific weight including the cooling system little, if any, greater than that of the air-cooled engine.

An increase in the power of any engine, however brought about, makes necessary the dissipation of heat at a greater rate by the engine's cooling system. The first argument advanced in support of the view that a liquid-cooled engine could deliver more power than an air-cooled engine of the same size was that whereas a radiator could be made of any cooling capacity required, the total cooling capacity from fins which had to be constructed on the cylinder itself had a definite limit.[5]

In order to explain the other arguments used to support the view that the power of the liquid-cooled engine could be increased much more than that of the air-cooled, it is necessary to understand that the power of any engine varies with the product of two factors, the rpm, or frequency with which each cylinder is fired, and the "mean effective pressure" within the cylinder, which depends primarily although not exclusively on the degree to which the engine is supercharged. In 1930 the liquid-cooled engine had a considerable advantage in rpm, the Conqueror being rated at 2,450 rpm against 1,900 for the Cyclone, for example, and it was generally and correctly believed that this advantage could be maintained, both because the push-rod valve gear of the radial is less suited to high speed than the overhead camshaft of the in-line, and because the cylinders of in-line engines were normally smaller and their pistons and rods correspondingly lighter than those of the radial.

[4]At the beginning of the 1930's the dry weight of the direct-drive D-12 and the geared Conqueror was 0.59 lb/cu in., against 0.53 for the direct-drive Wasp and 0.50 for the geared Cyclone; in 1943 the two-stage Merlin weighed 0.99 lb/cu in. against 0.90 for the two-stage R-2800. The difference is primarily due to the fact that the in-line engine has a much greater weight of crankcase and crankshaft per cylinder.

[5]A deficiency in cooling is made up at high output in all types of engines by what is known as "fuel-cooling". The evaporation of liquid fuel lowers the temperature of the charge at any mixture ratio, but fuel-cooling consists in the supply, for its cooling effect alone, of more fuel than can be burned in the given amount of air. The limited possibilities of air cooling seemed to be indicated in the early 1930's by the fact that a good deal of fuel cooling was necessary at full throttle simply to avoid overheating of the engine, whereas fuel cooling was used in liquid-cooled engines only to avoid detonation (see below) and over-heating of the exhaust valves.

It was in mean effective pressure, however, that the advocates of the liquid-cooled engine believed that the greatest relative gains could be made. In 1930 the brake mean effective pressure of the unsupercharged production Conqueror was barely equal to that of the slightly supercharged American air-cooled engines, but the experimental supercharged Superconqueror had about 20% higher bmep, and it was believed that this advantage could be still further increased.

The great obstacle to advance in mean effective pressure has always been the problem of detonation. Detonation is destructive, over-rapid burning of the charge which occurs when the temperature and pressure of the charge become excessive as the charge is compressed by the piston and heated both by this compression and (to a very slight extent) by absorption of heat from the cylinder before it is fired by the spark. Detonation can occur even without any supercharging whatever, and supercharging makes it more likely to occur and more difficult to avoid because the pressure and temperature of the charge are increased by compression in the supercharger even before the charge enters the cylinder.[6]

There are three principal methods of preventing detonation in an engine. First is the use of fuels which are naturally less liable to detonate. This is applicable to either a liquid- or an air-cooled engine, although some fuels which are very good in antiknock value in a liquid-cooled engine are less effective in an air-cooled engine, whereas the reverse is never true.[7] Second, the compressed charge can be cooled in an intercooler before it enters the cylinders. Since intercoolers add so much to the weight and drag of an airplane that they were never used in service engines with single-stage superchargers, the comparative suitability of air- and liquid-cooled engines for intercooling has no place in this section. Third and last, detonation can be prevented by elimination of "hot spots" in the engine itself, usually the spark plugs and exhaust valves, which are among the most important causes of detonation. In the liquid-cooled engine such hot spots could be largely avoided by arranging the flow of coolant so as to prevent the formation of vapor pockets at these points. In air-cooled cylinders the design could to some extent be arranged to increase the flow of air past potential hot spots, but the results were much less effective.

At the very beginning of the 1930's one piece of experimental evidence was of particular importance in convincing Wright Field engineers that these theoretical arguments in favor of the liquid-cooled engine were sound in fact. This was a series of experiments conducted during 1930-1931 at Wright Field by S. D. Heron on a water-cooled version of the air-cooled cylinder which Heron had

[6]For a more complete discussion, see Heron's discussion above, pp. 568-571.

[7]This is due to the existence of hot spots in the air-cooled engine, to be discussed below.

developed in 1923-1924 for the Liberty engine. The experiments were begun largely with the purpose of investigating whether mean effective pressures already in use were about the limit which could be attained with poppet valves, so that any increase in output would have to be achieved with sleeve valves, as had been recently asserted by the British engineer, H. R. Ricardo. In order to obtain the additional cooling needed at higher power a water jacket was built around the barrel of this cylinder and a spray of water was directed on the head. The mean effective pressures which were easily attained were so astonishingly high — 360 psi on the first test, in comparison with roughly 150 psi used in current service engines — that a regular water-jacket was constructed around the entire cylinder and the experiments were continued with the object of developing a really high-performance liquid-cooled "Hyper" cylinder. This second series of experiments produced mean effective pressures of up to 480 psi at a compression ratio of 5:1 while Ricardo was obtaining only 450 psi from a sleeve-valve cylinder with a compression ratio of only 4:1. These results seemed to some to indicate that so much greater power per cubic inch could be easily obtained with liquid cooling than could even be hoped for with air that the resulting weight per unit of power of the complete power plant could not fail to be about as low as that of the best air-cooled engines.[8]

There was no reason to believe, however, that air-cooled engines would stand still while liquid-cooled engines were being developed to surpass them. In Britain the Chief Engineer of the Bristol Aero Engine Department, Roy Fedden, had obtained mean effective pressures of about 200 psi from experimental air-cooled cylinders even before 1930, and in the first half of the 1930's the NACA computed that mean effective pressures of 400 psi, not very much less than those obtained from the liquid-cooled Hyper cylinder, could be obtained from a Wasp cylinder with extremely fine finning. While these fins were so fine that it would have been extremely difficult to produce such cylinders in quantity, and they would have been insufficiently rugged in any case for a service engine, Bristol already had in production forged heads with machined fins, which could be made much closer together than cast fins whenever the latter ceased to be adequate.[9] Thus although the performance computed by the NACA was not actually achieved until years later, nevertheless the NACA report indicated the nature of the possibilities which were gradually achieved during the 1930's in the improvement of the air-cooled cylinder. Advances in

[8]Ford L. Prescott ultimately obtained over 500 psi from a liquid-cooled poppet-valve cylinder at Wright Field: see his article "Aircraft Engines of the Future," *Mechanical Engineering* 58, 1936, pp. 157-161.

[9]Part of the reason why the American companies used forged heads much later than the British was that they were able to make or buy much better castings than the British; cf. above, Chapter VI, p. 148, n. 39.

design, culminating at the end of the decade in the replacement of the cast aluminum head by the forged aluminum head with machined fins, together with the improvement made in fuels, made it possible between 1930 and 1940 roughly to double the mean effective pressures used in air-cooled engines. The rpm of air-cooled engines was also increased, although proportionally less, as cooling and mechanical design were improved.

While even these advances gave the air-cooled engine an output per cubic inch which was still considerably under that of liquid-cooled engines, they did mean that the advantage held by the former in the early 1930's was not increased, and the difference was in general more than compensated by the lesser weight per cubic inch of the air-cooled engine and the absence of radiator and coolant. When the war came the air-cooled engine still had a considerably lower ratio of weight to power at sea level and at moderate altitudes. Figures indicating this are given below, pp. 676-678.[10]

To the weight of the power plant must be added, as was said initially, the weight of the fuel necessary for the length of flight to be made and the weight of the tanks to contain it. In the 1920's the liquid-cooled engine could make up by a somewhat lower fuel consumption some of its disadvantage in installed weight. But the advantage in fuel consumption which had been large in the early 1920's had become very small by the beginning of the 1930's. Using 1931 figures, and assuming a weight of 0.5 lb/hp for the radiator, piping, and coolant of a water-cooled engine, the specific weight of the D-12 plus fuel became less than that of the Wasp only for flights of over 20 hours, and the specific weight of the Conqueror became less than that of the Cyclone only after 15 hours. Flights approaching such duration were rarely attempted at the time, and the flights ordinarily made in either military or commercial operations were so short that the slight difference in specific fuel consumption was unimportant. During the 1930's, moreover, the situation was actually reversed, and American air-cooled engines, which were the only engines in the world really developed for commercial service, had lower fuel consumption than the best foreign liquid-cooled engines,

[10]By the time of the Second World War, although not much before, the total installed weight of liquid-cooled engines was somewhat reduced in Britain below the weight of a corresponding installation in the United States by reductions in the weight of the radiator. As is set forth in Chapter VIII, Rolls Royce succeeded during the years 1936 to 1940 in reducing the weight of the radiator with its coolant by about 50%. In the United States the manufacturers of liquid-cooled engines took no responsibility whatever for radiators, and the single company which supplied most of them to the airframe builders did research and development to an extent determined by the value of the radiator business alone, not by its importance as an essential part of the whole power plant. Coolant radiators for liquid-cooled engines were in fact usually modeled on the oil-cooling radiators of air-cooled engines, although the differences between the properties of oil and those of water or glycol meant that the two problems were really considerably different.

which were designed primarily as fighter engines at a time when range was considered relatively unimportant in a fighter.[11] Even in America the need for long-range escort fighters was scarcely realized before the country was actually in the war. Lower fuel consumption was always of interest, however, and it was definitely a factor, if only a secondary one, in both the Army's and the Navy's support of liquid-cooled development during the 1930's.

Performance at High Altitude

The use of a supercharger to supply the engine at sea level with air more dense than atmospheric in order to increase its sea-level power has already been discussed. If the supercharger is able at sea level to supply air even more dense than the engine is able to use (because of mechanical limitations, insufficient cooling, or detonation), then up to some particular altitude, known as the critical altitude, it will be able despite the decreasing density of the atmosphere to supply air at least as dense as the engine can use and thus prevent any falling off of the power of the engine.[12]

We have already seen that supercharging at sea level creates serious difficulties with detonation, and in the case of air-cooled engines with cooling as well. The same problems arise even when it is not a question of increasing the intake pressure above a given value, but simply of maintaining the given pressure to a higher altitude. There is difficulty with detonation because, despite the fact that the air at altitude is colder than at sea level, compressing it to sea-level density results in a temperature and pressure considerably above those prevailing at sea level even with a very efficient supercharger and still further above with the generally inefficient superchargers of the 1930's.

As for detonation, the same arguments which were used to support the belief that the liquid-cooled engine could be more highly supercharged at sea level were used to support the view that it could be supercharged without detonation to higher altitude.

As for cooling, difficulty arises with air-cooled engines at altitude because as altitude increases the density of the atmosphere decreases

[11]In 1937 Pan American Airways regularly got a specific fuel consumption of 0.43 lb/hp hr from its air-cooled engines in transpacific service, while on the stand (where fuel cooling was less necessary) various American air-cooled engines were repeatedly tested at well under 0.40.

[12]It is important to emphasize that critical altitude is not by itself any criterion of merit, either of the engine or of the supercharger. With a given supercharger, weakening the mechanical strength of the engine or using fuel with a lower anti-knock value would increase the critical altitude, although the power of the new critical altitude would be no higher than it was before, and at all lower altitudes the power would be less. With a given basic engine a high degree of supercharging with an inefficient supercharger can give a higher critical altitude but less power at all altitudes than less but more efficient supercharging.

proportionally more than the temperature difference between the atmosphere and the cylinder fins increases. Thus a fin area which is able to dissipate the heat generated at a given power output at sea level is not able to dissipate the same heat from the same power at altitude. Here the liquid-cooled engine has a double advantage: not only is the size of the radiator free from any inherent limitation, but up to a very high altitude there will be no need to increase it, because, even with glycol cooling, the radiator is so cool compared to the fins of an air-cooled engine that the proportional increase in the differential between radiator and atmospheric temperature fully compensates for the decrease in air density.

Ever since the end of the First World War the Army had been fostering the development of the turbosupercharger in order to make possible high-altitude operation, but until the latter half of the 1930's the air-cooled engine was quite generally[13] believed unsuited to the high degree of supercharging provided by this device. In 1931 the Conqueror engines of a dozen P-6 fighters were equipped with turbosuperchargers to form the first service-test group of turbo-supercharged airplanes. A good deal of flying was done with these airplanes, and the merits thus demonstrated were a considerable encouragement to the turbo development program. In contrast, attempts made in 1932 and 1933 to use a turbosupercharger on the air-cooled Wasp of the P-12 were unsuccessful, although in part this lack of success was due to the use of too large a supercharger rather than to the inherent problems of the air-cooled engine.

Thus it is not surprising that when the Army set out in 1932 to develop a new two-place fighter with the new "side-type" turbo-supercharger it was built around the Conqueror, which was the only liquid-cooled engine in production, despite the fact that the Army believed that this engine was now obsolescent if not obsolete. The original prototype was the Detroit XP-900 or YP-24, ordered and built in fiscal 1932. After the intermediate stages represented by the Y1P-25 and PB-2, 50 PB-2A's were purchased from Consolidated, the successor of Detroit, in 1935. This airplane developed its maximum speed of a little over 230 mph at an altitude of 15,000 feet; the turbo was designed for no higher altitude primarily because of tactical considerations, although some of the Wright Field engineers were also afraid that it would not operate successfully at higher altitude. The PB-2 was the first of the fighters designed for modern tactics of fighting in groups and relying on speed and altitude rather than maneuverability. It was made obsolete only when the P-35 and P-36 appeared with the R-1830 engine developing 950 hp, or 36% more than the last model of the Conqueror.

[13]It was not until 1936, for example, that a representative of Pratt & Whitney could write (*SAE Journal (Transactions)* 39, 1936, p. 287) that this belief "is beginning to appear unsound."

It is true that the turbosupercharger itself was not in full production until 1939, and that from the appearance of the first supercharged Wasp in 1927 the gear-driven single-stage supercharging of American air-cooled engines was superior to that of the production Conqueror, but the theoretical superiority of liquid cooling for any type of supercharging was amply confirmed by the performance of the British Kestrel (cf. above, p. 252). The lack of a liquid-cooled engine with a gear-driven supercharger in the United States may have been due in part to technical difficulties,[14] but a tolerably successful Superconqueror with a geared supercharger was built before 1930 and was being operated by 1934 with more supercharging (about 12,000 feet) than any contemporary American air-cooled engine. The real reason that the development was not completed was that the Army, the only customer for the Conqueror at this time, preferred the turbosupercharger as being a way of getting the supercharging "free", i.e., without having to deduct from the engine power the power needed to drive the supercharger.

By the middle of the 1930's improvements in the cooling of air-cooled cylinders, improvements in fuels, and improvements in air-cooled cylinders to permit the use of these fuels had begun to reduce the superiority of liquid-cooled engines at altitude.[15] In 1938, when the Merlin II was in production with a critical altitude of 12,250 feet at "international" power on 87-octane gasoline, the R-1830-SCG had a critical altitude of 11,000 feet for the same type of power rating on the same fuel.

The turbosupercharger was not fully successful in service until nearly the middle of the Second World War, and as far as engines with gear-driven superchargers are concerned, air-cooled engines actually surpassed liquid-cooled engines in altitude supercharging in 1939 when the Pratt & Whitney R-1830 was put in production with a two-stage supercharger. Very probably the reason why Pratt & Whitney had begun this development as early as 1935, whereas Rolls Royce did not start work on a two-stage engine until 1940, was the fact that because the liquid-cooled engine could take a higher mixture temperature than the air-cooled it could be supercharged with a single-stage supercharger to the highest altitudes required by military operations in the 1930's whereas the air-cooled engine could not. Whatever the reason, the American air-cooled R-1830 in production with two-stage superchargers beginning late

[14]First, a supercharger complicates considerably the problems of the induction system of an in-line engine, whereas an integral supercharger actually simplifies those problems in a radial. Second, the drive of a geared supercharger is less likely to break when attached to the short, rigid crankshaft of a radial than when attached to the long, flexible shaft of an in-line engine.

[15]In 1934 a successful installation of turbosuperchargers on air-cooled engines was finally made, on the Cyclones of the Martin B-10A bomber, and in this same year Pratt & Whitney began work under Navy contract on a two-stage gear-driven supercharger, on which see above, p. 305, n. 7.

in 1939 had better altitude performance than the Merlin until a two-stage version of that engine was put in service late in 1941.[16]

The two-stage supercharger which was fitted to the Merlin in 1941, was, however, superior to the contemporary Pratt & Whitney two-stage supercharger in two respects: (1) it was appreciably more efficient, and (2) the installation included an aftercooler, which reduced the temperature of the charge after it had been compressed and thus permitted the use of higher manifold pressures than would have been possible with an intercooler between the two stages such as was used on the American engines. The greater efficiency of the Merlin supercharger at this date has nothing to do with the characteristics of the engine as such and thus is irrelevant for our present purpose. The design of an aftercooler for the Merlin was, however, very considerably easier than it would have been for a radial engine, where it was believed necessary in the 1930's to have an individual aftercooler for each cylinder; Wright had tried such aftercoolers on the compound R-1820-29 in 1934 and had had very poor results. It was only after the war was over and the great benefits to be obtained from aftercooling had been demonstrated on the Merlin that Pratt & Whitney began the development of an aftercooler for the R-4360.

By the middle of the Second World War, when the difficulties with the turbosupercharger itself and with its controls had at last been eliminated, air-cooled engines such as the Wright Cyclone of the B-17 and the Pratt & Whitney R-2800 of the P-47 could be turbosupercharged to altitudes fully as high as the Allison of the P-38. If we wish to compare air-cooled engines with the Merlin, we must consider models with two-stage gear-driven superchargers, since there was no airplane with a turbosupercharged Merlin. In this case, if we consider the supercharging as a thing by itself, it is true that even at the end of the Second World War the air-cooled engine was less well supercharged in the sense that its power fell off more rapidly with altitude than that of the Merlin, although the difference between the two types in this respect had been greatly reduced. This, however, is not the really significant comparison, since what matters is not how much difference there is between power at sea level and power at the desired altitude, but which of the two types gives the greatest power for given weight at the desired altitude. By the middle of the Second World War the R-2800, which was very much lighter per unit of power at sea level and low altitude, was at least as light as or slightly lighter than the liquid-cooled engine per unit of power at the highest altitudes used in service, as will be shown in the following section.

[16]The R-1830-76 of the F4F-3 had a critical altitude of 19,000 feet at its normal rating of 1,000 hp on 100-octane fuel, against the Merlin II's approximately 10,000 feet at its international rating of about 1,100 hp on the same fuel.

Comparison of the Weights of an Air-Cooled and a Liquid-Cooled Fighter Power Plant in World War II

No quantity of theoretical arguments concerning the comparative weights of air- and liquid-cooled engines could be decisive; the one conclusive argument would be direct comparison between two equally well developed engines. No American liquid-cooled engine has ever been as fully developed as various American air-cooled engines, but it is legitimate to compare the best American air-cooled engines with the British Merlin, which was as highly developed as any engine in the world. Since the really relevant figure, however, is the total installed weight of the engine and not its bare weight on the test stand, it is necessary to compare the engines as actually used in particular airplanes. Such a comparison could be completely valid only if two airplanes had been designed with equal skill for exactly the same objectives, the only difference being in the power plant, and no such case is available. We do, however, have detailed figures comparing two different American fighters which will give a very good approximation to an exact answer concerning comparative engine weights,[17] even though a comparison of the performance of the two airplanes would be invalid. These airplanes are the F4U Navy fighter with the air-cooled R-2800 and the P-51 Army fighter with the liquid-cooled V-1650 (Packard-built Merlin), both engines having a two-stage gear-driven supercharger. Both sets of figures apply to the first part of 1943, although not precisely to the same date, and these two engines were undoubtedly the two best fighter engines to see service in the war. The summary results of the detailed breakdown of weights are as follows:

[17]The chief points on which the engine weights themselves are not strictly comparable are the following:

(1) The division into bare engine weight and installation weight is not quite exact. The bare weight of the R-2800 is undervalued (although very slightly) by including under cooling-system installation the weight of the intercooler supports and of the ducts connecting the intercooler with the supercharger (both of which are integral with the engine in the liquid-cooled case).

(2) Both the bare and the installed weight of the R-2800 are comparatively slightly exaggerated because its oil cooler is designed for service in hotter climates than that of the Merlin.

(3) The installed weight of the R-2800 is relatively undervalued because of the omission of fuel and oil and their tanks. These have been excluded because they are excessively incomparable; the ranges of the two airplanes are different and are computed differently, and there are great differences in the actual design of the fuel tanks resulting from differences in the airplanes which are completely unrelated to the type of cooling system used in their engines. If the airplanes as such were really comparable, the tanks and fuel supply for the R-2800 would have to be larger than those for the Merlin in proportion not only to the higher power (which would not affect the relative *specific* weight) but also to the poorer fuel economy of the air-cooled engine.

	V-1650-3 Merlin		*R-2800*	
Engine with two-stage mechanical supercharger and with aftercooler (Merlin) or intercooler (R-2800)	1,639 lb		2,517 lb	
Cooling system including coolant (both engines have oil coolers)	652		95	
TOTAL ENGINE WITH COOLING SYSTEM		2,291		2,612
Engine mount and cowl	284		303	
Cooling system mount, ducts, control mechanisms (including cowl flaps for R-2800)	116		101	
Intake and exhaust system, starter, engine controls; propeller and controls	624		681	
TOTAL ASSOCIATED WEIGHT		1,024		1,085
TOTAL INSTALLED WEIGHT OF POWER PLANT		3,315 lb		3,697 lb

When we go on from the weights of the power plants to compute the ratio of weight to power two important difficulties appear. On the one hand the R-2800 was available at this time with water injection, which was not used on the V-1650 until later. The addition of water injection to the Merlin increased its output substantially, although proportionally less than that of the R-2800 because of differences in the characteristics of air-cooled and liquid-cooled engines. On the other hand, the Merlin had a more efficient supercharger than this model of the R-2800 and it had aftercooling instead of intercooling. Addition of either of these features to the R-2800 would have improved its performance substantially. What evidence there is would indicate that the better supercharging and aftercooling added about as much to the performance of the Merlin as water injection did to that of the R-2800, so that the figures for the R-2800 with water injection are the more comparable to those for the Merlin.

Altitude:	Take-off	5,000 ft	10,000 ft	15,000 ft	20,000 ft	25,000 ft
Military Power						
Liquid-cooled	1,375 hp	1,430 hp	1,490 hp	1,435 hp	1,260 hp	1,260 hp
Air-cooled	2,000	1,800	1,800	1,800	1,650	1,465
Air-cooled, water injection	2,250	2,100	2,100	2,040	1,915	1,540
Specific Weight of Engine with Cooling System:						
Liquid-cooled	1.7 lb/hp	1.6 lb/hp	1.5 lb/hp	1.6 lb/hp	1.8 lb/hp	1.8 lb/hp
Air-cooled	1.3	1.4	1.4	1.4	1.6	1.8
Air-cooled with water injection	1.2	1.2	1.2	1.3	1.4	1.7
Specific Total Installed Weight:						
Liquid-cooled	2.4 lb/hp	2.3 lb/hp	2.2 lb/hp	2.3 lb/hp	2.6 lb/hp	2.6 lb/hp
Air-cooled	1.8	2.1	2.1	2.1	2.2	2.5
Air-cooled with water injection	1.6	1.8	1.8	1.8	1.9	2.4

At sea level and all altitudes up to about 20,000 feet the specific weight of the air-cooled engine is decisively less than that of the liquid-cooled. At 25,000 feet the advantage almost vanishes; if the weight of the air-cooled engine were increased in accordance with its slightly higher fuel consumption the specific weights of the two engines would be equal for all practical purposes.

Drag

During the 1920's the violent debates which were waged over the comparative drag of air-cooled and liquid-cooled engines were based on very little if any scientific evidence. What little evidence there was consisted in comparison of top speeds of airplanes with different engines, and since other factors than the cooling system were changed when engines were changed even these comparisons proved nothing.[18]

Theoretically the drag due to any engine can be separated into two parts: cooling drag, due to the resistance offered to the air which must pass over the cooling fins or through the radiator in order to cool the engine, and form drag, due to resistance offered by the engine, and the radiator if any, to the part of the air stream which does not serve for cooling at all.[19] Form drag was by far the larger part of the total drag due to these engines of the 1920's. The air-cooled engines were either completely exposed to the air or had a cowl over the center of the engine which was virtually worthless. Liquid-cooled engines had a radiator ordinarily mounted in the full slip stream of the propeller,[20] in the belief that this reduced drag by making possible the use of a radiator of the smallest possible cross section; in reality this not only created a very great amount of form drag due to turbulence in the air passing around the radiator but also actually gave rise to a maximum of cooling drag inside the radiator.

It was not until the late 1920's and early 1930's that engineers finally understood the basic principles to be applied to minimize the drag of either type of engine. These were: (1) that the drag directly due to cooling was minimized if the heat-radiating surfaces were made as large as possible and the velocity of the cooling air over them reduced to a minimum; (2) the stream of cooling air should be made to rejoin the general air stream in such a way as to cause as little turbulence as possible; (3) the air not used for cooling should be led around the engine, and the radiator if any, as smoothly as possible.

These basic principles were, surprisingly enough, applied to air-cooled engines before they were applied to liquid-cooled engines. The first great step in the reduction of power-plant drag was the development of the NACA cowl in 1927. This accomplished part, though not all, of the rationalization of the control of the air flow about the air-cooled engine; it made a definite separation between the streams of cooling and noncooling air and made the former rejoin the latter smoothly.[21]

The aerodynamic effectiveness of the cowl designed by the NACA was excellent, but it reduced the flow of cooling air so much that in some cases the power which could be taken from engines larger than the Whirlwind was seriously limited by overheating, with the result that top speed was scarcely if any increased by the use of the cowl. This was true of the Wasp-powered version of the Army Curtiss Hawk. In preparation for the 1929 National Air Races, baffling which greatly improved the cooling under the cowl was developed at Wright Field by Captain Green, Captain Breene, and Mr. Brelsford, and an NACA cowl with this baffling was installed on the XP-3A Hawk. The speed attained with this combination was clearly superior to that obtained with the Townend Ring.[22] Despite this superiority, however, the Army for several years continued to use the Townend Ring on service fighters (P-12C and

[18]Experiments made in 1926 and 1927 by the Navy with a Wasp engine on the F6C-4 Curtiss Hawk, designed as the F6C-3 for the water-cooled D-12, showed equal top speeds for the two engines. This is not proof, however, that the drag of the two engines themselves was equal. (1) The D-12 ran at a higher speed, and its propeller was probably less efficient as a result. (2) At the speeds in question (about 160 mph), the "induced" drag due to the weight of the airplane was important even at top speed, and the lower weight of the air-cooled engine contributed to speed by lowering this induced drag. While it is true that it is total drag that matters, it is important to distinguish, since as airplanes became cleaner and airplane speeds increased, the effect of weight on top speed through induced drag became relatively much smaller while the effect of direct engine drag became relatively much greater.

[19]Interference drag is here included with form drag in the strict sense.

[20]Cooling drag was reduced to almost nothing with the wing radiators used in racing planes, but these radiators were too vulnerable for military use, and they were never developed to be sufficiently reliable for commercial use.

[21]The NACA cowl was by no means the first cowl to be tried which completely surrounded an air-cooled engine. The early rotaries often had such cowls. Various attempts were made to use the same sort of full cowl on fixed air-cooled engines; examples are, in the United States the Dayton-Wright XPS-1 of 1922, designed by Colonel V. E. Clark in 1921, with a Lawrance J-1 engine, and in Britain an Armstrong Whitworth airplane of about 1925 designed by Major F. M. Green. None of these attempts was successful, however, owing in the first instance to difficulties with cooling, but ultimately to the fact that the builders were unable to do the work which would have been required both to perfect the cowl and demonstrate its advantages and to find a solution to the cooling problem. Thus the NACA by no means invented the enclosing cowl, but it made essential contributions to its development by the determination of the best form and the demonstration and measurement of the reduction in drag which it made possible.

[22]The Townend Ring was a ring of airfoil cross-section completely surrounding the cylinder heads of an air-cooled engine, but not closed down in front and without the long skirt of the NACA cowl. It was invented by H. Townend of the British National Physical Laboratory in 1927, the same year in which the NACA cowl was developed. The two lines of work were contemporary and completely independent.

P-26), chiefly because the pilots insisted that it was necessary to be able to see between the cylinders.[23]

While the NACA cowl was remaining largely unused, the cooling drag of liquid-cooled engines was greatly reduced toward the end of the 1920's by the Army's development of high-temperature cooling with ethylene glycol instead of water (cf. above, p. 667). This development made possible a great reduction in cooling drag, since the cooling surface required was only about a third of that needed with water. Although this improvement also remained unused in service for some time, owing to the lack of a production engine operating successfully with glycol cooling, it gave some substance to the argument that the total drag of liquid-cooled engines could be kept below that of air-cooled engines.

In the early years of the 1930's the problem of drag finally became rationalized by the actual introduction of the NACA cowl to large-scale service on air-cooled engines and by the development of a complete and correct theory of the drag of the liquid-cooled radiator. The use of the NACA cowl was brought about by the realization that, whatever the problems it created for cooling, it was absolutely necessary if the desired airplane speeds were to be attained. The cooling problems were even more serious than before, since two-row engines were then in production and were harder to cool under a cowl than single-row engines had been, but once the need of the cowl was realized these problems were solved by the energetic and systematic development of better baffling. The largest part of this development was done by Pratt & Whitney, which was the first to have two-row engines in production (R-1535 and R-1830). It was in the course of this work, about 1932, that the fundamental principle of modern baffling was rediscovered: that rather than simply deflecting the airstream around the rear of the cylinder the baffling should definitely force the air through the fin passages and cut off all other air flow.[24] The same development made the last remaining essential step in establishing the principles of cooling an air-cooled engine with minimum drag. This was the demonstration

[23]The first fighter equipped with the NACA cowl to be submitted to Wright Field was very soon involved in a collision with another airplane. The pilot of the other airplane was killed, and the fact that the pilot of the cowled airplane blamed the collision on the lack of visibility due to the cowl made a very strong impression on other Army pilots.

[24]The classic treatment of the work done from 1932 to 1934 is the paper by Rex B. Beisel, A. L. MacClain, and F. M. Thomas, "The Cowling and Cooling of Radial Air-Cooled Aircraft Engines," *SAE Journal* (*Transactions*) 34, 1934, pp. 147-166. The need for "close baffling" had apparently been fully realized by F. W. Lanchester before 1900 ("Cylinder Cooling of Internal Combustion Engines," Institution of Automobile Engineers, London, *Proceedings* 10, 1915-1916, pp. 59-158, esp. pp. 68, 83 ff, 116 ff), but its effective adoption on modern engines was not accomplished until this independent work was done in 1931 and 1932.

that the best way of reducing the flow of cooling air when less than maximum cooling was required was by varying the size of the exit from the cowl; the first adjustable cowl flaps of the type which became standard were tested in 1934.

It was during this same period that Wright Field engineers developed the correct principles for designing the cooling system of a liquid-cooled engine; Rolls Royce in Britain was doing exactly the same thing at the same time, and the conclusions have been set forth in the story of that company's work in Chapter VIII. Once the nature of engine and cooling drag was understood, it became possible to discuss it more effectively by separating it into the two components already defined: cooling drag proper and form drag.

Cooling Drag

It is inherently easier to minimize the loss of energy to resistance in a radiator than in an air-cooled engine for two reasons. First, all the surface "wetted" by the air in a radiator is used for cooling, while in an air-cooled engine it is difficult to prevent air from flowing over surfaces which need no cooling but which nevertheless contribute to frictional resistance. Second, the possibility of having perfectly straight, smooth air passages in a radiator makes it easy to keep turbulence losses to a minimum, whereas in an air-cooled engine the airflow must follow the engine configuration and turbulence losses are much more difficult to reduce. The air-cooled engine, however, has an inherent advantage in the conversion into thrust of the heat energy absorbed from the engine (Meredith effect). This is because the recovery of energy from heat increases, other things being equal, as the temperature difference between metal and air increases. The temperature of the cylinder walls has roughly the same limit (fixed chiefly by fuel, lubricants, and metallurgy) in both types of engines, but in the air-cooled engine the air takes heat directly from these walls, whereas in the liquid-cooled engine this temperature drop must be divided into two parts, one from cylinder wall to coolant fluid and another from fluid to radiator surfaces.

On the whole, it would be probably recognized by most engineers today and was probably so recognized in the 1930's that the liquid-cooled engine with high-temperature cooling has a slight, but only a slight, advantage over the air-cooled engine in respect to cooling drag proper. The real case for the lower drag of the liquid-cooled engine was based on consideration of form drag.

Form Drag

In discussing form drag, it is necessary to distinguish between multiengine and single-engine installations.

In multiengine planes the radiator has usually been installed in the nacelle immediately below the engine. In order to have a cooling drag as low as that of an air-cooled engine the radiator has to be so large that the nacelle is little if any smaller than that required by an air-cooled engine, and form drag and total drag of the liquid-cooled engine thus installed have been just about equal to those of the air-cooled engine.

From very nearly the beginning until almost the end of the 1930's the engineers at Wright Field were convinced, however, that the form drag of a liquid-cooled power plant could be reduced to zero in large, multiengine airplanes by submerging the entire power plant, both engine and radiator, within the wing of the airplane. The wings of bombers and transports were from 36 in. to 48 in. thick at this time, and by using an opposed cylinder arrangement a 12- or 24-cylinder engine could be made much thinner than this; even with the accessories it need be no more than 24 in. to 28 in. thick. The desire to make a submerged installation was responsible for the cylinder arrangements chosen for the Continental O-1430 in 1934 and for the Allison V-3420 and the Pratt & Whitney X-1800 in 1937. In the latter half of the 1930's this idea began to appeal not only to the Army but to a leading maker of commercial transports, and at least one of the airlines was very much interested.[25]

The sort of reasoning which excited this interest is fairly illustrated by an Army memorandum of 1938, which pointed out that 31.5% of the drag of a B-17 was due to the engines,[26] and concluded that the development of liquid-cooled engines suitable for submerged installation should be pressed with all haste.

As more careful studies were made, however, most of the people who had at first been anxious to try submerged installations gradually lost their interest. In part this was because the reduction in drag was not so great as it seemed at first. True cooling drag was the larger part of the drag of a rather old air-cooled installation like that on the B-17, whose prototype had been built in 1935. The part of the drag which would be affected by a submerged installation, the form drag, was less than 15% of the total drag of the airplane, and even of this 15% a considerable part could not be eliminated by a submerged installation, since the propeller shaft, housing, hub, and control mechanism would still be exposed, and these had a frontal area equal to about a fourth of the total frontal area of an air-cooled nacelle.

The advantage of a submerged installation was still great enough, however, to have convinced some of the strongest advocates of air-cooling that if this installation was practical it would lead to the

[25]About 1934 Rolls Royce made a mockup of a completely submerged power plant, but was unable to arouse the interest of the airplane manufacturers.

[26]In 1937 G. J. Mead calculated that 25% of the total drag of a 48,000-lb airplane with air-cooled engines at 225 mph at 10,000 feet was engine form plus cooling drag; "Aircraft Powerplant Trends," *SAE Journal (Transactions)* 41, 1937, pp. 462-463.

supremacy of liquid cooling. The real objection to submerged wing installation about 1937 was that the reduction of drag was obtained at a very high cost in other disadvantages. Space for fuel and armament was much reduced, and the situation was made still worse by the fact that with the nacelles eliminated the landing gear would have to be retracted into the wing or the fuselage. Furthermore, this type of installation, if it could be achieved at all, would be accompanied by a very serious increase in the structural weight of the airplane,[27] and would give rise to increased fire hazards and greatly increased difficulty of maintenance. And although even these disadvantages might have been outweighed by the reduction in drag, submergence in the wing ultimately became completely impossible in fast airplanes because of the reduction in wing thickness and the increase in engine power and size necessitated by increasing airplane speeds.[28]

Even if the engine was not submerged, the radiator could be submerged within the wing. This was done in one notable production airplane, the extraordinarily fast British de Havilland light bomber called the Mosquito. This installation did in fact have appreciably lower drag than the conventional one, but it was used in no other multiengine service airplane. In military aircraft this situation was probably due in part to the greater vulnerability of the wing radiator, but even in military aircraft the chief reason, and in civilian aircraft the sole reason, for keeping to the conventional nacelle radiator was the fact that maintenance was far easier than with a submerged radiator.

Single engine airplanes, on the other hand, presented a considerably different picture. The ideal pure fighter would have a fuselage just large enough in cross section for the cockpit, but such a cross section was not wide enough for a radial engine; the Wasp and the R-1830 were both over four feet in diameter, and the Cyclone, used in one Navy fighter, was a full four feet and a half. Liquid-cooled engines, on the contrary, fitted beautifully; none of the vee-type engines used or designed for use in the Second World War was more than about 2½ feet wide or a little over 3 feet high. In these single-engine airplanes the radiator could be and was located wherever it was most convenient. The magnitude of the advantage of the liquid-cooled engine is shown by the fact that the substitution of the Allison for the R-1830 in the Curtiss Hawk in 1939 reduced the total drag of

[27]Since for aerodynamic reasons the propeller must be kept at a certain distance in front of the wing, a submerged installation would also suffer a small weight penalty because of the long shaft required.

[28]In June 1944 Douglas flew an experimental medium bomber, the XB-42, with two Allison engines submerged in the fuselage and counterrotating propellers behind the tail. As late as 1947, a feeder-line transport, the Beechcraft 34, was designed and built with (air-cooled) engines completely submerged within the wing.

that airplane by 22%.[29] Still later evidence is afforded by the new Hawker Fury fighter, of which prototypes were tested in 1944-1946. One version of this airplane had the air-cooled Bristol Centaurus in a completely modern low drag cowling; another had the liquid-cooled Napier Sabre with radiators submerged in the wings. The over-all drag of the Sabre version was definitely the smaller, although the exact amount of the difference is not known. Even in the earlier Tempest fighter (first flown in 1942-1943), where the liquid-cooled version had a large beard-type radiator, the total drag of the Tempest V with the Sabre was a little less than that of the Tempest II with the Centaurus, which had the same sort of low drag cowling that was used later on the Fury.

Thus the whole story is not told by the figures given in the previous section, which showed that the air-cooled engine produced as much power as the liquid-cooled engine per pound of weight at the highest altitudes, and a good deal more at lower altitudes. If we could deduct from the power of each type of engine the amount required to overcome the drag due to the power plant itself, we should find the picture rather more favorable to the liquid-cooled engines — at least in those cases where the radiator is installed for low drag and not for convenient maintenance. Unfortunately, numerical data are not available to measure the extent of this difference.

Greater Power from a Single Engine

One of the most important objectives in aircraft engine development has always been the attainment of the highest possible output from a single engine.

The gross output of an engine can be conveniently divided into the product of two factors: the so-called specific output, or power per cubic inch of cylinder displacement, and the total displacement of the engine. As for the former factor, we have already seen (above, p. 668 ff.) that throughout the 1930's it was generally and correctly agreed that the liquid-cooled engine had a definite advantage. Although there was much dispute what the ultimate extent of this advantage would be after both types of engine had undergone further development, it has remained at roughly one-third from the early 1930's to the present. Thus if the air-cooled engine was to compete with the liquid-cooled in total power, it was always necessary to be able to build it at least a third larger than contemporary

[29] Computed from flight-test performance. The XP-40 with an Allison rated 1,090 hp did 366 mph at 15,000 feet; the P-36 with an R-1830 rated 900 hp did 300 mph at 10,000 feet. Even after Pratt & Whitney had spent great pains on a new installation of the R-1830 in this airplane in 1942, its speed of 389 mph at 22,700 feet with 1,100 hp indicated 8% more drag than the XP-40, and by this time vastly better installations of liquid-cooled engines could be made.

liquid-cooled engines. The problem of the possibility of such construction has two rather separate chronological phases: the first, which pertains to the 1920's and the first years of the 1930's, is that of the development of the first successful two-row radials; the second, which lasted from the early 1930's until the early 1940's, extends from the time when it finally became certain that the two-row radial would be a success to the time when the first successful radial was built with more than two rows.

By 1930 it was quite generally agreed that a single-row radial — or one row of a multirow — had reached its limit of displacement at about 1,800 cu in.[30] There was never any doubt that a good liquid-cooled engine of the classic 12-cylinder vee form could be built with a displacement at least this large and thus with considerably greater output than any single-row radial. A vee-type air-cooled engine was of course no solution, since there was nothing which tended to make it possible to build a larger vee with air cooling than with liquid cooling, and the latter would have the advantage in specific power.

Thus the only solution which could provide a considerable increase in total power from air-cooled engines at the beginning of the 1930's was the construction of a two-row radial or of a four-bank in-line engine of X or H form. At this time opinions concerning the practicality of a two-row radial were varied. In this early stage of the development of the art of air cooling, there were always serious difficulties with the cooling of single-row engines, and the problem was sure to be aggravated by the addition of a second row. New mechanical problems entered also: the most successful radial engines of the end of the 1920's, in both the United States and Britain, used a solid master rod and a built-up crankshaft, and it was not yet certain in 1930 either that this construction could be achieved in a two-row engine or that the split master rod could be made to work. It is true that Armstrong Siddeley had been in production in England since about 1921 with the two-row Jaguar of 1,512 cu in. displacement, but the conclusions to be drawn in 1930 from the history of this engine were uncertain. From about 1923 until about 1926 it had been used in the most successful British fighters. Its power had never, however, been equal to that of the big single-row Bristol Jupiter, and after 1926 or 1927 the power of the latter increased more rapidly than that of the Jaguar. Certainly the Jaguar was not evidence that a two-row radial could be built with a good deal *more* power than a single-row.

[30] The 1,860-cu in. single-row "B-Series" Hornet of 1930 had nine cylinders of 207 cu in. each. No successful radial has ever had more than nine cylinders in a single row, and no successful air-cooled engine has ever had cylinders of greater individual displacement than 207 cu in. In fact, the 1860 Hornet never went into full production and was abandoned not long after 1930, leaving the 1820 Cyclone as the largest single-row engine.

Actual development of two-row engines was begun in the United States by Pratt & Whitney in 1929 and by Wright in 1930,[31] but this work at first centered on engines smaller or not appreciably larger than the large single rows. The largest of these early two-rows was the Pratt & Whitney R-1830, which did not reach a 1,000-hp take-off rating until about 1936.[32] When the Army in 1931 wanted a 1,000-hp engine, it was able to persuade Pratt & Whitney to undertake the development at its own cost of a four-row 20-cylinder liquid-cooled radial, the R-2060. Design of this engine was begun in May 1931, and single-cylinder tests started in August of the same year, but when the complete engine was run toward the end of 1932 the output was found to be very poor and the project was soon abandoned. It was as a result of this failure that at the beginning of 1933 Pratt & Whitney first made a general study of the problem of obtaining appreciably higher output from an air-cooled engine, and then decided on the development of a 14-cylinder two-row R-2180, with a displacement nearly 20% larger than that of the R-1830. It was not until the end of 1935 that Wright at last solved the very serious troubles which had plagued it in its small two-row engine and finally undertook the development of an engine of displacement greater than the single-rows. This was the 14-cylinder R-2600, which was aimed at an initial output of about 1,500 hp. A month or two later, in January 1936, Wright also began the de-

[31]From 1926 to 1928 Curtiss had developed a two-row engine, the 12-cylinder H-1640 Chieftain. This engine, however, was of a peculiar form, different from that already used in the Jaguar and which ultimately became standard. It had the cylinders of the second row directly behind those of the first row, instead of being staggered, and the valves were operated by an overhead camshaft for each pair of cylinders rather than by push-rods for each individual cylinder. The H-1640 was never a success, and contributed little or nothing to the further development of two-row engines.

[32]Pratt & Whitney's original investigations were of a 2,270-cu in. engine, the size being determined by the use of parts from Wasp and Hornet engines, but these experiments were of the nature of research and were not an attempt actually to develop an engine of this size. The design of the 2270 was begun in January 1929, but it was not until May 1930 that the complete engine was run. It was first flown in April 1931. In January 1931 Pratt & Whitney began the design of the first two-row intended for actual development, the R-1830, and the first entry in the log was made in April 1931. The Navy, however, which was the first customer to be seriously interested in a two-row engine, at first wanted to use the two-row construction not to obtain higher power but to obtain smaller diameter in an engine of about the same power as was got from the big single-rows. Accordingly Pratt & Whitney, although unconvinced that a two-row engine was desirable for these low outputs, began the design of the 14-cylinder R-1535 about May 1931, and the first entry in the log was made in November 1931. Wright had apparently begun its two-row R-1510 before the end of 1930, although it had done very little work before the end of the year. Even the R-1830 was intended to produce only some 15 or 20% more power than the big single-rows, and for four years after 1930 the 1830 was the largest engine under development in the United States. It passed its type test on February 1, 1933; the fiftieth engine was shipped in October 1934.

velopment of a still larger two-row engine, the 18-cylinder R-3350, initially aimed at about 2,000 hp.

By the middle of 1936 Pratt & Whitney had achieved or was about to achieve a 1,200-hp take-off rating with the new C model of the R-1830, and was about to go into production with the R-2180, which had a take-off rating of 1,400 hp and had been run experimentally at about 1,600 hp. The Wright R-2600 had passed its type test with a take-off rating of 1,500 hp in June 1937 and was in production in the latter half of the year. Any of these engines had higher power at low altitude than any liquid-cooled engine actually in production here or abroad. Moreover, when Pratt & Whitney learned of the Wright R-2600, it canceled its plans for the production of the R-2180 and began the development of a still larger, 18-cylinder two-row, of 2,600 cu in. displacement, enlarged in March 1937 to 2,800 cu in. Thus there were by 1937 three air-cooled engines under development in the United States of almost certainly greater power than the most prominent foreign liquid-cooled engine, the Rolls Royce Merlin, which had only 1,649 cu in. displacement.

Provided, however, that a larger and more powerful engine was desired, there was nothing to prevent a liquid-cooled engine from being built with considerably larger displacement than the Merlin, and in fact in 1937 Napier in England was already well under way with the development of the Sabre, a 24-cylinder H-type engine of 2,238 cu in. displacement, and Rolls Royce was beginning development of the Vulture, a 24-cylinder X-type engine of 2,590 cu in. displacement. Even the classic 12-cylinder vee could perfectly well be built very nearly this large; in Germany Daimler-Benz and Junkers were developing engines of 2,069 and 2,135 cu in. displacement respectively, and in January 1939 Rolls Royce began the development of the 2,239-cu in. Griffon. It was thoroughly possible, so far as could be foreseen at the time, that any one of these engines might be more powerful than the largest American air-cooled engines, which were at this time fully as experimental in status as these foreign liquid-cooled engines.[33]

[33]The Napier Sabre passed a type test in 1940 and during the early part of the war was the basis of most of the British plans for fighters to replace those powered by the Merlin. After the Sabre was in production in 1941 it ran into a host of troubles, but these were finally ironed out. By 1944 the Hawker Typhoons and Tempest V's were by a large margin the fastest piston-engine fighters in production up to at least 20,000 feet.

There was no model of the Sabre with high-altitude supercharging, but the reason for this would appear to be independent of the engine, which required only 17¼ lb boost (65 in. absolute) to reach its ultimate rating (3,000 hp take-off; 2,820 hp at 12,500 feet combat), or less than the 18 lb (66.5 in.) which was maintained up to 21,000 feet in the Merlin 64 used in the Spitfire IX and in the Merlin 72 and 73 used in the Mosquito. In any case, a turbosupercharger would have given as high a critical altitude with the Sabre as with a less highly boosted engine. As for the slowness of the Sabre development and the magnitude of the difficulties encountered, it should be remarked that while the R-2800 made much more rapid

Both the Army and the Navy in the United States were becoming seriously interested in engines of appreciably greater power than was aimed at in the largest two-row radials then being or about to be designed. At least as early as 1936 the Army was discussing with Allison the development from the V-1710 of a liquid-cooled V-3420, slightly larger and presumably considerably more powerful than the air-cooled R-3350, and this development was actually begun about the middle of 1937. Late in 1936 or early in 1937 the Navy issued a request for an engine of 2,300 hp take-off rating, and it was to be expected that the requirement would rise as time went on. Such outputs then seemed as far out of the range of the 18-cylinder two-row radial as the 1,000-hp goal had in 1930 seemed out of the range of the single-row, and radials of more than two rows do not seem to have been even seriously considered at that time in the United States.[34] The first response to the Navy request for a 2,300-hp engine was a proposal by Pratt & Whitney for a 24-cylinder 3,130-cu in. air-cooled X, made in February 1937. General opinion throughout the 1930's, however, was against the use of the in-line multibank form with air cooling, and the company quickly became doubtful of the future performance of such an engine. In the face of the fact that, only a year before, the Navy had rejected the Wright H-2120 chiefly on the grounds that it was liquid-cooled, Pratt & Whitney had already by April 1937 persuaded the Navy to alter the proposed contract to call for liquid cooling.

It seems, in short, to be true that during the period from about 1937 to about 1940 there was almost unanimous agreement in this country that the highest powers could only be obtained with liquid cooling. During these years Pratt & Whitney worked with enthusiasm on the development of the liquid-cooled H-3130 (later 3730) for the Navy, and about 1938 Wright contracted with the Army for the development of a high-power liquid-cooled flat engine, for which the liquid-cooled 42-cylinder radial "corncob" (R-2160) was substituted at the company's suggestion in 1939. It was not until 1939-1940 that the first systematic study of the possibility of the use of air cooling for these extremely high outputs was begun, after L. S. Hobbs was put in charge of Pratt & Whitney's engineering policy as vice president for engineering of United Aircraft. It was these studies which led to the beginning in 1940 of the development of the four-row 28-cylinder R-4360, which was in limited production with

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progress, the R-3350 was still slower, and produced less power when it finally did go into service. Concerning the Vulture and the Griffon, see Appendix to Chapter VIII.

[34]During the 1930's Armstrong Siddeley in Britain developed two three-row radials (the Hyena, first flown in 1933, and the larger Deerhound, first run in 1936). These engines were never successful, however, although this may have been due to inadequate development rather than any fault of the basic design, and in any case they were smaller rather than larger than the American R-2800 and R-3350 two-rows.

a rating of 3,000 hp before the end of the war and before any liquid-cooled engine was actually in production with an equal rating.

Maintenance, Reliability, and Durability

The simplicity of the air-cooled engine gave it a certain and undisputed advantage: the air-cooled engine has essentially no parts which are not also in the liquid-cooled engine, whereas the latter has all the parts of the former and in addition has the whole coolant system: pump, piping, and radiator. The absence of these parts made for less maintenance, and — what was at least equally important — the maintenance which had to be done was much easier on the exposed individual cylinders of the radial than on the liquid-cooled in-line engines of the late 1920's and the 1930's, where to get at an individual cylinder a whole bank had to be dismounted.

During the 1930's, the popularity of the air-cooled type was greatly enhanced in the United States by the fact that the best American air-cooled engines were considerably more reliable than their only liquid-cooled competitor, the Conqueror. Inferior reliability, however, does not seem to be inherent in the liquid-cooled type. In the early and middle 1920's the best water-cooled engines, such as the Wright model E Hispano in the United States and the Napier Lion in Britain were at least as reliable as contemporary air-cooled engines.

In the United States the Navy very early made much of the argument that although the water-cooled engine itself was inherently reliable enough, the radiator system was an important cause of engine failures which should be eliminated. The importance of cooling-system failures should not, however, be exaggerated; according to the Navy's own data in 1928, while one-fifth of all engine failures were due to the water-cooling system, an equal number were due to the oil system,[35] and there was really no reason why the coolant system could not be made as reliable as the oil-cooling system of air-cooled engines ultimately became. The case at present, in fact, appears to be that with modern secondary-surface radiators, the cooling system is fully as reliable as the engine itself.

There is no question that the initial adoption of the air-cooled engine on both military and commercial airplanes, in both the United States and Britain, was almost entirely due to its lower weight. Once the air-cooled engine had been adopted for commercial service, however, a wealth of experience was rapidly gathered which was soon used to improve the reliability of these engines tremendously. The Whirlwind was very extensively flown on Fokkers from

[35]Commander E. E. Wilson, *SAE Journal* 19, 1926, p. 622. Statistics compiled by Rolls Royce about this same time showed approximately 25% of all engine failures due to either the oil or the coolant system outside the engine itself.

1925 and on Fords from 1926; from 1927 the Wasp was extensively used on the commercial Boeing planes and in 1928-1929 it became an alternative choice for the Whirlwind on the Ford and replaced the Whirlwind on the Fokker trimotors. The Cyclone gained reliability after it was adopted on various mail planes and then on the Douglas transports in 1932. The liquid-cooled Conqueror, on the other hand, was used on only a very few commercial transports for a very short period around 1931; and in Britain the Napier Lion was almost completely eliminated from civilian transport operations in 1926, when Imperial Airways adopted two new transport types, one with the Armstrong Siddeley Jaguar and one with the Bristol Jupiter. The military services in both countries continued to use liquid-cooled engines, but they never did the sort of routine, day in and day out flying which contributes most to the development of reliability.

It is necessary, however, to distinguish between reliability and durability, or life between overhauls, and it is probable that when used for patrolling or for commercial service the air-cooled engine is inherently more durable than a liquid-cooled engine. As we have seen, the only way in which the liquid-cooled engine could during the 1930's or can now compete with the air-cooled on weight at take-off and at moderate altitude is by getting the last possible horse power out of each cubic inch, and such an engine is almost certain to be inferior in durability to a more conservatively rated air-cooled engine.[36] The correctness of this view seems to be borne out by the fact that even today, after Rolls Royce has expended considerable effort on producing a commercial version of its Merlin engine, this engine is still not equal in durability in commercial service to military R-2800's acquired as war surplus.

Vulnerability: Capacity for Overload

In one particular military use, ground support, a very important, perhaps the most important, advantage of the air-cooled engine is

[36]Following are figures showing the extent to which the Merlin in the DC-4M has to be pushed to compete with the R-2800 in the DC-6. If we eliminate the fuel tanks in both airplanes because the fuel capacity of the DC-4M is larger, the remaining total installed weight of the Merlin is 3,980 lb while that of the R-2800 is 4,087 lb, or only 2.7% greater weight for a 70% greater displacement. The take-off power of the R-2800 is 35% greater than that of the Merlin, but at 21% less specific power. For climbing at low altitude ("maximum continuous power on low blower"), the R-2800 has about 20% more power at 29% less specific power and with about the same specific fuel consumption. For climbing at high altitude (maximum continuous, high blower), the R-2800 has 14% more power at 33% less specific power and with 10% less sfc. As for fuel consumption in cruising, the sfc of the R-2800 at 10,000 feet is 1.5% lower at low cruising power and 1.5% higher at high cruising power; at 20,000 feet it is 5.5% higher at low power and 7% lower at high power.

its lesser vulnerability.[37] A single puncture in the cooling system of a liquid-cooled engine will put the engine out of operation in a minute or two, whereas in the Second World War air-cooled engines continued to function for hours even with bullet holes in a cylinder. This advantage was not of decisive importance in aerial combat, since if an airplane was fairly hit by a burst from the extremely heavy armament of another airplane it was likely to be fatal in any case; the decisive merit of airplanes in this sort of duty was the speed, altitude, and maneuverability which enabled them to hit without being hit. But the ability of the air-cooled engine to function after suffering a limited amount of damage was of very great value in all low-flying aircraft exposed to small-arms fire from the ground.

An argument frequently used in favor of the liquid-cooled engine during the 1930's was that it could sustain the maximum power of which it was instantaneously capable for a longer period of time than an air-cooled engine, because the reservoir of coolant acts as a buffer which takes time to overheat whereas air-cooled cylinders overheat almost instantly. In the 1920's and the first half of the 1930's this was perhaps a real advantage. Taking the Kestrel as an example, the use of 20% more power than the cooling system was designed for would have raised the temperature of the coolant only something like 5° F per minute. Since the cooling systems of that time ordinarily operated at about 180°F, this meant that 20% excess power could be used for about five or six minutes before boiling occurred; and if boiling did occur, it would take seven or eight more minutes to boil away 5% of the coolant.[38] Air-cooled engines of the first half of the 1930's, on the contrary, were barely able to cool sufficiently for their rated power, and there was virtually no margin at all between overload and failure.

The situation in modern engines, however, is quite different, owing to the reduction in the amount of coolant used. Taking the Merlin V-1650-3 as installed in the P-51B as an example, the use of 20% excess power would have raised the temperature of the radiator and coolant by about 21°F per minute, or if boiling was permitted would have boiled away 5% of the coolant in less than two minutes.[39]

[37]It is said on fair authority that the principal reason for the use of an air-cooled engine in the Focke-Wulf 190 fighter was its lesser vulnerability when used for ground support: H. R. Schelp, *Proposed Program, etc.*, 1942, p. 41 (Wright Field microfilm reel 3645 frame 905).

[38]These figures are obtained from the following assumptions: rated power 500 hp; power to coolant 50% of power output; 5.4 U.S. gal. of coolant assumed equal in specific heat and latent heat of evaporation to water; and thermal capacity of metal in coolant system completely neglected.

[39]These figures are obtained from the following assumptions: rated power 1,490 hp; power to coolant 40% of power output; 209 lb of coolant assumed equal in specific heat and latent heat of evaporation to water; 325 lb of radiator, specific heat assumed 0.1.

Air-cooled engines, on the other hand, could now stand during an appreciable period a considerably higher cylinder temperature than they were designed for. Probably an increase of 50°F in cylinder temperature over the design value would be sufficient to cool 20% excess output, and while this undoubtedly shortened the life of the engine, it did not ordinarily bring immediate failure.