CHAPTER VIII

The Rolls Royce Liquid-Cooled Engines

THE British government has always paid directly, under development contracts, for all development of military aircraft engines done by private firms. In the United States development done under such contracts has usually proceeded much more slowly than development financed by the firm from its own resources. The history of the activities of the leading British firm, Rolls Royce, will serve to indicate whether development contracts necessarily make for slow and ineffective development. This history will serve in addition to give a technical benchmark for evaluating the success of American liquid-cooled engines, the history of which will be examined in Chapters IX through XI.

ROLLS ROYCE AFTER THE FIRST WORLD WAR: 1919-1925

At the end of the First World War the production of aircraft engines was immediately reduced, in Great Britain as elsewhere, almost to nothing. The largest part of the current needs of the military services was filled by the use of war-surplus engines, and commercial aviation could scarcely be said to exist. Nevertheless the Air Ministry continued, to the limit of its very reduced means, to assist the development of the art and even undertook to subsidize the development of an entirely new type of engine, the large air-cooled radial. This did not mean, however, that the government abandoned the water-cooled engine; all the high-power engines at the end of the war had been of this type, and it was over half a decade before an air-cooled engine could be built of gross output equal to that of the largest water-cooled engines in service or about to go into service at the end of the war.

The outstanding British water-cooled engine in service at the end of the war was the Rolls Royce Eagle. This engine, designed by Henry Royce under considerable influence of the 1913 Mercedes racing-car engine built by the German firm of Daimler Motors, had the individual cylinders and welded steel water jackets typical of that family of engines. With 12 cylinders in vee form it had a displacement of 1,238 cu in.; the main production model, that going into service at the end of the war (Eagle VIII), developed about 360 hp. Late in 1917 Royce had begun design of a very similar but larger engine, the Condor, intended to bomb Berlin in the Handley-Page V-1500. This engine, except for the use of a spherical head and four valves instead of two, and corresponding changes in the valve gear, was virtually a scale-up of the Eagle to a displacement of 2,138 cu in.; the first experimental versions, which were ready by the beginning of 1919, developed up to 600 hp, but the engine was type-tested at only about 525 hp.

The only direct competitor of these two engines at the end of the war was the Lion, designed by A. J. Rowledge, and built by D. Napier and Son, Ltd. The basic design of this engine was fundamentally more modern than that of the Eagle and Condor, whose individual cylinders had really been rendered obsolete at the appearance of the monobloc Hispano-Suiza in 1916, even though the Condor was actually designed after the appearance and success of the Hispano-Suiza. The Lion did not have the complete monobloc construction of the Hispano-Suiza, but it did have a monobloc cylinder head which contributed greatly to the rigidity of the engine, even though it retained the individual cylinder barrels and sheet-metal jackets of the older school of design. With 12 cylinders in W arrangement giving 1,461-cu in. displacement, the Lion in 1919 developed about 400 hp, raised to 450 hp by 1921. It very quickly displaced the Eagle, and Rolls Royce produced no more of this type after the end of the war. The Condor, however, even though its basic type of construction was really obsolete, was still by far the largest British engine which was anywhere near being ready for service, and the government was anxious to have its development continued.

Immediately after the war, however, the incentives offered for further development of aircraft engines in Great Britain were extremely weak. The great surplus of war engines meant

that quantity orders were almost nonexistent, while the total resources of the government for engine development contracts were of the order of £200,000 per year at best, and in one year in the early 1920's there was only half this amount.* Thus even a large development contract of this time would amount to no more than £20,000 or £30,000. On the other hand, the market for Rolls Royce automobiles was large and seemed to be growing rapidly immediately after the war, and the belief of Rolls Royce management in this market was shown by its establishment in 1919 of an American factory. The profits to be made on a £25,000 development contract were insignificant compared with those anticipated from the sales of the automobile. Thus even though the government asked Rolls Royce to continue development of the Condor at government expense, the company, led by the managing director, Claude Johnson, refused to divert manpower and facilities from the development of the car. For two years the aviation department of Rolls Royce existed only as a place for the overhaul of wartime Eagles and Falcons, while the Napier Lion had an opportunity to establish itself as the one important British water-cooled engine.

By 1921, however, the postwar depression had arrived and the market for extremely expensive automobiles had suddenly shrunk; Rolls Royce was obliged in the next year to put on the market a second and lighter car, the so-called 20-horsepower. It was virtually impossible for the company to return to the aviation field on its own resources, since the two years of neglect had meant that while the Condor was still heavy for its power and far from being reliable enough for service the Lion had proved itself to be a really outstanding design. Thus the company was forced to go to the Air Ministry and request government development contracts for whatever engines the Ministry might think advisable.

The response of Lt. Colonel L. F. R. Fell, the Assistant Director for Engine Design and Research, was that Rolls Royce should develop the Condor to an output of 650 hp and improve its reliability in general. Whether a development contract was given or not is uncertain, but either at once or

*The pound sterling fluctuated between $3 and $5 in the 1920's.

very shortly thereafter the company was given a production contract or contracts for about 200 engines, even though there were at the time no airframes ready for an engine of this size. At the same time that it undertook to resume development of the Condor, Rolls Royce put in charge of its aviation work at Derby a new man, A. J. Rowledge, the designer of the Lion, who had just left Napier after a disagreement with the management. Subject to Royce's approval, Rowledge made a thorough redesign of the Condor, raising output to the desired figure and also improving the engine in various ways. Two years were required for the work, and the first experimental engine of the new model, known as the Condor III,[1] was put on test early in 1924.

Almost as soon as the first Condor III had been built and tested, Rolls Royce began work on various other developments of the engine. Early in 1924 a gear was built for an installation of the engine in the hull of a flying boat with the propeller on the leading edge of the high wing. At the same time, work was begun on a Condor with a turbine-driven two-stage supercharger, known as the Condor V, based on the experiments previously carried out by the Royal Aircraft Establishment with one of its own single-stage turbos installed on a Condor III. The Condor V was built and run on the stand in 1925 but was dropped by order from the Air Ministry before it was flown, principally because it had been realized that with a propeller designed for take-off conditions the power of the engine at altitude could not be utilized, whereas if the propeller were designed for altitude conditions the airplane could not take off; controllable-pitch propellers were not yet in existence. In the latter part of 1924 the Condor IV was built with direct drive, at a saving in weight of 36 lb compared with the geared version, but experiments showed clearly that the improved propeller efficiency obtained from gearing was more than worth the extra weight, and the Condor IV was dropped.

By 1925 really intensive development of the Condor had come to a stop, for two main reasons. First, the government about this time had made a survey to determine the productive

[1]The Condor II was identical to the Condor I except for the ratio of the reduction gear.

capacity of the aircraft-engine industry, and Rolls Royce had convinced the government that no other firm could possibly produce the Condor; the government had concluded that engines should be developed which would be less difficult to produce. Second, Royce had been making a series of design studies of completely new types of engines to replace the Condor, which after all was of a type really long since obsolete, and as we shall see had decided to develop an engine of modern monobloc construction. The result was that after 1925 only minor improvements were made in the Condor, although it continued in service for several years in the Hawker Horsley bomber. These modifications were made by converting Condor III's, and there was no new production of this engine.

The Kestrel

It was during the year 1924 that Henry Royce carried out with his design staff at West Wittering a comprehensive study of all possible types of aircraft engine, both air- and water-cooled, which might replace the Condor. On the basis of these studies he decided to develop a water-cooled engine of monobloc construction; a factor in the decision seems to have been the knowledge that the larger part of new airplane procurement by the government would be of fighters, the type of airplane which could profit most from a clean-lined, compact engine. The new engine was to be Rolls Royce's first with an integral gear-driven supercharger, a feature strongly desired by the government, which was becoming convinced that this was a better bet than the turbosupercharger and was pressing Bristol and Armstrong Siddeley to develop supercharged versions of their engines too.[2]

Royce's first choice was an X-type 16-cylinder engine. In January 1925, with full financial support from the government, he began the design of the Eagle XVI, which bore no resemblance at all to the old wartime engine of the same name. The Eagle XVI, of 1,209-cu in. displacement, was of monobloc construction with dry cylinder liners and had a detachable

[2]See below, pp. 223-224, on the development of superchargers, and above, Chapter VI, pp. 139, 145-146.

head sealed to the block by a gasket. The gear-driven centrifugal supercharger was two-sided and had four outlets from the volute, one for each bank of cylinders. The first experimental Eagle XVI was run in the middle of 1926, at which time it yielded 500 hp. Very shortly afterward, however, the development of both this engine and of the similar but larger Eagle XX, design of which had been begun at the end of 1925, was dropped because in the meantime the company had undertaken the development of another engine, the Kestrel, which was considered to be more promising.

In the year 1922 the Curtiss Aeroplane and Motor Company in the United States brought out a water-cooled engine known as the D-12, development of which had begun before the end of the war (cf. above, pp. 158, 172). With 1,145-cu. in displacement the D-12 developed over 400 hp, and quickly proved to be the best engine in the world at that time for high-speed aircraft. In 1922 the D-12, in a racing biplane also developed by the Curtiss company, set a new world's speed record of 224 mph; in 1923 it raised this record to 267 mph, and also, in a seaplane version of the racer, won the Schneider Trophy contest, which in that year was held in England. The performance of these Curtiss racers was so far ahead of any British airplanes that the engine naturally attracted a good deal of attention.

In 1924 C. R. Fairey, the head of the airframe firm, Fairey Aviation Company, Ltd, visited the United States and inspected the Curtiss airplanes and the D-12 engine. He obtained a license to produce the D-12 in England, and on his return he designed around it the two-seat day bomber and reconnaissance airplane which he called the Fox. This venture received no government support, but Fairey was able to finance it out of the profits on a large contract which he was currently executing for the two-seat general-purpose airplane called the 3F. In 1925 the prototype Fox astonished both the British government authorities and the airplane industry by having a speed and general performance at least equal if not superior to that of any of the single-seat fighters of the day. This had a very important effect on future British engine development, since the newest and best of these fighters were powered by air-cooled radial engines of about the same power as the D-12.

The opinion had been spreading since 1922 or 1923 that the air-cooled engine was the only one suitable for fighters, the water-cooled engine being useful chiefly in long-range airplanes, on account of its lower fuel consumption, or in very heavy airplanes for which there existed no air-cooled engine with sufficient power.[3]

Fairey attempted to persuade the government to finance him in acquiring facilities for producing the D-12 under the license which he had obtained. The government was sufficiently persuaded of the merits of the D-12 to obtain several samples for testing by the RAE at Farnborough, and from these tests concluded that it was absolutely essential that Britain should have an engine of the same type and of equal merit. As for Fairey's plans, however, the government refused to finance the creation of a new engine-producing concern, since there were already four engine manufacturers to be kept in existence with a very limited amount of production and development contracts. Fairey could, of course, have begun the manufacture at his own risk, but the chances of success were too small when the government was definitely opposed to the creation of a fifth engine company.[4] The government purchased about 30 D-12's from Curtiss to equip the first lot of Fox's and set out to persuade an existing British engine manufacturer to design and develop an engine of the same general type and size as the D-12.

The general policy of the government in 1925 toward the two builders of water-cooled engines was that Napier should be

[3]The Hawker Hornbill two-seater with a direct-drive Condor IV was actually slightly faster than the Fox, but it was by no means so well received and was never put in production, since the speed was achieved only by the use of a much heavier and more powerful engine (700 hp) which was not nearly so clean or reliable as the D-12.

[4]It is interesting to observe that a few years later Fairey did try to get into the engine business at his own risk. In late 1929 or early 1930 Graham Forsythe, until then an employee of the Air Ministry, went to Fairey and designed an engine, the P-12, later known as the Fairey Prince. This was a water-cooled V-12 with the cylinder block and the top of the crankcase in one piece. The displacement was 1,559 cu in. This engine was built, run, and flown at private expense. Even then the government insisted that Fairey did not have and could not acquire the staff necessary for development of the engine on the scale on which, for example, Rolls Royce engines were then being developed, and the engine had ultimately to be dropped. Subsequently Fairey proposed an H-type engine to the Ministry and again was refused support, for the same reason.

given the business in the 400-500 hp class, where it already had the Lion in production, while Rolls Royce was to be responsible for the 600-700 hp class, where it had the Condor. Accordingly the opportunity of developing the desired engine at government expense was first offered to Napier. That company, however, refused to develop an engine of the sort the government wanted. Napier, as we have seen, had in 1921 lost the engineer who had designed the Lion, and from then on had entered a period in which its development, although energetically conducted,[5] showed a definite lack of good judgment. The development of the Lion had been pursued with good success in the first half of the 1920's, but by 1925 it was very near its limit. The company, and especially the managing director, H. T. Vane, failed to realize this; the engine had dominated the market for water-cooled engines so completely during the whole time since the war, and seemed so well established in 1925,[6] that Vane was inclined to believe that it was simply the ultimate aircraft engine and would go on being sold forever. Instead of learning from its experience with the Lion, the company seems to have drawn exactly the wrong conclusions: the government had been willing to let it build the proposed V-12 with Lion-type construction, that is with only the heads en bloc and the cylinders individual, but the company had decided that the difficulties experienced with cracks in the head block of the Lion were too much trouble and decided to return to individual heads as well as cylinders. Napier proceeded in 1925-1926 to build a V-12 engine with this construction; the development was probably financed by a government contract. The new engine was originally built with a turbosupercharger for ground boosting.[7] When this worked poorly it was replaced by a gear-driven supercharger, but the basic engine itself gave so much trouble

[5]In the RAE's work on turbosuperchargers, for example, Napier had been probably the most interested of all the firms and had experimented with turbos on a number of Lions.

[6]The Lion was virtually the only power plant used for long-range military airplanes, especially flying boats, in the entire British Empire. In addition it was used in a large number of European air forces, and until 1926 it was used on almost all new commercial transports: see Stroud, loc. cit. supra, p. 141, n. 32.

[7]The intention to build a ground-boosted engine may have been in part responsible for the return to individual cylinder heads, since the company feared that with the higher stresses of a boosted engine the trouble already experienced with block cracks in the Lion would be aggravated.

and had such a high ratio of weight to power that it was dropped completely about 1927.

Meanwhile, as soon as Napier had refused to build the type of engine desired by the government, Fell had gone early in 1925 to Rolls Royce to propose that that company develop such an engine. Rolls Royce accepted the offer, despite the fact that it had already been working since the beginning of the year on the X-16 Eagle XVI, and in July 1925 Royce and his staff, who had been given a D-12 by the government, began the design of the engine which was later named the Kestrel.[8] Development of the engine was carried out under the direction of Rowledge.

The Kestrel was a 1,295-cu in. engine of block construction with the head and the cylinder block in a single piece. The cylinder liners were open on the end, like the Siddeley Puma and unlike the D-12 and the Hispano-Suiza. This was of great importance when high-temperature cooling was introduced in 1935, since at these higher temperatures it was extremely difficult to maintain good thermal contact between the steel and the aluminum in the Hispano-Suiza type of construction. Under the influence of the excellent performance of the Curtiss airplanes with the ungeared D-12 engine, the first Kestrel was ungeared. Like the Eagle XVI, the first Kestrel had a gear-driven, two-sided centrifugal supercharger.

By the time Rolls Royce's proposal for the Kestrel had reached the government, the funds immediately available for engine development had been already fully committed, and the government was forced to request the company to proceed for a short time at its own expense. It was clearly understood, however, that the project was approved by the government; a part of the initial costs were reimbursed when the government purchased the first experimental engine, and in any case the government had definitely declared that it intended to use the new engine in place of the D-12 in further Fox airplanes, so that once the engine had been successfully produced there was no possibility of lack of a market.

The first experimental Kestrel, the F-X, was run early in 1926, and almost immediately thereafter three important

[8]This engine was originally called the Falcon X; this name was shortly dropped and until 1931 the engine was known simply as the F.

changes were made in the design. The dry cylinder liners were replaced by wet liners, a reduction gear was added, and since the supercharger had given poor results on test, it was decided to make a separate job of its development and in the meantime to bring out an unsupercharged engine. In this engine lower fuel consumption was to be secured together with a certain degree of altitude performance by means of a very high compression ratio, originally set at 8:1 but lowered to 7:1 after a few experimental engines had been tested. The resulting engine, known at the time as the F type, was put into production before the end of 1927, with a normal rating of 480 hp at 3,000 feet for a weight of 865 lb.[9] Enough engines were produced in the first batch to equip about two squadrons of Fairey Fox's, and about a year later the Fox was succeeded by the Hawker Hart two-seater with the same high-compression unsupercharged engine.

Probably the chief reason for the poor results from the original Kestrel supercharger had been the lack, which was common to all the engine firms at this time, of engineers with the necessary training and experience for compressor development and particularly its aerodynamic aspects, which were completely different from the problems encountered in the rest of the development of reciprocating engines. This lack was remedied at Rolls Royce late in 1927, when at the government's suggestion the firm employed J. E. Ellor, the man until then responsible for all the RAE's supercharger work; Ellor had received a better offer from an American company than the government could match directly, and it took this means of keeping his services to the profit of British engines. The RAE had by 1927 already produced a one-sided centrifugal blower with an adiabatic efficiency of 70%; and it was not long after Ellor came to Rolls Royce that a blower of this type and about this same efficiency[10] was ready for the Kestrel. The supercharged engine was put in production in May 1928 in two versions, with supercharger gear ratios of 10.06:1 and 6.92:1.

[9]The engine was also produced in a 6:1 unsupercharged version with a normal rating of 490 hp at sea level.

[10]In both cases the figure excludes the losses due to the intake elbow and carburetor which were present in an actual installation on an airplane.

The more highly supercharged engine had a normal rating on 73% gasoline and 27% benzol of 480 hp at 11,500 feet; the maximum rating was approximately 520 hp at about 13,000 feet. Both supercharged engines weighed a little over 900 lb.[11]

Very shortly after bringing out the supercharger, Rolls Royce produced an automatic boost control of its own design which was put in production on the fully supercharged engine.[12] At about this same time (1927-1928) the company undertook the development of a ramming air intake for both supercharged and unsupercharged engines which was ready for use and patented by 1931 at the latest. The very first experiments with this type of intake added between six and ten mph to the speed of the Kestrel-powered test airplane.[13]

In 1930 improvements were made in the engine to produce the first series to which the name Kestrel was actually given. The normal ratings of these model I, II, and III Kestrels were the same as those of the F series, but the maximum power was raised by an increase in rpm: the fully supercharged model, with a compression ratio of 6:1, had a maximum five-minute rating of about 560 hp at about 15,000 feet.[14] The weight of the engine was increased to 992 lb. The most important early installation of the supercharged Kestrel was in the Hawker Fury fighter.

The next changes in the Kestrel were made in the new model series numbered from IV to XII which was developed primarily to take advantage of 87-octane fuel and was put in production in 1933. The most important improvements were in the mechanical and aerodynamic design of the supercharger and in the use of salt-cooled exhaust valves, which had been developed for the American Army at McCook Field (cf. above,

[11]This engine had 6:1 compression ratio. The moderately supercharged engine with a compression ratio of 5.5:1 was rated 525 hp normal at 2,000 feet and about 580 hp maximum.

[12]The RAE had been working on automatic boost controls for some time before this, but Rolls Royce used a different mechanical system to accomplish the same purpose.

[13]After the intake had been tried on the Kestrel it was used in the R racing engine of 1929 (see below), and at the speeds of over 350 mph at which that engine was flown the ramming intake was alone responsible for an increase of over 10% in absolute manifold pressure, or of about 250 hp in output.

[14]The moderately supercharged version had a maximum of about 655 hp at about 3,000 feet.

p. 197). The fully supercharged engines of this series weighed 945 lb and had a five-minute combat rating of 660 hp at 14,000 feet; the normal rating was 600 hp at 11,000 feet.

Some further improvements were made in the Kestrel after this time, but the Rolls Royce engine of real importance as a power plant for combat aircraft soon became the Merlin, and the story of the Kestrel can be dropped at this point.

The Buzzard and the Schneider Trophy Engines

About a year after the first Kestrel had been built, and at about the same time that the first production model appeared, in June 1927, Rolls Royce began, with full government support, the design of a scaled-up version of the supercharged Kestrel intended to power large flying boats. This engine, later known as the Buzzard, was intended to provide for the first time a modern replacement for the Condor; its displacement was ultimately set at 2,239 cu in., 87% greater than the Kestrel and a little larger than even the Condor. The first prototype of the Buzzard, completed in July 1928, developed 925 hp maximum at sea level and had a normal rating of 825 hp, for a weight of 1,460 lb.

The Buzzard was installed experimentally in a number of large aircraft, both flying boats and large land planes, but none of these was put in production. Less than 50 production engines were sold altogether, 32 of them to the Japanese. The military flying boat produced in the largest number at this time was the Short Singapore II, powered with four Kestrel engines. The Singapore I had been originally built, in 1926, around two Condors, and in 1929 these were replaced by two Buzzards; but the cleaned-up airframe built in 1930 which became the Singapore II substituted two tandem pairs of Kestrels for the two Buzzards. The principal reason for the change seems to have been that the greater total power afforded by the four Kestrels was needed for take-off; the government may also have believed that if four Kestrels could do at least as well as two Buzzards for large aircraft generally, there was no need for having an additional type of engine in production. For large civil aircraft the air-cooled engine had by this time

secured general acceptance in England as in the United States, and was used on all the important transports of this period: Bristol Jupiters on the deHavilland Hercules (1926) and the Handley-Page 42 or Hannibal class (1931); Armstrong Siddeley Jaguars on the Armstrong Whitworth Argosy (1926) and Double Mongooses on the Atalanta (1932). After 1927 air-cooled engines were used even on commercial flying boats, despite the problem of cooling at take-off. The Short Calcutta of 1927, a civilian version of the Singapore, was equipped from the beginning with Bristol Jupiters; this boat was used by Imperial Airways and also to some extent even by the RAF (in a slightly modified version called the Rangoon). The same engines were used on the Short Scipio in 1931. The reason for this preference of the commercial operators for air-cooled engines was certainly in part the continual troubles experienced at that time with the plumbing of water-cooled engines. In the United States an even more important reason was the lower specific weight of the air-cooled engine, and the same was almost certainly true in Britain.[15]

Within a few years Rolls Royce had completely abandoned the Buzzard, but the work done on it was of great importance in a way which had not been foreseen when the engine was undertaken: it was used as the basis of the R engine which won the Schneider Trophy in 1929 and 1931. Late in 1928 the British government had decided to participate in the 1929 contest, and was faced with the problem of finding a suitable engine. The previous contest, that of 1927, had been won with an unsupercharged Napier Lion with extremely high compression ratio (10:1), but the Assistant Director for Engine Development in the Air Ministry, Major G. P. Bulman, believed that it was very unlikely that the output of the Lion could be raised sufficiently to win a second time, especially since Napier had still done nothing toward the development of a supercharged version of this engine, while Napier's effort to develop a supercharged V-12 was already abandoned. A contract was given to Napier

[15]If we assume ½ lb/hp for the weight of the cooling system and coolant, the Buzzard with its cooling system weighed 2.1 lb per take-off hp and the geared and moderately supercharged Kestrel used in the Singapore weighed 2.3 lb per take-off hp in 1931. The geared supercharged air-cooled Jupiter X weighed only 1.7 lb per take-off hp in 1928.

to develop a supercharged Lion, but at the same time Bulman approached Rolls Royce in the hope of obtaining a better engine. The managing director of the company at this time, Basil Johnson, was strongly opposed to the company's participation in any sort of racing, but the Ministry put strong pressure on the directors, and eventually Henry Royce himself gave his assurance that the job would be done. Time being too short for the design and development of a completely new engine, Royce proposed to raise the output of the Buzzard to 1,800 hp, and this proposal was accepted by the Ministry.

Design of the R engine was begun in November 1928 by Royce and his staff headed by A. G. Elliott at West Wittering. The principal changes from the Buzzard were the substitution of a completely new supercharger, designed by Royce with the assistance of Ellor, and a new reduction gear which could withstand the more than doubled output. The supercharger was designed to have the largest diameter which would fit within the cross-sectional area set by the airplane designer, but even so it was necessary to use a two-sided compressor in order to obtain sufficient air flow. As we have seen, such a compressor had been used on the experimental Eagle XVI and experimentally on the Kestrel, but this was the first time at Rolls Royce or elsewhere that one was actually successful. After these leading features of the design had been provided by Royce, the engine was developed at Derby under the direction of Rowledge, who was responsible for the strengthening which had to be done to most of the parts of the engine as well as the general cleaning up which was required to fit the engine into the highly streamlined Supermarine S-6 airplane, and which involved even the design of a new crankcase. Half a dozen or more engines were built for use in the development.

The first endurance run of the R was made in May 1929; by August the promised figure of 1,800 hp was maintained in a one-hour run. About this time, however, trouble began to be experienced with a falling off of power after about 20 minutes of running. Pure benzol had been the fuel hitherto; F. R. Banks of the Associated Ethyl Company, Ltd, suggested that this might be the cause, and within the short time available

running was done with other fuels suggested by Banks. The one finally adopted was 78% benzol with 22% naphthenic-base Rumanian gasoline and 2.5 cc lead per U.S. gallon. The Schneider Trophy was won in September by the Supermarine S-6 with the R engine yielding 1,900 hp for a weight of 1,530 lb. Two days after the race the same airplane and engine set a new world's speed record of 358 mph.

The decision to compete in the next Schneider Trophy contest, to be held in the fall of 1931, was not reached until January 1931, so that Rolls Royce again was forced to modify its existing engine rather than to undertake a completely new design. The 1929 engine was changed principally by the use of a higher supercharger gear ratio and a larger air intake; still more power was to be got by running the engine at a higher speed. This increased output meant, however, that changes had to be made in virtually every stressed part of the engine. It was necessary to replace the blade-and-fork connecting rods with articulated rods, and salt-cooled exhaust valves were used for the first time on any Rolls Royce engine.[16] Over a dozen engines were built. It was realized this time that extensive fuel development would be necessary in addition to the development of the engine itself, and extensive running was done on fuels blended by Banks of the Ethyl company.

A one-hour endurance run of the new engine at the design power of 2,350 hp was made in August 1931; when the race was won by the Supermarine S-6B on September 13 the engine developed 2,300 hp at 3,200 rpm at 67.2 in. manifold pressure, for a weight of 1,630 lb. The fuel used was 20% straight-run California gasoline, 70% benzol, 10% methanol, and 3.3 cc lead per U.S. gallon.[17] The same day the same airplane, engine, and fuel were used to set a new world's speed record of 378 mph. A short while later the same airplane and engine were run on a new fuel to produce an output of 2,530 hp and set a new speed record of 407.5 mph. This new fuel was 30% benzol, 60% methanol, 10% acetone, and 4.2 cc lead per U.S. gallon. With it a one-hour endurance bench run was actually

[16]Salt-cooled valves were later adopted on the Kestrel IV and all later models of that engine; cf. above, p. 209.

[17]92 octane number by the modified motor method.

made at an output of 2,783 hp at 3,400 rpm with a manifold pressure of 72.3 in.

The 1929 and 1931 Schneider Trophy contests were of the greatest importance in the history of Rolls Royce engines and of aircraft engine development generally. They were an enormous stimulus to the development of ground-boosted service engines. Ground boosting had previously been tried only occasionally in purely experimental engines, and the Schneider Trophy had been won as late as 1927 by an unsupercharged Lion. The possibility of ground boosting is intimately connected with fuel development, and concerning the effect of the 1931 contest on the history of fuel development S. D. Heron has written in a letter to the author: "The fuel development done by Banks on the 'R' engine for the 1931 Schneider Trophy race appears to have resulted in the first recognition in England of the fact that the most desirable fuels for rich mixture operation at maximum power were of necessity of different composition from those giving the best performance at lean mixture. It does not appear that this finding led to immediate recognition in England of the necessity for determining knock ratings under both rich and lean conditions. It seems, however, that the finding was largely responsible for the later British practice of specifying both rich and lean knock ratings. Findings similar to those of Banks were made a little later in the United States but were either ignored or misinterpreted by those specializing in aviation fuels. Pratt & Whitney, about 1930, developed findings similar to those of Banks but were misled as to their significance by Heron."

The high boost of the R engines in the two races could be tolerated for two reasons: the use of a large proportion of benzol under rich-mixture conditions, which in a liquid-cooled engine relatively free from hot spots contributed greatly to improve the antiknock value of the fuel, and in the case of the 1931 race by the use of a large proportion of alcohol as a charge-cooler. Such a fuel was completely impractical for general service, because of the high freezing point of the benzol and because of the poor heat-to-weight ratio of the alcohol, but in 1932, when 87-octane gasoline was introduced into England from the United States and all engine development began to be based on it, Rolls Royce's previous experience with the R made the firm immediately inclined and able to take advantage of it in ground-boosted engines.[18]

The R engines were also of great importance in their psychological effect on the attitude of the government and the airplane industry toward liquid-cooled engines in general and Rolls Royce engines in particular. The 1929 race virtually marked the end of the Napier Lion, since the Gloster entry with the first supercharged Lion had been badly worsted by the Supermarine S-6 with the Rolls Royce R. After 1929 the Lion was put in no new aircraft. To a large extent it was superseded by air-cooled engines, although the most numerous military flying boats of this period, the Singapores, were powered with Kestrels.

As for the attitude toward liquid-cooled engines in general, the races contributed a very great deal toward establishing two convictions. The first was that only the clean, liquid-cooled engine could be used in the fastest types of aircraft, especially fighters. Even before 1929 the airplane industry had been forced by the Fairey Fox to alter its conviction that only air-cooled engines were suitable for fighters, but industry had continued to produce and the government to procure fighters with air-cooled engines, notably the Bristol Bulldog with a Bristol Jupiter, and it was not until 1931 that the first squadron was equipped with the Hawker Fury with the Kestrel. Once the Kestrel-powered Fury had been tried, however, only a very few squadrons were equipped with new fighters with air-cooled engines. The second conviction was that far greater power could be obtained from a liquid-cooled engine than from an air-cooled engine. It was in fact not until the 1940's that an air-cooled engine anywhere in the world equaled the 2,783 hp maintained for an hour by the Rolls Royce R in 1931.

The Merlin, to the Outbreak of the War (1939)

About the middle of 1932 Rolls Royce decided, on its own initiative, that future fighters should have a larger engine than

[18]Until this time the standard fuel had been between 73 and 77 octane. The 87-octane fuel was the first standard British fuel to contain lead, although lead had been used for racing at least as early as the 10:1 Schneider Trophy Lion of 1927. 87-octane fuel went into full service availability in 1934.

the Kestrel, which had been brought out five years before and was beginning to be thought outgrown, but smaller than the Buzzard, which was considered to be too large and heavy for an interceptor; the new engine was to fit in an airplane little if any larger than those based on the Kestrel. The engine would be designed as an almost exact scale-up of the Kestrel to 1,649 cu in. of displacement instead of 1,295, to yield about 750 hp. Rolls Royce originally proposed, in agreement with the Air Ministry, to build the engine for inverted installation, both in order to give improved visibility and for certain technical reasons. The airframe builders, however, were generally hostile when a mockup of the inverted engine was shown to them toward the end of 1932, owing to their dislike of the problems involved in inverted installation, and all Merlins beginning with the first were built for upright operation.

Aside from its larger size, the original design for the Merlin differed from the Kestrel in only two respects. The cylinder block and the upper half of the crankcase were made in a single casting while the head was separate, and the cooling system was a modification of the steam-cooling system used on an experimental version of the Kestrel known as the Goshawk (cf. below, pp. 233-234). Experiments with the Goshawk had shown that serious difficulties were likely to be encountered in a steam-cooling system, and Rolls Royce now decided to try so-called composite cooling, using both a radiator and a condenser.

Detailed designing of the Merlin began early in 1933, and drawings were issued to the shop in April. Just after the decision to undertake development of the larger engine had been reached, Sir Henry Royce died, on April 22, 1933. A. J. Rowledge was already in poor health, and A. G. Elliott, until then the head of Royce's design staff at West Wittering, became the new Chief Engineer. E. W. Hives, formerly head of the experimental department, became general manager of the company and the director of all engineering policy.

Although the Air Ministry was kept fully informed of Rolls Royce's intention to begin this development and approved fully of the plan, no funds were available at the moment to support it. As a result Rolls Royce itself bore the expense until October, by which time the first pair of experimental

engines had been built and were just ready for test.[19] From the time that experimental running was begun, in October 1933, all development was directly paid by the government under development contracts.

By the end of 1933 the Merlin was well enough along for the two airplane companies which were working on interceptors based on the Goshawk to begin work on designs based on the Merlin. In January 1934 Hawker dropped its plans for a monoplane based on the Goshawk and began the design of what was later named the Hurricane. Early in 1934 the government issued the specification F 5/34 for an eight-gun fighter, and the design of the Hurricane was modified to fit. In the latter half of 1934 Supermarine also dropped its plans for a new monoplane based on the Goshawk[20] and began design of the airplane which eventually was named the Spitfire, incorporating at the same time the eight-gun armament called for in the new fighter specification.

The early running of the first two experimental engines (the so-called PV-12's) showed up the usual difficulties, but after the block casting had been strengthened and the reduction gear redesigned, one of the two passed a type test in July 1934, nine months after the first running, with an international (30-minute climb) rating of 790 hp at 12,000 feet; this engine weighed 1,177 lb.

In the same month, July 1934, design was begun of a new version of the engine, with a new type of cylinder head. Before 1927 Elliott had designed for use on the Rolls Royce automobile a new cylinder head giving shortened flame travel and a high degree of turbulence in the charge. This two-valve head had been very successful on the automobile, and early in 1934 single-cylinder work had been begun on a four-valve head intended to accomplish the same objectives in the Merlin. This was the so-called ramp head, with two flat roofs of unequal width and inclination. The design of the Merlin B with the new head and the corresponding changes in valve gear was

[19]For this reason the first two engines were known as PV-12's (Private Venture 12-cylinder).

[20]This airplane was to have been the successor to the experimental F 7/30, also powered by the Goshawk, which had been flown in February 1934 and dropped shortly thereafter.

completed in October, and two Merlin B's were built and ready for test by February 1935. The B delivered 950 hp under conditions corresponding to 11,000 feet altitude. The ramp head was used on all the experimental Merlins from the B through the F, which was the prototype of the first production engine, the Merlin I. The next significant change in the basic design was the decision to have separate castings for the crankcase and cylinder block. The primary reason for this decision, reached after only 50 hours of running on the Merlin B, was to simplify the manufacture of the castings. The first two Merlin C's, with the new construction, were tested in April 1935.

Flight testing of the Merlin began in April 1935 in a Hart modified to take the new engine instead of the Kestrel;[21] the engine was one of the original PV-12's. Troubles immediately began to appear with the composite cooling system, and after eight hours of flying time the cooling system was altered to use pure ethylene glycol with no boiling. This was the cooling system on which the American Army had been working since about 1923, and it was from there that Rolls Royce got the idea; Rolls Royce had tried this system previously in the 1929 Schneider Trophy racer but had abandoned it in that case because the glycol leaked past the rivets in the wing-surface radiators.

Meanwhile bench testing of the experimental Merlins of the B and later models gradually revealed extremely serious difficulties with the ramp head: local detonation produced very bad erosion, distortion led to exhaust-valve failures, and there were frequent cracks in the head due to its asymmetrical shape. A Merlin C attempted but failed a civil 50-hour type test in May 1935 at a rating of 1,045 hp maximum, and although a Merlin E finally passed the 50-hour civil test in December 1935, it failed its attempt at the 100-hour military type test in March 1936. As an emergency solution it was decided to scale the standard Kestrel flat head up to Merlin size, and to retain the Kestrel construction with the head and cylinder block in one piece in order to save time, even though it was realized in advance that the space between cylinders in the Merlin was too

[21] A Merlin was flown in the Hurricane for the first time in November 1935 and in the Spitfire in February 1936.

small to permit a really reliable seal between the liner and the head with this type of construction at Merlin power. Designs of the Merlin G with this head were issued in May 1936.

Meanwhile, however, there was very great pressure to get into production to equip the Hurricanes and the Fairey Battle two-seat day bombers, production of which was about to begin. The government and the company had agreed that in order to meet the first needs the Merlin F, a slightly improved version of the E built during the first half of 1936, would be put into production at once as the Merlin I, and that the type-test regulations would be relaxed for this model to permit replacement of the valves during the test. The first production Merlin I was delivered in July 1936. Even the relaxed type test could not be passed, however, until November, while the Merlin G with the integral flat Kestrel head had gone through its type test with no trouble at all a month before, in October. Hawker was accordingly instructed in December to wait for the Merlin II production version of the G, and production of the Merlin I was stopped after 180 engines had been built, all of which were used on Battles. The first production Merlin II was delivered in August 1937. The original, 1936 combat rating of both the I and II on 87-octane fuel was 1,030 hp at 16,250 feet; the engines weighed 1,335 lb.

The trouble anticipated with the Kestrel-type integral head and block, leakage between the top of the liner and the water chamber, did not fail to be experienced very shortly. In March 1938 development was begun of a new block with a separate head, but although the development proceeded rapidly production commitments held the company to the old construction until the Merlin 61 appeared in 1942 (cf. below, p. 230, n. 36). Merlins with separate heads of this design were actually produced by Packard before they were produced by Rolls Royce.

In January 1934 Rolls Royce had already begun work on a two-speed drive for the supercharger of the Kestrel, in order to eliminate the sacrifice of power for take-off and low-altitude flight which was entailed by the use of a supercharger designed for about 15,000 feet and which was particularly bothersome in bomber applications. In January 1935 work was begun on the design of a two-speed drive for the Merlin supercharger. The original design soon ran into a number of difficulties, however, and Rolls Royce shortly decided to take a license for the Farman drive which had been developed in France.[22] The two-speed supercharger with Farman drive for the Merlin was first flown in September 1937, and production of the Merlin X bomber engine with this feature began in December 1938. Except for a few details, such as a different reduction gear ratio, the Merlin X was otherwise the same, including the design of the compressor itself, as the Merlin II.

It was with these two basic models, the Merlin II and the Merlin X, differing only in their supercharger drives, that Rolls Royce entered the war.[23] The combat ratings, on 87-octane fuel, were 1,030 hp at 16,250 feet for 1,375 lb weight in the II (same rating but 40 lb heavier than in 1936) and 1,010 hp at 17,750 feet or 1,130 hp at 5,250 feet for the X with a weight of 1,430 lb.[24]

Beginning just at the outbreak of the war one important change was introduced as standard on all new models of the Merlin. This was a new cooling system. Development done since 1936 (cf. pp. 238-239) had shown that a pressurized cooling system containing 70% water with 30% glycol added simply as an anti-freeze was distinctly superior to pure glycol at atmospheric pressure; cylinder temperatures were at least 70°F lower for any given coolant temperature when the new system was used, and in addition the mixture had much less tendency to creep through joints than pure glycol and was not inflammable. The reduction in cylinder temperature meant considerably prolonged engine life. There was no increase in drag or weight with the new system, since by maintaining the pressure at 18 lb (i.e., at a temperature of 255°F) the same size radiator sufficed as with pure glycol. The new cooling system was used on all production models after the single-speed II (and the al-

[22]Rolls Royce's original drive was designed to fit in the same space as the old single-speed drive, so that the engines would be interchangeable, whereas the Farman drive was several inches longer.

[23]Before the beginning of the war Rolls Royce also put in production the Merlin III, which was identical to the II except for the propeller shaft and the accessory drive, and the Merlin IV, identical to the III except for the cooling system, on which see below.

[24]The international ratings were 990 hp at 12,250 feet for the II and 1,035 hp at 2,250 feet or 960 hp at 13,000 feet for the X.

most identical III) and the two-speed X. It was introduced to production on the Merlin IV (basically the same in other respects as the II), deliveries of which began in August 1938, but very few engines of this model were produced, and the first important production was on the Merlin XII, production of which began in September 1939.

100-Octane Fuel

At the beginning of the war the first-line British fighters, the Hurricane I and Spitfire I, both with Merlin engines, seem to have been superior to the German first-line fighter, the Me 109, in top speed and in the altitude at which the top speed was attained. They were inferior, however, in speed above this critical altitude, and in climb at all altitudes. The reason was simply that the Daimler-Benz 601A engine of the Messerschmitt Me 109E fighter developed about the same power for about the same weight to about the same critical altitude as the Merlin, and was installed in a considerably lighter airplane.[25] Since despite the fact that the DB weighed very little more than the Merlin (1,460 against 1,375 lb) it had a 25% greater displacement (2,069 cu in. against 1,649), Rolls Royce was obliged both to develop the Merlin to tolerate much higher manifold pressure, in order to obtain equal performance at the lower altitudes, and to develop superior supercharging, in order to compete at the higher altitudes.

The development to tolerate higher manifold pressure was the simpler of the two problems, since the Merlin was inherently a stronger engine than the DB (as can be seen from its weight of 0.83 lb/cu in. of displacement against the 0.71 lb/cu in. of the DB). Rolls Royce had already in 1937-1938 done a good deal of development on a special, very highly boosted Merlin with which it had for a time hoped to recover the world's speed record; in May 1938 this special engine had been approved for flight at 84.9 in. manifold pressure, at which it de-

[25]The normal loaded weight of the Hurricane I fighter in April 1940 was 6,730 lb; the figure for the Hurricane II in November 1940 was 6,970 lb. The Spitfire II A of 1940 weighed 6,300 lb all-up. The all-up weight of the Me 109E in service in 1939-1940 was 5,520 lb.

veloped 2,160 hp at 3,200 rpm.[26] The fuel used in this racing engine, however, was of a character unsuitable for service use.[27] Beginning about 1938 Rolls Royce experimented with the use of water injection to prevent detonation, but by 1940 had decided that the necessary apparatus was too complex and gave it up.[28] In 1940 Rolls Royce experimented with an air-cooled intercooler for engines with single-stage superchargers, and flew such a device with a single-stage blower running at 1,400 fps impeller tip speed on a Merlin engine in a Fairey Battle, but this too was given up as being too heavy for the gain to be made.

Thus an increase in the permissible boost for service Merlins depended almost entirely on the appearance of a service fuel which would tolerate more boost without detonation, and fortunately 100-octane fuel was made standard for service use by the RAF just in September 1939. A little engine development had been done on 100-octane fuel during the two years previous, but the work had not been intensive since there were no production facilities for tetraethyl lead in Britain and it was considered very doubtful that 100-octane fuel could be available in time of war. The importance of the new fuel can be seen from the fact that the Merlin II, which with a maximum manifold pressure of 42.6 in. on 87-octane fuel had a combat rating of 1,030 hp at 16,250 feet at the outbreak of the war, was authorized before the end of 1939 to use 48.2 in. manifold pressure on 100-octane fuel and received a combat rating of 1,160 hp at about 13,500 feet with no increase in rpm. Before the middle of 1940, a manifold pressure of 54.3 in. was authorized, giving a combat rating of 1,310 hp at 9,000 feet, again with no increase in rpm. Combat ratings based on 62.5 in. manifold pressure became authorized early in 1942, when the Merlin II and III were no longer in front-line service, but at the beginning of 1942 a combat rating of 1,440 hp at this pressure was authorized on

[26]The N 17 Spitfire with this engine made about 410 mph.

[27]It consisted of 20% straight-run gasoline, probably of California type, 60% benzol, 20% methanol, and 3.3 cc lead per U.S. gallon.

[28]During the war Packard experimented with water injection and at the very end of the war went into production with a small number of engines so equipped. Packard's original purpose was to obtain with American 100/130 fuel the results obtainable without water from British 100/150 fuel, but the reason for ultimately going into production was to get a 2,200-hp combat rating on 115/145 fuel from a long-range engine with 7:1 compression ratio.

these engines for catapulted take-off from merchant ships. The engine development for this rating consisted simply in an alteration in the automatic boost control.

An increase in permissible boost contributes nothing at all, however, to the performance of an engine at altitudes equal to and greater than the critical altitude under the old boost rating; improvements in performance at these altitudes can be obtained only from more supercharging, more efficient supercharging, or both. In the earlier part of the 1930's it would seem that relatively little progress had been made in either of these respects: the supercharger used on the Kestrel had very early attained an efficiency of about 65% over all (including elbow and carburetor losses) at a pressure ratio of 2:1, while that of the production Merlins of 1939 had only a slightly higher ratio (2.3:1) and about the same efficiency. Fortunately, however, Rolls Royce was nearly ready to introduce very great improvements in both respects. The subject of the company's supercharger development is important enough to be worth tracing from the beginning in a separate section.

Development of Superchargers

The British, and particularly the Royal Aircraft Establishment at Farnborough, were very early in taking a serious interest in supercharging. Work on this problem went on at Farnborough continuously from 1915 under the direction of James E. Ellor. After trying both reciprocating and Roots blowers in 1915, Ellor suggested the use of a centrifugal blower. The first centrifugal blower tried had an adiabatic efficiency of about 60%, or as good as the Roots blower, and since the centrifugal blower had no need of a tank to equalize a pulsating air delivery, the other types were given up at once. A gear-driven centrifugal supercharger was tried out on the Raf 1A in 1916 and on other engines before the end of the war, and an integral gear-driven supercharger was included in the RAE's original 1916 design of the two-row radial which became the Armstrong Siddeley Jaguar (cf. above, p. 132).

After the war the RAE left the mechanical development of the geared supercharger to the engine companies, but continued to be the only center of work on the aerodynamic problems of the centrifugal compressor, since there were no engineers in the engine companies with the necessary qualifications for work in this field. During the first half of the 1920's the RAE added rotating guide vanes or inducers to the impeller, probably the greatest single step ever made in the development of the centrifugal compressor. By 1927 the RAE had produced a compressor with an efficiency of 70% on the stand at a pressure ratio of 2:1.

During the period from 1918 to 1924 or 1925, the RAE also experimented extensively with turbosuperchargers. After a first design had been prepared by Ellor in collaboration with the Metropolitan-Vickers Electrical Company, Ltd, it was learned that the Frenchman Auguste Rateau was further advanced, and a Rateau turbo was obtained and flown on a Raf 4D in the fall of 1918. The RAE then went ahead to design further improved turbos, and for several years after 1918 believed that this type of supercharger was the most promising. All the engine builders, particularly Bristol and Napier, showed interest in the work by supplying engines to be tested with turbos, and a number of flights were made by the RAE up to 30,000 feet altitude. Two of the engine companies, Bristol and Rolls Royce, were led to design turbos of their own.

It was impossible, however, without a controllable-pitch propeller to take advantage of full engine power at such great altitudes unless intolerable sacrifices were made at take-off. In addition there were necessarily at this time very serious difficulties with the exhaust manifolds, with the blading and the bearings of the turbine, and with distortion of the casing. About 1925 the government definitely decided to give second place to the turbo and concentrate on the development of engines with geared superchargers aiming at much more moderate altitudes, between about 10,000 and 15,000 feet, where a fixed-pitch airscrew could still give reasonably good performance. As we have seen, this change in government policy led in the case of Rolls Royce to the inclusion of a geared supercharger on the Eagle XVI built in 1925 and on the first experimental Kestrel (the F-X), built early in 1926. These superchargers, however, had given poor results, owing to Rolls Royce's lack of

engineers who had had experience with centrifugal compressors. This lack was finally remedied when the firm hired Ellor from the RAE at the end of 1927.

All the supercharger development done by Rolls Royce from this time on was supported directly by the government, by means of special development contracts apart from the contracts under which the development of the engine as a whole was done. The terms of these contracts were technically very liberal; the company was not obliged to perform a series of experiments strictly defined in advance, but was left free to pursue the agreed objective as seemed best from time to time.

Under Ellor's direction a supercharger was designed for the Kestrel, having, as we have seen, about the same efficiency as the most recent RAE machine, some 70% before deducting elbow and carburetor losses, or about 65% over all, at a pressure ratio of about 2:1. After this rather rapid achievement, however, supercharger development made relatively little progress for a number of years, except for the production of the superchargers for the Schneider Trophy R engines of 1929 and 1931. These were remarkable more for their large air flow than for their pressure ratio, which was about 2.2:1, or their efficiency. The supercharger used on production Merlins of 1939-1940, which had been designed in 1936, had only a slightly higher ratio (2.3:1) than the original Kestrel blower and about the same efficiency.[29]

There was a very considerable amount of work to do before any real progress could be made. In order to avoid surging, there was a tendency to work with air flows well above the surge point, and measurement techniques and the science of compressors generally had not yet developed to the point where it was realized that this margin of protection against surging was often being made so large that there was a very serious sacrifice of efficiency. One of the chief reasons for the lack of information on what exactly was happening inside the supercharger, and on the effect of particular changes in the design of its various parts,

[29]The 2.3:1 pressure ratio and 60%-65% over-all efficiency (including carburetor and intake losses) of the supercharger used on production Merlins in 1939 were not appreciably better than the corresponding figures for the contemporary German Daimler-Benz and Junkers superchargers.

was the fact that the intake elbow of superchargers was usually an integral part of the blower casing. Since this made it difficult to test the supercharger without the inlet attached, few experiments were made on either the compressor alone or the inlet alone, and the result was that it was not realized that in the effort to reduce the length of the engine so that it would fit more easily into the airplane the elbow had been made so short that very serious losses took place inside it. These losses, furthermore, tended to mask any real improvements which might be made in the design of the compressor proper, so that little progress could be made in the design even apart from the more or less fixed elbow. In 1935 an axial entry was designed for the supercharged Kestrel, and bench tests run with this installation in 1936 showed that very great gains could be made by an improvement in the entrance. No immediate use could be made of the lesson, however, because the great pressure for development of a serviceable Merlin (cf. above, p. 219) prevented development at this time of a practical entrance elbow which would minimize these losses.

The low efficiency resulting from these various causes was not only a loss in itself, but was one of the most serious obstacles to an increase in the pressure ratio of the compressor even apart from the problem of efficiency. This was because the inefficiency of the compressor implied an eddying air flow (the immediate cause of the losses), and as tip speeds were increased in order to increase the pressure ratio these eddies became strong enough to set up really violent vibration and break the compressor vanes, which were already more and more highly stressed by centrifugal force as tip speed increased. In addition to the vibration problems, tip speeds were approaching the speed of sound, i.e., the point where compressibility phenomena or so-called Mach Number effects are encountered, and the whole science of compressible flow was only in its infancy at the beginning of the 1930's. There was, furthermore, little incentive to develop superchargers with higher pressure ratios until late in the 1930's. The main technical reason was the lack of controllable-pitch propellers, but in any case the Air Staff had decided that the maximum performance of fighters ought to be in the neighborhood of 15,000 feet, and the Kestrel

supercharger of the early 1930's actually gave maximum air speed at an altitude slightly higher than this.

The first serious attempt by Rolls Royce to make large increases in the pressure ratio of its superchargers was made in connection with the special racing engine of 1937-1938 (cf. above, pp. 221-222). New impellers and diffusers were designed and were run at very much higher speeds than ever before, up to 1,500 fps tip speed, but even then no new casings were developed. The efficiency obtained at these high tip speeds and pressure ratios was too low for other than racing use, and no appreciable increase was made in the pressure ratio of service superchargers until a completely new and much more efficient design had been developed.[30]

Toward the end of 1937 Rolls Royce began a new and much more systematic program of supercharger development, entering into the detailed observation of the flow of air through each part of the device. A large part in this program was played by Stanley G. Hooker, who joined the firm in 1938. In part the work consisted in the gathering together of information which already existed in scattered form and of which full use had not been made; for instance, the best "nondimensional" method of presenting the results of tests on superchargers, a method which for the first time made it easy to predict from ground-level tests the performance of a compressor at high altitude, had been published in 1930[31] but did not come into use in the practical designing of superchargers until Hooker took it up. In addition to making full use of existing knowledge, extensive testing was done beginning at this date both on the compressor itself with an axial entry and on the intake system without the compressor. An elbow was developed which gave intake losses virtually as low as those with an axial entry. Tests with

[30]In September 1939 the Merlin XII (the power plant of the Spitfire II) went into production with a supercharger gear ratio 6% higher than that of the Merlin II, but this change was simply an incidental result of redesigning and strengthening the gearing, and had no appreciable effect on pressure ratio. The main difference between the XII and the II, and the reason the new model was produced, was the use of a different type of starter and the substitution of pressure for glycol cooling.

[31]R. S. Capon and G. V. Brooke, *The Application of Dimensional Relationships to Air Compressors, with Special Reference to the Variation of Performance with Inlet Conditions* (Aeronautical Research Committee, "Reports and Memoranda," No. 1336) (London: His Majesty's Stationery Office, 1930).

a carburetor with larger air passages showed that an important improvement could be made in that component, information which eventually led to the substitution of a speed-density metering system for a carburetor (cf. below, p. 527). The separate tests of the blower showed that various refinements of design, and particularly a central entry, would improve the efficiency of that component considerably.

The changes made in the intake system as a result of this work gave an improvement in over-all efficiency of some 5%, while the refinements in the blower itself made it possible to increase the pressure ratio considerably without any corresponding loss in efficiency: blowers of 3.0 or 3.1:1 pressure ratio could now be made with an over-all efficiency of 65%-70% instead of the 60%-65% efficiency of the 2.3:1 blower of the 1939 Merlin.[32] The new supercharger was first used on the Merlin XX, with a two-speed supercharger drive, which went into production in July 1940; this model replaced the Merlin X in bombers and was also used in the Hurricane II, production of which began in August. A little later the new supercharger was used on the single-speed Merlin 45, which went into production in January 1941 to replace the Merlin XII and was used in the Spitfire V, which entered service in the summer of 1941 as an answer to the much improved Me 109F which had appeared in May of that year. The XX had a combat rating at this time, at 48.2 in. manifold pressure on 100-octane fuel, of 1,175 hp at 20,500 feet, to be compared with 1,160 hp at about 13,500 feet for the Merlin II on the same 48.2 in. and the same 3,000 rpm. Before the end of 1941 the 45 was rated 1,315 maximum hp at 16,000 ft at 54.3 in.; this is to be compared with a rating of 1,280 hp at 10,500 ft for the Merlin XII with the same supercharger gear ratio, the same 54.3 in., and the same 3,000 rpm. The improved efficiency of the supercharger meant, of course, that the performance of both the new engines, the XX and the 45, above their rated altitude was considerably better than that of the II and XII. The Hurricane II with

[32]Tests of this new supercharger conducted at Wright Field according to the NACA standard procedure showed an efficiency of 71% at a pressure ratio of 1.6:1 instead of the 66½% of the old Merlin supercharger, 68% at 2.2:1 instead of 64½%, and 67% at 2.9:1 where the performance of the old supercharger was too poor to be reported.

the Merlin XX and the Spitfire V with the Merlin 45 turned even the new Me 109F into a definitely second-rate fighter.

The final important step in the development of the wartime Merlin was the introduction of two-stage supercharging. Rolls Royce's first attempt at extremely high pressure ratios, that made in connection with the special Merlin III racing engine of 1937-1938, had used only a single-stage supercharger. The RAE about 1936-1937 had recommended two stages for pressure ratios as high as Rolls Royce was trying to obtain at that time, but Rolls Royce had at first believed that the desired pressure ratio could be got from a single stage, and wanted to avoid the difficulty, inherent in a two-stage compressor, of having the faults of the first stage magnified in the second. The efficiency of the 1937-1938 single-stage blower, however, had been so poor at pressure ratios of 4:1 and higher that it was decided well before the war that a service engine could not be equipped with a single-stage gear-driven supercharger giving such a ratio.

Shortly before the war Rolls Royce reconsidered the use of the turbosupercharger,[33] but concluded from analysis and from tests made in 1938 of a Swiss Brown-Boveri turbo on a Kestrel engine that the turbo was undesirable. The firm believed that for attainment of maximum speed in a fighter it was as effective to make use of the energy in the exhaust by means of the jet exhaust stacks which it had developed and which were used on all Spitfires and Hurricanes, and held that the turbo implied serious metallurgical difficulties, additional weight and drag, and (especially in fighters) serious problems of installation and control. The decision was certainly the right one since the turbo could probably not have been developed in time, although later experience showed that the turbo is actually better even for top speed and very much better for climb and fuel economy.

This discussion of superchargers for very high altitudes seems to have been conducted in terms principally of fighters, and preliminary drawings of a fighter engine with a two-stage mechani-

[33]It will be recalled that the last previous interest of Rolls Royce in the turbo had been in 1924-1925, when a Condor V with a turbo was built and run on the bench but never flown. Cf. above, p. 202.

cal supercharger were made about the time of the outbreak of the war. It was not until March 1940, however, that detailed design of a two-stage supercharger began, and by this time the project was not connected with fighters, for which it was believed that the new and more efficient single-stage supercharger of the Merlin XX and 45 would suffice, but with the intention to develop the Wellington VI as a high-altitude day bomber. This supercharger was designed from the beginning to operate with an aftercooler in order to permit higher boosts.[34] The first bench tests of the two-stage supercharger were made in April 1941, and the first flight was made in a Wellington VI in July. Production of the Merlin 60 began in November 1941. It is quite remarkable that even though the pressure ratio of this two-stage supercharger was 4.9:1 in high gear, it had an efficiency of 70%-75%,[35] where the single-stage supercharger of the Merlin XX, with a pressure ratio of only 3.1:1, had an efficiency of only 65%-70%.

Even before production of this two-stage bomber engine had begun, it had been decided that a two-stage engine should be developed for fighters. The new fighter engine, the Merlin 61, differed from the 60 bomber engine essentially only in the choice of supercharger gear ratios.[36] It was first run in August 1941, and was first flown in September. Late in 1941 the German Focke-Wulf 190 fighter, powered by an engine very much larger than the Merlin, appeared on the front with performance decisively superior to the Spitfire V, and as a result the Merlin 61 was hurried into production in March 1942. The new engine was the power plant of the Spitfire IX, which started going

[34]American development took the alternate course of using intercooling between the two stages, which was less effective than aftercooling, with water injection to permit these higher boosts. Recent experiments by Pratt & Whitney indicate that aftercooling is superior to intercooling plus water injection, but aftercooling was much harder to design into a radial engine than into an in-line engine. Aftercooling can be combined with water injection, of course. Cf. above, p. 222, n. 28.

[35]A water-cooled hollow diaphragm separating the two stages provided a negligible amount of intercooling.

[36]There was one other difference between the 60 and the 61 in that the latter had a two-piece cylinder block, but this was simply a general improvement which had no connection with the particular use of the Merlin 61; development of the two-piece block had begun in March 1938 and had not been used earlier simply because of production commitments. Cf. above, p. 219. The 60 was soon replaced by the 62 with the same two-piece block as the 61 but with identically the same ratings as the 60.

into service late in 1942, and was more than a match for the Fw 190.

By the end of the war the best low-altitude compressors used on the production Merlins, with a pressure ratio of about 2:1, had an efficiency of 79% on the stand; the highest pressure ratio experimentally attained with a single-stage blower by this time was 5.24:1, with an efficiency of 68% on the stand. At the end of the development of the two-stage supercharger, pressure ratios of 7.2:1 were in production with an efficiency of 62% over all, including the aftercooler, and 8.2:1 had been obtained experimentally at 65% over-all efficiency.

Development of Cooling Systems by Rolls Royce

Throughout the 1920's a large part of the failures of liquid-cooled engines in service was due not to the engine proper but to the cooling system. According to Rolls Royce's figures, about a fourth of all engine failures at the end of the 1920's were due to some trouble in either the cooling system or the oil system outside the engine itself.[37] In addition to this, the radiator, plumbing, and coolant added a very large amount to the weight of the engine, and thus constituted a very serious handicap in competition with air-cooled engines. Until 1929 in England, however, and at all times in the United States, the manufacturers of liquid-cooled engines took no responsibility for the development of cooling systems or for their proper installation in the airplane; the development of the components was left to the suppliers of those components, usually small companies with inadequate resources for development and no facilities at all for testing on actual airplanes, and the problems of installation were left to the airplane builders, who were naturally not specialists in this sort of problem.

In 1929 Rolls Royce established an installation-engineering department. For a long time this department was primarily occupied with the problems of the cooling system, and although its activities came to include the problems of other accessories as well and eventually the complete power plant as a unit, only the cooling system will be treated here. For four years the de-

[37]Cf. the United States statistics above, p. 169, n. 8.

partment was able to conduct tests only on the bench at Derby, but in 1933 a small flight-testing establishment was set up at a municipal airport near Derby, and then in December 1934 a hangar was acquired at Hucknall with three single-engine experimental airplanes.

Installation engineering by an engine builder was at first resisted by the airplane manufacturers, but it gradually established itself in their confidence by the results which it produced, and in the end no airplane manufacturer would have thought of attempting an installation of a Rolls Royce engine without obtaining all the aid possible from Rolls Royce. The work of the installation department was completely financed by special government contracts from the beginning, and as the results of the work showed its importance the size of the support grew, until finally the Hucknall establishment became the largest of its sort in the world.[38]

Header Tanks

During the first years following 1929 Rolls Royce worked on various details involved in getting the existing type of cooling system to work properly. Probably the worst of the many difficulties being experienced with water-cooled engines in 1929 was their tendency to lose all their coolant and thus become completely disabled when the average water temperature was still well below the boiling point. This difficulty was usually due to the design of the "header" or water-expansion tank and the way in which it was installed. When local boiling occurred in the cylinder jackets, the steam thus generated usually blew the water out through the vent in the header tank, emptied the cooling system, and thus disabled the engine. Furthermore, the typical tank, designed primarily for easy installation within the cowling, was wide and shallow and was mounted to the

[38]It should be recalled, however, that the other principal British manufacturer of high-power engines, Bristol, also manufactured airplanes, and thus had at its immediate disposal very considerable test facilities without setting up a special department. The same was true of Armstrong Siddeley, a firm which was at least as important as Bristol in the 1920's, although it faded out in the 1930's as a builder of high-power combat enigines. Despite this situation, the aerodynamic installation of air-cooled engines in Britain was about as far behind that in the United States during the 1930's as the installation of liquid-cooled engines was ahead.

rear of the engine and only slightly above it, so that when the airplane was on the ground or in a climb the front cylinder jackets were not completely full of water and local boiling was aggravated.

Rolls Royce's first solution for this problem was the development of a new combined header tank and separator which could let the steam escape without losing water. The mixture of steam and water was made to strike a plate at a small angle; the water stayed on the plate and ran to the bottom of the tank, while the steam was allowed to escape. This vapor-separating header tank fitted in the same space as the older tanks and could be easily substituted for them. It was standard during most of the 1930's, being used, e.g., on the Kestrel-powered Fury throughout its life.

In the second half of the 1930's Rolls Royce developed a more fundamental remedy for the difficulty of partially empty coolant jackets. This was a completely new installation of the separator-type header tank, in front of rather than behind the engine, so that the block remained full of coolant even when the airplane was on the ground or climbing. This tank was mounted directly on the engine rather than on the airplane. The new type of tank had been proposed by 1935, but development did not begin until about 1938, and its first important use was on the Lancaster bomber and the Beaufighter II, which went to the squadrons early in 1942.

Reduction of the Weight of the Cooling System

During the whole first half of the 1930's Rolls Royce felt under the strongest pressure to reduce the weight of the cooling system, since the weight of contemporary air-cooled engines per horsepower of output, at least at low and medium altitudes, was very markedly below that of Rolls Royce liquid-cooled engines plus their cooling system and coolant (cf. above, p. 211 and n. 15). Once a header tank had been developed which could separate steam from water, Rolls Royce immediately attempted to remedy this disadvantage by developing a new cooling system based on intentionally allowing the water in the cooling jacket to boil. A given weight of steam will give off about 30 times as much heat when it is condensed to water in a condenser as the same weight of water will give off when cooled in a radiator over a 30° F temperature difference, the maximum used in practice. Thus it was believed that by letting the water in the coolant jackets boil and condensing the vapor, instead of cooling the water before it boiled, a very large part of the weight of the water in the radiator could be eliminated.

A new version of the Kestrel, ultimately called the Goshawk, was designed with steam cooling beginning in 1928 and extensively tested on the bench beginning about 1929. Flight tests of the Goshawk were begun in 1930 in a Hawker Hart. The engine itself worked very well with steam cooling, and various new fighters were designed around the Goshawk beginning in 1930.

As more flying was done, however,[39] serious difficulties showed up in the operation and installation of the cooling system, and when development of the Merlin was begun in 1933 it was designed for a composite system having both a radiator and a condenser. Such a system had been tried and had worked quite well in Goshawk-powered biplanes with the condenser in the upper wing above the engine, but when the Merlin with this system was tried out in flight, in April 1935, a fundamental difficulty appeared. This was the difficulty of pumping the condensate back to the engine from a condenser located below the header tank; since the condensate was virtually at the boiling point, any slight reduction in pressure due to the pump caused it to boil and this action prevented the pump from working. The composite cooling system for the Merlin was abandoned after only eight hours of flying and was replaced by high-temperature cooling with ethylene glycol.

Cooling with ethylene glycol, which Rolls Royce adopted in 1935 under the stimulus of studies made by the RAE,[40] had originally been developed by the Wright Field establishment of the U. S. Army, which had begun work on the system in 1923

[39]Altogether 24 steam-cooled engines were flight-tested, in 12 different airplanes.

[40]Rolls Royce had tried ethylene glycol cooling in 1929 on the Schneider Trophy racer, but had discovered that glycol would leak out around the rivets in the wing-surface radiators where water would not and had been forced to give it up.

and had required its use on all new liquid-cooled engines since about 1930. Because ethylene glycol has a considerably higher boiling point than water,[41] the radiator could be kept much hotter than a water radiator, and thus the necessary heat dissipation could be accomplished with a smaller and lighter radiator with a lesser weight of coolant. The saving in weight was between a half and two-thirds the weight of the water radiator with its water.

Reduction of Radiator Drag

In the first years of the 1930's, as we have seen, Rolls Royce's cooling system development centered on two problems: making the system reliable, and reducing its weight. Relatively less attention was paid at this time to the drag due to the radiator, which was usually just an appendage on the outside of the airplane of a form convenient to manufacture, with shutters in front to prevent overcooling when the engine was not running at maximum power, and perhaps with some rudimentary fairing over the outside.[42]

As the speed of the airplanes increased, the importance of drag increased relatively to that of weight, and as the airplane itself became cleaned up — particularly when the externally braced biplane was replaced by the internally braced monoplane[43] — the drag of the radiator became a much larger part of the total drag of the airplane.[44] About 1935 various airplane builders were informing Rolls Royce in very clear terms that with the existing cooling system the liquid-cooled engine was inferior to the air-cooled in both weight and drag.

The first attempts at making a large reduction in drag had consisted of eliminating the separate radiator completely and

[41]The boiling point of the 97-3 mixture of glycol and water which was actually used rather than pure glycol is about 325° F.

[42]The Hawker Hart, which had a retractable radiator to reduce drag when full cooling was not required, was exceptional, and the Hawker Fury reverted to a fixed radiator.

[43]The first monoplane fighter designed in Britain since pre-1918 times was the Supermarine F7/30, designed in 1930.

[44]Experiments at Wright Field showed that the combined radiator and radiator-interference drag was 22½% of total drag even on a biplane pursuit of about 1930. *SAE Journal (Transactions)* 41, 1937, p. 324.

using the surface of the airplane itself as a radiator. This was done in many racing planes beginning early in the 1920's and including the Supermarine racers with Rolls Royce engines which had won the Schneider Trophy in 1929 and 1931. Such radiators, however, were both extremely vulnerable in military service and extremely difficult to make and keep leak-proof. The use of a conventional radiator of the much smaller size permitted by the higher temperature of glycol offered a much more practical solution.

Until the early 1930's it had been generally believed that the drag of a radiator operating at any given temperature was reduced to a minimum by using the smallest possible cross section, and in order to get the necessary cooling from the smallest section the radiator was located in a place where it was struck by the full velocity of the slip stream. The theory of radiator design and location was completely revolutionized in the early 1930's, when work done by Rolls Royce and at the same time and independently by the U. S. Army at Wright Field showed that exactly the opposite tactics should be used: the internal drag of the radiator became a minimum if the cross section was made as large as possible while the velocity of the air striking it was reduced by properly designed ducting to the minimum necessary for cooling. A corollary was that when less than maximum cooling and therefore less air flow was needed the reduction should not be made by retracting the radiator or by reducing its area with shutters directly in front of it, but by reducing the air flow through the duct in some way which did not spoil the duct's low-drag property. The easiest way of doing this was to use shutters at the exit from the duct, since any simple kind of shutters at the entrance would create turbulence and drag inside. Only internal drag, of course, was reduced by increasing the size of the radiator; if the radiator was left outside the airplane, the external drag increased as the size increased. In addition, the weight of the radiator increased with its cross-section. Thus there was an optimum size which should not be exceeded. If the radiator could be wholly or partially located within the airplane, however, all or part of the external drag could be eliminated; the optimum cross section would be greater and the total drag less.

In 1935 a second revolutionary idea was added to the theory of radiator drag when F. W. Meredith of the RAE showed[45] that the energy losses due to forcing air through a radiator were to some extent offset by the conversion into thrust of the heat given off by a properly ducted radiator. The propulsive energy regained from heat in this way increased with the speed of the airplane and actually increased faster than the cooling drag, so that above a certain speed it was theoretically possible to obtain a net thrust rather than a drag from the radiator.

About 1933 Rolls Royce decided that low-drag radiators could be properly developed only by extensive flight testing; this was one of the primary reasons why the company set up its Hucknall flight-testing establishment in December 1934. As soon as Hucknall was ready for use experiments were begun on the effect of radiator cowling and ducting. The drag of the Hart airplane on which these first tests were made was so great, however, that any change in drag due to a change in the radiator installation was masked by experimental error in the measurement of the total. It was largely because the cleanest possible airplane was required for this particular purpose that Rolls Royce in March 1936 bought a Heinkel He 70 four-place transport, the cleanest airplane of the right size available "off the shelf."[46] It had the additional advantage over the two-seat Hart of carrying a sufficiently large crew of engineers and observers.

All possible locations for the radiator and all kinds of cowling and ducting were tried on this airplane during the next year or two, and confirmed in general the principles of radiator design which had been worked out by the RAE and by Wright Field. The experiments included tests of a radiator entirely within the frontal area of the Heinkel, although not actually inside the

[45] F. W. Meredith, *Note on the Cooling of Aircraft Engines* (Aeronautical Research Committee, "Reports and Memoranda," No 1683, August 1935) (London: His Majesty's Stationery Office, 1937).

[46] The He 70 was not used for radiator development only; it was on this airplane that Rolls Royce for the first time developed jet exhaust stacks, of which the first suggestion in Britain had been made by Meredith in the same paper in which he had pointed out the possibility of recovering the energy in radiator heat. Ellor of Rolls Royce had previously patented (Br. 447,283; applied for November 15, 1934) the use of the exhaust to induce additional air flow through a radiator, but Meredith was the first to suggest converting the energy (either heat or kinetic) of the exhaust into thrust.

airplane, and showed that this was the most desirable location. Installation problems prevented the use of a submerged radiator in most of the British airplanes which actually saw service; and in one of the cases where the radiator was completely submerged, the Mosquito, which had its radiators in the wings, the radiators were too small to give really satisfactory performance. It is said to have been claimed by Westland Aircraft, Ltd, however, that the radiators of its Whirlwind fighter, which were submerged in the wing, did in fact exert a thrust rather than a drag.[47]

Pressure Cooling

When ethylene glycol cooling was substituted for composite cooling on the Merlin in 1935 it was quickly found that it brought a new set of problems, the worst of which was its "loading" of the engine. In order to minimize the weight and drag of the radiator the glycol was operated at about 266° F, some 70° hotter than an ordinary water system, and the increase of temperature which the engine had to withstand was still greater than this, since even at the same coolant temperature, the temperature of the cylinder walls was at least 70° F higher with glycol as the coolant than with water. Glycol had other, though less important, disadvantages as well, chief of which were its inflammability and its tendency to seep through joints which would be tight against water.

The work on the reduction of the drag of radiators begun in 1936 with the tests on the Heinkel showed that with proper installation and ducting the larger radiator required with water gave no more drag than a glycol radiator, while the life and reliability of the engine were much improved. The Merlin I and II production engines were already committed to a glycol system, and the later III and X were identical to the II as far as the basic engine was concerned, but it was decided by 1936 to change to water cooling as soon as the necessary minor changes in the engine could be made. Thirty per cent glycol was

[47]The radiators were almost completely submerged in the wings of the Sabre-powered version of the new Hawker Fury designed in 1943; Hawker reports a small but positive cooling drag. The radiator in the Mustang was completely submerged in the fuselage; its builder, North American Aviation, Inc., reports very small drag but no positive thrust.

added, but purely as an antifreeze, and the 30-70 mixture had virtually the same coolant properties as pure water.

Airplanes in tropical service need either a larger or a hotter radiator for any given power output than is needed in a cooler atmosphere. The boiling point of water rises as the pressure on it increases, and in order to avoid putting a larger radiator on these tropical airplanes Rolls Royce began development on the Kestrel of a sealed cooling system operating under a pressure greater than atmospheric. A Merlin II was type-tested for pressure cooling late in 1936. Later on, as the power of the Merlin was increased, a pressurized system was adopted for all uses to avoid increasing the size of the radiator. Owing to the lower and more uniform cylinder-head temperatures which obtained with water as the coolant, it soon became possible to authorize operation for one hour with the radiator at 257° F; use of this temperature had been restricted to five minutes when glycol was used as the coolant.

The first Merlin with a pressurized cooling system to be put in production was the Merlin IV (like the III except for this feature and a different propeller shaft), deliveries of which began in August 1938. The first model with the new cooling system to be produced in large quantity, however, was the Merlin XII, deliveries of which began in September 1939, just after the outbreak of the war.

Development of Lighter and More Reliable Radiators

The standard radiator for aircraft throughout the 1930's was of the honeycomb type.[48] These radiators were manufactured by a number of small firms specializing in aircraft radiators; the large automobile-radiator industry used a completely different type of construction but it would appear that no other construction than the honeycomb was seriously considered for aircraft engines until about 1937.

The first systematic research in England on the design of the honeycomb radiator seems to have been done during the late

[48]A honeycomb radiator consists of a large number of hexagonal tubes running fore and aft, enclosed in a watertight casing: air passed from the front to the back through the tubes, while water circulated from top to bottom and back in the spaces between the tubes.

1920's and early 1930's by Captain Anderton Brown and others of the RAE at Farnborough. This work was concerned with the proper size and shape of the air tubes and with the proper spacing between them, i.e., the size of the water passages. The work of the RAE was to a certain extent assisted by rig tests conducted by Rolls Royce and Napier, but both companies were at this time interested primarily in simply getting a leak-proof system, and the work of the RAE was largely independent. The results of this work were available by 1932 if not earlier.

In 1936-1937 Rolls Royce itself entered into the study of the design of the radiator, convinced that if the subject were left entirely to the suppliers, progress would continue to be insufficiently rapid. The company did not attempt to manufacture its own radiators, but it then for the first time set specifications of dimensions for sample radiators, suggested changes in construction, conducted comparative tests, and eventually set the exact specifications for radiators put into service. The principal object at first was the development of the lightest possible radiator to accomplish the required rate of heat transfer. The variables considered were the length and the diameter of the tubes of the honeycomb, since the RAE had already settled the question of the proper proportional spacing of the tubes from each other. About two years of development led to the conclusion that for minimum weight a honeycomb radiator should have tubes only 5 mm in diameter instead of the previously standard 7 mm. Although 4% more frontal area was required after this change, the radiator need be only 300 mm deep instead of the previous 450 mm, and the total weight including coolant was reduced by some 19%. Radiators built according to this specification went into general production and service about the beginning of 1938 and continued to be standard until about the end of 1939.

During the years 1938-1939 Rolls Royce continued to work on the improvement of the honeycomb radiator, concentrating particularly on improving its reliability. The greatest step made in this direction was the substitution, suggested and tested by Rolls Royce, of copper for brass as the tube material.

Brass had a tendency to crack in service, and copper proved to give a much more reliable radiator.[49]

At about the same time that the new specifications for the dimensions of the honeycomb radiator were set, toward the end of 1937, Rolls Royce began to suspect that an even greater improvement could be made by abandoning the honeycomb radiator altogether. In the honeycomb radiator every portion of the metal forming the air passages has the same area exposed to the water on one side as it has exposed to the air on the other. Analysis of the transfer of heat through the surface film of air or water to or from the metal had shown that heat could be carried from five to ten times as rapidly through the film of water as through the film of air, and this obviously meant that there was a tremendous amount of unnecessary water surface in the honeycomb radiator. Since the size of the water passages between the air tubes could not be reduced below a certain minimum without serious danger of their becoming silted up and without greatly increasing the amount of power required to pump the water through, the unnecessary water surface implied a very large unnecessary weight of water. What was needed was a radiator which would have five to ten times as much metal exposed to the air as was exposed to the water.

This was exactly what was accomplished by the secondary-surface radiator which had been standard for years in automobiles and was extensively used in refrigerating equipment and industrial heaters.[50] This radiator was actually cheaper to

[49]Even after the honeycomb radiator had been abandoned (see below) the honeycomb construction was retained for oil coolers, and Rolls Royce continued to work on its development. One of the important changes introduced during this period was the lengthening of the expanded portion at the ends of the tubes, where they are soldered together to form the watertight container, from about 0.2 in. to 0.5 in. An even more important change was the abandoning of the arrangement where oil flowed across the tubes in favor of an oil flow parallel with the tubes (axial flow) in order to obtain better distribution throughout the matrice. When this change had been made hexagonal tubes were no longer an advantage, and circular tubes were reintroduced. These were able to withstand higher oil pressures before collapsing, giving a greater margin of safety for cold starting.

[50]In this radiator the water passages consist of vertical tubes, quite thin from side to side and broad from front to back, passing through a series of horizontal sheets of metal which serve as cooling fins. The water surface extends only over the metal forming the tubes themselves, while the air can receive heat both from the surfaces of the tubes and from the entire area of the fins.

build than the honeycomb, since for a given size of radiator there were far fewer joints which had to be soldered water-tight, which meant that this type was also likely to be more reliable in service. This was the chief reason why it had been adopted so widely in fields other than aviation. In addition it was much less liable to become silted up than the honeycomb type, since its water passages were straight rather than zig-zag.

In 1938 and 1939 Rolls Royce conducted experiments with small samples of secondary-surface radiators, enough to become fully convinced that they were superior to the honeycomb type. The company had, however, been unable to do anything about putting them in actual service because the small manufacturers who supplied aircraft radiators were unable to manufacture them, while the large manufacturers of automobile radiators were not interested in producing special types in the very small numbers required by peacetime aviation.

At the outbreak of the war the manufacture of automobiles was almost completely stopped, and the manufacturers of automobile radiators suddenly became anxious to develop aircraft radiators in order to have something to keep their establishments in existence. Development of secondary-surface aircraft radiators now began at full speed. In accordance with specifications furnished by Rolls Royce, the Radiators Branch of Morris Motors, Ltd, supplied some radiators constructed with exactly the same water tubes as their automobile radiators, but made deeper by having more rows of tubes from front to back. Tests made by Rolls Royce showed that the aerodynamic losses suffered by the air passing through these radiators were unduly high, and suggested reducing the number of tubes from front to back by using tubes which were about 2 in. wide instead of only ½ in. or ¾ in. The new design proved satisfactory. With the same depth as the previous honeycomb radiator it required 10% less frontal area for the same heat dissipation and with its coolant weighed 38% less. The weight of the radiator and coolant had thus been cut in half between 1937 and 1940. This type of radiator went into service in 1940 and remained standard throughout the war.

Summary

The fact that Rolls Royce was working under development contracts rather than at its own expense did not in any way delay its development of either of its two important post-1919 engines, the Kestrel and the Merlin. Direct government payment to Rolls Royce was the only thing which made possible that firm's extensive development of accessories not a part of the engine, and that development led to very great improvement in those accessories over what could have been accomplished by independent suppliers.

APPENDIX TO CHAPTER VIII

The Vulture

In September 1935 Rolls Royce began designing a very large, new engine called the Vulture. This was a 24-cylinder X-type engine consisting in over-all lines of two Kestrels on a common crankshaft (giving a displacement of 2,590 cu in.), although no single Kestrel part was actually interchangeable with the Vulture. It was originally intended as a bomber engine, specifically for the two-engine Manchester bomber, although as early as April 1937 it was taken by Hawker as one of the two alternative engines for a new fighter, the other being the Napier Sabre.

Actual testing and development of the Vulture began in 1937, and the Vulture II passed its first type test in August 1939. By 1940 its rating, on 87-octane fuel, was 1,710 hp at 3,000 rpm at 15,000 feet for combat, with 1,800 hp for take-off at 3,200 rpm, for a weight of 2,450 lb. Production of the Vulture began in January 1940, and the first Manchesters went into service early in 1941. Trouble was experienced in service with the connecting rods at the 3,200-rpm take-off rating, and this soon had to be lowered to 3,000 rpm. It was later found that the trouble was due to inaccurate manufacture of certain parts of the rods, done by a subcontractor, but the take-off thrust was almost as good at 3,000 rpm as at 3,200, owing to better propeller efficiency, and the old rating was never restored. In March 1941 the take-off power was increased to 2,010 hp when 48.2 in. manifold pressure was authorized on 100-octane fuel instead of the 42.1 in. limit with 87-octane.

Early in 1941 plans for production of the Hawker Tornado fighter with the Vulture were dropped because the Napier Sabre, the power plant of the alternate Typhoon version of the fighter, seemed to be making satisfactory progress and had no other application. The Manchester bomber with the Vulture began to seem a poor bet about this same time. It was an attempt at a heavy bomber which would obtain from two very large engines performance equal to that obtained in the Stirling from four Bristol Hercules engines or in the Halifax from four Merlins. The results were not up to the anticipations, which had been based on very optimistic estimates of what could be got from the engines. In 1940 the Vulture II, weighing 1.43 lb/hp at 15,000 feet at its combat rating on 87-octane fuel, was nearly as good as the Halifax's Merlin X, which weighed 1.44 lb/hp at 17,750 feet at its combat rating on the same fuel, but it proved beyond the company's capacities to increase the power of the Vulture at the same time and as rapidly as it was increasing that of the Merlin. The 24-cylinder poppet-valve engine had proved to be very difficult both to design and then to install and to maintain because of the difficulty of giving access to the spark plugs and tappets. Finally, the Lancaster bomber powered by four Merlins, which was derived from the Manchester but was somewhat larger, proved to have very much better performance, both because of the superior specific performance of the Merlin and even more because of the greater gross power available. The Lancaster entered service early in 1942, and production of the Vulture was stopped in April of that year, after only 508 production engines had been built. The general difficulties with this X-type poppet-valve engine had been so great that Rolls Royce's next venture into the field of 24-cylinder engines, the Eagle (development of which began in 1943), had sleeve valves and was laid out in an H arrangement.

The Griffon

On January 1, 1939, Rolls Royce began planning for a larger V-12 engine to be an improved scale-up of the Merlin and to become a replacement for it. The new engine, called the Griffon, was to have a displacement of 2,239 cu in., 36% greater than the Merlin. A straight scale-up would have meant, however, that the length of the engine would have increased by 11%, and that as a result the new engine could not be installed in any of the existing airframes designed around the Merlin. To make possible the substitution of the new engine for the old in existing airplanes, the camshaft drive was taken from the rear of the engine and put on the front in the same plane as the reduction gear, and the magneto was also moved from the rear to the front of the engine. The length of

the Griffon was thus no greater than that of the Merlin, and it fitted in the same cowling.

After the first experimental Griffons had been built it was found that the weight was excessive. Heroic measures were taken to redesign the engine completely in a very short time, and by June 1940 the Griffon II was ready for test. It was some time, however, before the Griffon could be developed into an engine really superior to the Merlin, since the greater background and experience with the latter engine made it possible for a time to keep its power virtually equal to that of the heavier Griffon, especially at altitude.

Production of the Griffon began in March 1942, for use in the low-altitude Spitfire XII. At this time the Griffon delivered 1,720 hp at sea level, where the Merlin 46 used in some Spitfire V's could deliver only 1,230 hp. It was not until the middle of 1944 that Spitfire XIV's entered service with the two-stage Griffon 61, the first Griffon to be decisively superior to the Merlin at altitude.