CHAPTER VI

Engine Development for Use of Improved Fuels

UP to the outbreak of war in Europe in 1939 aircraft engine manufacturers in the United States and England had been vigorously pushing development of engines to take the maximum possible advantage of 100 PN fuel. This development was devoid of outstanding landmarks such as occurred in fuel development but it was equally vital. Engine development in general consisted of a repeated process of redesign followed by test to destruction. Efficient use of 100 PN fuel involved a great deal more than merely using the fuel in existing engines. In many cases, however, existing engines designed and developed for lower PN fuels gave very considerable improvements in performance when operated on 100 PN fuel without changes other than in carburetor adjustment. Existing engines designed for lower PN fuels, however, were usually deficient in cooling capacity, durability, and reliability when operated on 100 PN fuel. (L. S. Hobbs of Pratt & Whitney has stated that it is not possible to make engines reliable without at the same time making them durable.) The use of 100 PN fuel in place of 68 PN fuel usually resulted in greater power output or operation on leaner mixture or both.[1]

[1]Either increased output or operation on leaner mixtures resulted in the cylinders' giving up more heat to the cooling air or cooling liquid, and this necessitated a vast amount of cooling development, particularly so in the case of air-cooled engines. High PN fuels were almost entirely responsible for the development of the forged aluminum cylinder head on air-cooled engines in the United States as opposed to the cast aluminum head which had proved adequate (in the United States at least) for fuels of lower PN. The forged aluminum head as a part of the modern air-cooled engine originated with The Bristol Aeroplane Co., Limited, in England before there was any serious use of high PN fuels and was the result of British inability to produce castings of the standard attained in the United States. The American technique for casting aluminum cylinder heads originated in England at the RAE and was first applied and then developed by E. H. Dix at McCook Field in 1922. When Bristol was forced to adopt the forged head, British head casting technique had degenerated to a level far below that with which Dix started his work. The forged head provided greater strength, less liability to unde-

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EXHAUST VALVES AND SPARK PLUGS

Sodium Cooled Exhaust Valves

Where increase of fuel PN was used to increase compression ratio as a means of obtaining lower fuel consumption, cooling problems were not increased, in fact rather the reverse. With 100 PN fuel the use of sodium cooled exhaust valves became almost mandatory since either more power obtained by more supercharging or operation on leaner mixtures increased exhaust valve temperature. This increased valve duty had to be counteracted by internal valve cooling to reduce corrosion by lead and also to prevent the valve material from becoming so weak as a result of higher temperature that valves would either break or stretch. Sodium cooling was not mandatory with the British who had developed the sleeve valve engine, and had sodium cooling not been available in the United States an alternative in the form of a more highly developed version of the mercury cooled valve of Midgley and Kettering (see Schlaifer above, p. 197) would no doubt have been evolved.

Development of Exhaust Valve Materials

The use of 68 PN leaded fuel, and still more so the use of 100 PN fuel, rapidly forced development of exhaust valve materials since sodium cooling alone was inadequate. It was found that a facing of Stellite[2] applied to the seating faces of exhaust valves by welding greatly increased the life when operated with leaded fuel. This discovery was made independently and simultaneously in the United States and in England, and was a revival of an old idea since Stellited valves were used in production in the United States on the Wills St. Clair automobile engine about 1920 but were later abandoned in this car. Stellited valves were also supplied to McCook

tectable defects in the material, and the ability to provide a very great increase in fin cooling surface.

[EDITORS' NOTE: *The author, S. D. Heron, had a major role in the development of air-cooled cylinder practice in this country. For discussion, see Schlaifer above, pp. 177-180.*

[2]An alloy of cobalt, chromium, and tungsten produced by the Haynes Stellite Company; the grade used on valves contains approximately 65% cobalt, 30% chromium, and 5% tungsten.

Field about 1922. Stellite was and still is a cutting tool material and one also supplied in welded-on facings for resistance to wear at high temperature, and its availability and usefulness for exhaust valves were happy accidents. After the discovery of the value of Stellite, the British determined that Brightray was even better than Stellite under some conditions, and this alloy was still being used in 1949 in exhaust valves although for a slightly different application than that originated by the British. Brightray contains 80% nickel and 20% chromium and is a very slight modification of an alloy invented in the United States by A. L. Marsh and used since 1906 for electrical heating purposes.

Development of Spark Plugs

The aviation spark plug with mica insulation had become almost a world standard by 1932 although the Liberty engine in World War I had used porcelain plugs (similar to those then used in automobiles) with very satisfactory results. With the use of lead in 68 PN fuel the defects of mica became apparent but spark plug porcelain available in the United States was equally defective since both were vigorously attacked by leaded fuels. With the advent of 100 PN fuel containing less lead than the 68 PN fuel, the troubles with mica plugs were increased as a result of the more severe operating conditions, and the type of porcelain used in automobile spark plugs became still less suitable. Siemens & Halske A. G. in Germany by 1935 had made considerable progress with aviation spark plugs using sintered corundum (virtually a low-grade synthetic sapphire) as a porcelain-like material substituted for mica or porcelain. The Siemens & Halske material was much stronger and more shock-resistant than porcelain and also was virtually unattacked by leaded fuel.[3]

In 1935 the British decided that mica was a weak link in aviation spark plugs for use with leaded fuels of 68 and higher PN. The British decided that sintered corundum was the

[3]The Germans, despite the availability of sintered corundum, did not succeed in making a good aviation spark plug with it since the availability of the last word in insulator material did not mean that the design talent was available to embody this material successfully in an aviation spark plug.

most promising material with which to start an intensive program of spark plug development. Several British spark plug companies were then making sintered corundum spark plug insulators, two under licenses from Siemens & Halske and Robert Bosch A.G. (title changed to Bosch (Robert) G.m.b.H. in 1937) of Germany and others using modifications of the Siemens & Halske idea, these modifications resulting in much easier manufacture. The British, by 1935 or thereabouts, had decided that the problem of lead corrosion of spark plug electrodes was a very serious one and also one which must be eliminated or at least greatly reduced, without worrying about the cost of the method of improving performance in this respect. They decided that platinum and alloys of platinum with other metals of the platinum group were the most promising and pursued this development to a very successful end. The platinum or platinum alloy electrode is currently the best which has been found for high PN fuels containing lead and, in general, the only objections to it are those of first cost and availability in time of emergency.

By the outbreak of war in 1939, the British had limited supplies of spark plugs using sintered corundum insulators with platinum electrodes. In the Battle of England these plugs were invaluable for use in Hurricane and Spitfire fighter aircraft equipped with Rolls Royce Merlin engines and were worth many times their weight in gold since the supply was inadequate. In the United States development of a substitute for the mica spark plug was much slower than in England. From about 1930 to 1939 The B G Corporation (founded by Brewster Goldsmith, a New York jewelry manufacturer) was virtually the only maker of satisfactory aviation spark plugs and used mica insulation entirely although it was experimenting with materials of the sintered corundum type. B G did not at first have its own plant for production of sintered corundum or other ceramics and it is a matter of history that all first-class ceramic aviation spark plugs have been produced by concerns which have their own facilities for production of ceramic insulators.

By 1931 or 1932 Wright Field was convinced of the necessity for development of a ceramic spark plug both because of leaded fuel and because Wright Field feared that mica plugs would be unsuitable for war due to difficulties in obtaining mica supplies and also in manufacture of mica plugs on a large scale. Testing of plugs with porcelain insulators by Wright Field was undertaken in 1931 or 1932, continued intermittently up through 1935, and then continued through 1939 with improved insulator materials, one of which was of the sintered corundum type. This test program indicated that ceramic plugs were not then so good as the best of the available mica types. Failure to evolve a suitable ceramic plug appears to have been due to a number of causes including a very clumsy and lengthy test procedure in which it took about two years to obtain test approval or disapproval from the time the plugs were made available for test.

Legal restrictions on experimental contracts let by the Army and the Navy were also a retarding influence; it was possible to let six $10,000 experimental contracts to six concerns which would each just scratch the surface of the problem by the time the money was spent. To let a contract for $60,000 to a single concern with experience in the field of ceramic spark plugs was a difficult or impossible solution to the problem of development. Such procurement problems have, in the past, been a common difficulty of the Armed Services and particularly so in the case of accessories. In many cases where development by the Armed Services themselves is impossible (it is almost always undesirable) the Services have to gamble with public funds by opening experimental development contracts to competitive bidding. In many cases of this kind the development engineer (but rarely the contracting officer) realizes that it is almost certain that the low bidder will enter the lowest bid because he does not understand the problem and also because he would like some apparently profitable work in his shop. If the low bidder is granted the contract, in many cases the net result is a considerable waste of the time of the engineers of the Armed Services and an almost total loss of any public funds paid out to the contractor. The contract regulations are, of course, the product of legal minds and the importance of time in experimental work has not yet been made clear to such minds. It seems impossible to convey to legal minds the fact that an experimental product may be worth $30,000 six

months from now but may not be worth 50 cents two years from now. The extreme importance of time in experimental work is due to the fact that the value of an experimental product is almost entirely related to who gets it first. If two competitive governments have the same idea at the same time and one government by swift and efficient procurement gets its first version of the idea plus two successive additional developments of the idea before the second and clumsier government receives delivery of the first version of the idea, the second government is hardly a competitor. Time is, of course, of equal importance in competitive commercial development and the concern cautiously and slowly spending money on development might often equally as usefully have poured the money down a rat hole. While cautious and slow expenditure of corporate or public funds on development is often pure waste, lavish spending can be just as wasteful, and both types of spending can freely mingle at the bottom of the rat hole. In any case, it is uncertain whether spending large sums of money would have obtained a satisfactory plug, since the necessary mental attitude does not appear to have developed.

By 1939 Pratt & Whitney was convinced that mica was without a future as an insulator material in aviation spark plugs and announced this view very vigorously in print.[4] By the middle of 1940 Pratt & Whitney had tested experimental American ceramic plugs which were far more satisfactory than any mica plug it had yet seen.[5] and began to apply strong pressure on the spark plug industry for the development of production ceramic plugs. Satisfactory quantity production of American ceramic plugs did not become available until about the middle of 1941. Failure to obtain satisfactory ceramic plugs was not due to lack of suitable insulator materials since sintered corundum was available from at least two sources by 1939.

[4]Val Cronstedt, "Shortcomings of Mica Insulation for Aviation Spark Plugs," *SAE Journal (Transactions)* 46, June 1940, pp. 233-235, 242. This paper was presented at the annual meeting of the Society, Detroit, Michigan, January 16, 1940, by the author, who was Research Engineer, Pratt & Whitney Aircraft, Division of United Aircraft Corp., at that time.

[5]Testing by Pratt & Whitney, ceramics (sintered corundum) by Champion Spark Plug Company, design and construction by Ethyl Corporation — no government contracts and only verbal agreements among the three partners.

Superchargers and Propellers

Need for Supercharger Development

To a large extent high PN fuels were and are currently being used to obtain increased power by means of increased supercharging. Application of increased supercharging resulted in using supercharger capacity to produce more power at sea level with the result that supercharger capacity was not available to maintain this power at altitude. Even in 1932 and with 68 PN fuel the necessity for supercharger development was apparent[6] and became still more marked when 100 PN fuel came into use in 1936. As a result, the Army and Navy backed supercharger development, and the engine manufacturers and General Electric all increased their activity in this field.

British Experience with Superchargers

In England, Bristol and Rolls Royce intensified their activities on supercharger development. Rolls Royce was especially interested in high altitude performance and developed a single-stage single-speed supercharger giving outstanding performance of the Merlin engine in the Hurricane airplane at 15,000 ft. Rolls Royce had a head start on supercharger development since its "R" engine, which had won the 1929 and 1931 Schneider Trophy international seaplane races, had been fitted with a single-stage single-speed supercharger which gave what was then phenomenal performance. In the 1931 race the supercharger, which was in turn supercharged by use of the forward velocity of the airplane (ramming air intake), produced an induction system pressure of about 17 psi. This supercharger (believed to be the first to use the currently standard ramming air intake) enabled a power of about 2,500 hp to be obtained from a development of an engine which had been in use in military service at about 800 hp (see Schlaifer above, pp. 212-213). The supercharger alone would not have produced the increase in power output which necessitated a large amount of intensive engine development, but the power

[6]See above, p. 594.

could not have been obtained without it. Fuel of more than 100 PN was used and contained considerable quantities of both benzol and wood alcohol. The wood alcohol served to produce a reduction in mixture temperature similar to that which would be produced by a mixture radiator.

Two-Speed Superchargers

In the United States, development produced first improved single-stage single-speed superchargers[7] similar to that in the Rolls Royce Merlin. These gave improved altitude performance but increased the mixture temperature very considerably and consequently sharply reduced the power available for take-off and low altitude operation. The single-stage single-speed supercharger for high altitude performance with its attendant high mixture temperature penalized the air-cooled engine much more severely than it did the Merlin, and since the United States was principally interested in supercharged air-cooled engines the two-speed single-stage supercharger was rapidly developed.[8] The two-speed unit was in effect two superchargers, since it provided high power with low mixture temperature for take-off and low altitude operation in addition to the excellent high altitude operation available with the single-stage single-speed unit. The single-stage two-speed unit was followed by a variety of developments including the

[7]Successful aircraft superchargers up to 1949 have been entirely of the centrifugal type, very closely resembling the generally known centrifugal water pump. As in water pumps, superchargers may have one or more stages. A stage consists of a rotating impeller delivering liquid or gas to a stationary portion. In multi-stage units the outlet of the first stage is delivered to the intake of the second stage and so on. Centrifugal water pumps and industrial air compressors are built with at least ten stages; successful aircraft superchargers have not yet been built with more than two stages. The pressure rise (increase of pressure from inlet to discharge) of a centrifugal water pump will vary as does the square of its rate of revolution; thus if a water pump has a pressure rise of 10 psi at 1,800 rpm, the pressure rise will be 40 psi at 3,600 rpm. Centrifugal air compressors essentially follow this law and the ratio of the discharge pressure to the pressure at the intake is known as the pressure ratio.

Aircraft superchargers may be single-stage single-speed, single-stage two-speed, single-stage infinitely variable speed (as used in German World War II engines), two-stage two-speed, two-stage three-speed, and two-stage with one stage having only one speed and the other stage with an infinitely variable speed (as when a radial engine with built-in supercharger was used with a turbosupercharger; these were used in such planes as the B-17 and B-29 bombers).

[8]The two-speed single-stage supercharger originated in France — one of the very few modern contributions to the aircraft engine by the French.

two-stage two-speed type with a radiator which reduced mixture temperature. Pratt & Whitney developed such a unit for the Navy which was in experimental flight operation in 1935 and in service use by 1940. Rolls Royce developed what was probably the most advanced type of integral supercharger. This was two-stage two-speed and used a mixture cooler. When used with suitable fuel, this supercharger produced an induction system pressure of 30 psi at low altitudes and was exceedingly successful on the Merlin engine in the later stages of World War II.

Exhaust Turbosupercharger

The Army with General Electric had pursued the development of the exhaust turbosupercharger since World War I. This supercharger was driven by the exhaust gases of the engine and several times had obtained the world altitude record when used with engines lacking integral superchargers. The turbosupercharger had in effect a very wide range of speeds which could be adjusted as required by the altitude. It delivered air to the engine carburetor after passing through a radiator and consequently did not penalize the engine or the fuel by high mixture temperature. In the early 1930's the Army applied the turbosupercharger to Wright and Pratt & Whitney air-cooled engines having integral single-stage single-speed superchargers, and this combination gave a two-stage supercharger with an almost infinite range of speeds plus a radiator to keep mixture temperature down. The turbosupercharger applied to an air-cooled engine with an integral supercharger was widely used during World War II and was particularly successful in Army bomber aircraft such as the B-17, the B-24, and the B-29.[9]

Controllable Pitch Propellers

The use of superchargers as a means of restoring engine power otherwise lost as the altitude of operation is increased,

[9]The turbine blades (buckets) in the most successful version of the turbosupercharger involved an alloy (Vitallium — a close relative of the Stellite used on exhaust valves) and a casting process originally evolved and still widely used for dental purposes. The use of the alloy and of the casting process was an accident and came about as a result of the shortage of capacity to produce forged blades during World War II. (See Schlaifer above, p. 497.)

as distinct from supercharging for power at sea level, would have been largely lacking in military or commercial value without the development of the controllable pitch propeller (later the controllable constant speed propeller which can be set to maintain any chosen engine speed between, for example, 1,200 and 3,000 rpm, the chosen speed being almost independent of engine power output in any given engine-propeller combination). If an engine equipped with a fixed pitch propeller is operated in level flight at all altitudes with sea level air pressure in the induction system, the rate of revolution will steadily increase with altitude and the power output will increase almost exactly in proportion to the increase of rate of revolution. If the propeller is designed for the maximum permissible rate of revolution at the maximum altitude at which it is desired to operate, the available engine power is considerably reduced at any lower altitude and take-off of the airplane with any load may become impossible. If the propeller is designed to permit development of the maximum permissible rate of revolution in level flight at an altitude of 200 ft, engine power in level flight has to be reduced as altitude is increased although full engine power in climb can be maintained to a considerably increased altitude.

In Europe (and maybe elsewhere) it was realized as early as 1917 that maintenance of substantially constant engine power irrespective of altitude by means of supercharging depended, for its effective use, upon the development of a propeller whose pitch could be varied while in flight. The need for such a propeller was one thing and developing it was an entirely different matter. F. W. Caldwell can be said to be more responsible than anyone else for the successful development which culminated first in the Hamilton-Standard two-position controllable pitch type and later the controllable constant speed type by the same company. Use of the controllable pitch propeller in the United States produced learned theoretical discussions in Europe which proved that such complicated propellers were either unnecessary or disadvantageous.[10]

[10]During World War I the British had clearly established the fact that airplane performance was improved by the use of gearing between the propeller and the engine, the gearing resulting in the propeller having a lower rate of revolution than

(*Footnote continued on next page*)

the engine. In the United States up to about 1923 there was a steady production of learned dissertations which proved either that no propeller gearing system could be made to stand up mechanically on an aircraft engine (despite the fact that all British liquid-cooled engines were then fitted with geared propellers) or that if gearing was used, the airplane performance would be reduced and particularly so in climb as a result of the increased weight of the necessarily larger propeller and of the gear itself. About 1923 the value of the learned dissertations was reduced to nothing in the United States by the late E. T. Jones who was then Chief of the Power Plant Branch at McCook Field.

Jones was struggling with a transport airplane equipped with a direct drive Liberty engine. This transport would barely take off even without load. In order to avoid argument with the theoretical pundits Jones produced some flimsy excuse for equipping the airplane with a geared Liberty engine, the gear being a line-for-line copy of the one fitted to the Rolls Royce Eagle engine during World War I. The first flight of the transport equipped with the geared engine showed such a vast improvement in take-off and climb that Jones required no further excuses for his experiment. Jones was then personally responsible for development of the exhaust turbosupercharger at McCook Field as well as being Chief of the Power Plant Branch and was troubled by the conflict in propeller requirements at sea level and high altitude of aircraft equipped with turbosuperchargers. Controllable pitch propellers were not then available in satisfactory form so Jones had a two-speed propeller reduction gear built for the Liberty engine by Allison Engineering Company and this provided a satisfactory alternate to the controllable pitch propeller. The two-speed reduction gear resembled the syncromesh transmission used on automobiles and was an amusing toy to the test pilots who liked to demonstrate their skill in shifting gear. The gear was finally seriously damaged by a bad shift during a dive.

The increased engine power and altitude performance made available by supercharging and high PN fuels can be said to have greatly accelerated the adoption of geared propellers in the United States. After Jones' demonstration no completely new design of ungeared liquid-cooled engine was developed; the direct drive Curtiss V-1570 came out subsequent to Jones' findings and was in service until about 1933 but this was, in the author's view, simply an enlargement of the Curtiss D-12. It was known how to gear a liquid-cooled in-line engine but a radial air-cooled engine was another matter. The first satisfactory gearing system for a radial engine appears to have been due to Farman (Avions H.M.D.) in France. This gear, which resembles the differential used in the rear axle of an automobile, was first fitted to a Bristol engine being built under license by Gnome & Rhône (Société des Moteurs) in France. The Farman gear was taken up by Bristol in England and later was used on the earliest satisfactory geared radials in this country.