CHAPTER I

Discussion and Summary

The joint development of aviation engines and fuels has followed an interesting pattern. The development has been due to: private enterprise using its own funds, private industry financed by government, original investigation by government, and cooperative activity of the engine industry, the oil industry, and government.

The Role of Private Enterprise

Some of the most important fuel developments, namely lead and the synthesized branched chain paraffin hydrocarbons, were the products of private enterprise and were not evolved for use in aviation. Thomas Midgley and C. F. Kettering's development of lead was a straight end result of the commercial, competitive system and, except during World War II, aviation was an unimportant part of the market for the product. Graham Edgar's discovery of the knocking properties of the branched chain paraffins was a product of private enterprise but can hardly be said to be a result of competition. It was a result of an almost academic desire to increase knowledge and improve accuracy of measurement rather than of pressure to increase corporate income. The most important end use of the discovery was far removed from its original purpose. It seems very improbable that either lead or branched chain paraffins would have been successfully applied to aircraft engines by private enterprise. The idea of using lead in aviation engines was the product of private enterprise, but it was government funds and government pressure which forced the development of aircraft engines so that they would tolerate it.

The Role of Government

The idea of applying branched chain paraffins to aviation fuels originated with the United States Government (if it originated elsewhere, Wright Field[1] at least had the idea completely independently), and it appears that the synthetic branched chain paraffins[2] would not have been applied to use in either aviation or other fuels for several years had the United States Government not both demonstrated their value and backed manufacture on a relatively large scale by providing a market. It appears certain that branched chain paraffins would have come into use in any case since the then increasing studies of hydrocarbons found in both crude oil and natural gas would have demonstrated the value of isopentane. The real value of isopentane in aviation fuels, however, would not have been appreciated without tests in a full-scale aircraft engine. The Wright Field tests of 100 PN[3] gasoline made with octane, when published by F. D. Klein,[4] resulted in greatly accelerating engine studies of pure hydrocarbons from both natural and synthetic sources.

Competition in Methods of Manufacture of Fuel

Once the importance of branched chain paraffins was established, development of methods for their manufacture was the result of commercial competition. This commercial competition was a result of the profit motive, but was far from profitable, as is often the case in aviation, and was really competition for technical prestige. Technical prestige in the case of aviation often punishes the corporate balance sheet but may be said to be profitable in the sense that a company solely engaged in any branch of the aviation business goes out of business sooner or later if technical prestige is lacking. Technical prestige in petroleum products for aviation use is not essential to an oil company but is very important if the company is marketing aviation products such as fuels. The major marketers of aviation petroleum products compete very vigorously for technical prestige. The market for aviation products in peacetime is often insufficient to amortize the cost of this prestige if strict accounting is adhered to, but achievement of such prestige often has profitable results in connection with the large peacetime market for automobile fuel. The application of both lead and branched chain paraffins to aviation use was almost entirely the result of competition of a different sort, military competition between governments. In military competition between governments, technical prestige is a very important phase and often results in a profitable export business which serves partly to finance an aircraft industry.

[1]Wright Field succeeded McCook Field as the center of army development of aircraft engines in October, 1927.

[2]The synthetic materials then required elaborate, expensive, and difficult manufacturing processes in contrast to isopentane which occurs naturally but which had not been evaluated and recognized as important at the time of the Wright Field work with octane.

[3]See p. 603, n. 4, for an explanation of Performance Number or PN.

[4]F. D. Klein, "Aircraft Engine Performance with 100 Octane Fuel," *Journal of the Aeronautical Sciences* 2, March 1935, pp. 43-47.

The work of H. R. Ricardo and co-workers in England was at first the result of scientific curiosity but was soon supported and extended by private enterprise with considerable profit and the gaining of invaluable prestige.

Catalytic cracking was the product of highly competitive private enterprise and was embarked upon without any thought of aviation use. Aviation merely picked up and used an available and extremely useful product. Aviation as a market for catalytically cracked gasoline was only important during World War II, and the small current market for aviation fuel does not warrant more than very limited use of catalytically cracked gasoline.

Isopentane, which was an extremely important constituent of aviation fuel during the war and still is in 1949, came into use as a result of private enterprise. It was the product of then relatively small business which had only limited resources but which was determined to use the available resources to the limit.

There was considerable development of methods for manufacture of components for 100 PN fuel. The larger part of this development was concerned with the synthesis of octanes and other branched chain paraffins. This development was the product of commercial competition, and it is very questionable whether it would have been financially justified except for the enormous demand resulting from World War II.

It is noteworthy that practically all the extensive fuel development after 1928 was the result of the Army's investigation of California gasoline and lead, both of which were then available but not in use. Compared with the 40 PN fuel then used by the Army, California gasoline gave about a 25% improvement in PN and lead gave about 50%; the two together gave about 90% improvement although the first service use was at an improvement level of 70% in PN.

Engine Development

Engine development made it obvious that better fuels were needed, and when the improved fuel was used it immediately became evident that further engine development was necessary to make suitable use of the available fuel. As the engines caught up with the available fuel it became evident that still better engine performance would result from even better fuel. As a result, the engine builder and user have, over a period of years, consistently demanded better and better fuel. At times the demands have been unjustified since it was and is often easier to ask for better fuel than to overcome difficulties by engine development. Both the engine builder and the engine user have tended to ignore the possibilities of improved performance resulting from building mild engines which are better than severe engines on any fuel and particularly so on sensitive fuels.

The engine development which has been the result of better fuels has all been the result of competitive forces. Much of the competition has been the result of efforts to obtain military supremacy or national prestige. Increase of fuel PN led to remarkable advances in performance of military aircraft, and military supremacy could not be attained without such high performance. High performance alone was not sufficient to attain military supremacy if an insufficient number of aircraft were available. In this connection, however, the British have officially stated "that the Battle of England could not have been won without 100 PN fuel."[5]

[5]There is a tendency in some quarters to claim that the Battle of England was won by 100 PN fuel. This claim is adequately set aside by Winston Churchill's "so many owing so much to so few" tribute to the RAF pilots. Claiming the

United States Resources for Manufacturing Fuel

While military supremacy could be obtained by the use of high PN fuels and the necessary associated engine and aircraft development, this was not a game that the United States could play without being imitated by other nations. High PN fuels were, however, a much stronger card in the hands of the United States than they were in the hands of any other nation, since the United States was the only nation with raw material and manufacturing resources for their production on a large scale and in addition possessed a much greater technical know-how in regard to their manufacture. The Germans did a marvellous job of manufacturing high PN synthetic fuels which they, however, considered inferior to those used by the United Nations. While the Germans considered that their highly aromatic fuels were inferior to Grade 100/130, it seems probable that the German fuels could have been made to give better performance than Grade 100/130 in the German water-cooled engines. The German water-cooled engines offered an outstanding opportunity for engine development for high performance on aromatic fuels, but the Nazi hierarchy in Berlin, which controlled aircraft development, ruled that engine development was not necessary. The German highly aromatic aviation fuels (about 40% aromatics) were available only in relatively small quantity and probably represented the best type of high PN material which could be made from coal as a raw material. D. P. Barnard, who investigated the German aviation fuel manufacturing plants, has stated[6] that they required 20 times as much steel per daily gallon as was necessary for Grade 100/130 production in the United States.

Competition in Aircraft

Competition for national prestige in aircraft led to government support of the Schneider Trophy seaplane races by the United States, Great Britain, and Italy, and this competition

Battle of England as won by 100 PN fuel also ignores the magnificent contribution of the aircraft and the engines which were used. The claim likewise ignores the exceedingly important contribution of radar to the outcome of this battle.

[6]Private communication.

led to the use of high PN fuels of limited availability (and almost no military usefulness) in association with engines suitable for such fuels. This may possibly be stated more realistically in reverse by saying that the engines were produced and fuels were then evolved to suit them. The Napier Lion unsupercharged racing engines using high (10 to 1) compression ratio were built first and fuels were then evolved. These engines set records for fuel consumption which have not yet been equaled. The Rolls Royce "R" engine was designed and built without any knowledge of what fuel it would require and suitable fuels were developed while the engine was being tested. The "R" engine was used for two successive races; power output was considerably higher in the second race, in part the result of fuel development. The Curtiss water-cooled engines, i.e., D-12, V-1400, and V-1570, had distinguished careers in both the Pulitzer and Schneider Trophy races. These engines were not supercharged and never used compression ratios beyond 7 to 1, and as a result Domestic Aviation Gasoline (DAG) plus about 20% benzol served adequately as fuel. The Curtiss racing engines consequently were without effect on fuel development.

Airplane racing currently has no useful effects upon either engine or fuel development. The gladiators (pilots) who are to be thrown to the lions and their backers fiddle around with inadequate facilities and, if anything, retard development by pestering the engine and petroleum industries with their problems. Airplane racing to the petroleum industry means only expenses without any return in prestige; to the engine industry the most likely result is bad publicity arising from a crash. In any case, the Schneider Trophy races resulted in engine development which was available for use when high PN fuels suitable for military purposes were adopted.

Engine development hinging on the use of high PN fuels from 1935 onward was strongly competitive, and commercial competition was a very important and very useful spur in this development phase. Rolls Royce Limited and The Bristol Aeroplane Co., Limited in England each endeavored to produce an engine which would become the leading British or, preferably, leading world engine. Neither Rolls Royce nor Bristol

had any British competition worthy of the name in their respective fields of liquid-cooled and air-cooled engines. In the United States there was no American competition in the liquid-cooled field (and precious few liquid-cooled engines). In the air-cooled field, however, there was vigorous competition between Wright Aeronautical Corporation and Pratt & Whitney Aircraft Co. It may be safely said that the important world position of the American air-cooled engine before 1939 was largely the result of the competition between Wright Aero and Pratt & Whitney. This competition sought the leading position in regard to domestic military and commercial sales and also was aimed particularly at foreign commercial sales with an eye on overseas military sales. This competition was an important factor to the Army and Navy in respect to steady improvement in engine and aircraft performance. Without this competition the Services would doubtless have had to resort to direct government development of engines in respect to fitting them for operation on high PN fuels.

Support of the Military Services

While commercial competition produced rapid advances in engine development, which would not otherwise have occurred in such a short period, it is nevertheless true that such competition depended upon support of the Military Services in both the United States and Great Britain. Without the military market and military development funds, the commercial market could probably not have adequately supported even one major engine manufacturer for both England and the United States, let alone four. Without past military support, it is unlikely that aircraft would be currently using Grade 100/130 fuel.

It is difficult to see how joint development of fuel and engines could have been speeded up very much. Possibly 100 PN fuel could have been in use in the United States about four years earlier if unlimited development funds had been available and if the Army and Navy had operated almost without red tape and, in addition, had been devoid of the continual fear of Congressional investigation of experimental contracts.

When the Army adopted 100 PN fuel, it took a rather considerable risk of Congressional investigation since it could easily have been shown that few of the engines actually in service needed this fuel. The Army very wisely took the view that unless the fuel was put in general service there would be little incentive to build plants to produce it, and that engines to take full advantage of the fuel would not be developed unless the fuel was in service use. The Navy was likewise convinced of the importance of 100 PN fuel and the necessity of promoting the building of plants for its manufacture. The Navy, however, was more cautious (and more investigation proof) than the Army and procured 76 PN fuel containing ½ cc lead in place of the 100 PN fuel with 3 cc lead which the Army was buying. The Navy justified its purchase of 76 PN with ½ cc lead in place of 76 PN with 3 cc lead[7] on the grounds that the increased cost of the lower lead content fuel would be saved by reduced engine maintenance. If aircraft engine development had been vigorously pursued in both the United States and Great Britain immediately following the 1918 Armistice rather than being in the doldrums and existing on very small handouts, it is possible that the supercharged engine would have become a serviceable article several years earlier and thus would have focused earlier attention upon the necessity for better fuel.

While, as mentioned above, unlimited development funds might possibly have accelerated the rate of development, it seems that in fact additional funds would have had little or no effect. Rather does it appear that the development in the main depended upon the rate of progress of technical thought. While additional funds would probably not have accelerated development, any considerable reduction would have practically stopped it. It was due to the vision and foresight of Major C. W. Howard that a significant proportion of the experimental funds available at Wright Field was diverted to fuel development in the Power Plant Branch. Only the determination and courage of Howard and of Lieutenant E. R. Page (who succeeded Captain T. E. Tillinghast as Chief of the Power Plant Branch) kept the Army development of leaded

[7]The Army and the Navy at this time did not have unified fuel specifications.

fuels alive.[8] Less courageous executives would have dropped the program in face of the deluge of trouble.

The supercharged engine did not really get going until 1928. If the major supercharged development had occurred with water-cooled engines, reasonable fuel development would have been possible by using the best naturally occurring gasolines and by taking advantage of Ricardo's findings in respect to aromatics. In the United States at least, the major development in supercharged engines occurred with the air-cooled type. The air-cooled engine started off by requiring better fuel than the water-cooled engine of equal performance and, in addition at that date, did not like aromatic fuels which, in any case, were not available in adequate quantity in the United States. Large expenditures of development funds probably would have made aromatics available since the know-how of one method of manufacture was available by 1928 or 1929. It was the supercharged air-cooled Pratt & Whitney Wasp engine which had been responsible for the first serious service use of lead by the Navy in 1927, and the later choice of good gasoline plus lead by the Army as a basis for its 68 PN fuel was based upon both the suitability of this fuel for air-cooled engines and upon its availability. Lead was not freely available until about 1926 so not much time was lost in applying it to aviation use.

Importance of Edgar's Discovery

The value of the branched chain paraffins was not known until 1926. Octane was little more than a laboratory curiosity when the Army started to consider it as a component of aviation fuel and still was when the Army took active steps to test it in 1934. The first octane synthesized by Edgar in his laboratory cost about $4,000 per gallon but this was soon reduced to about $25 per gallon. The first quantity production of octane for use by the Army essentially followed the method used by Edgar to produce the material at a cost of about $25 per gallon. The quantity production for the Army was, however, accomplished at a cost of about $1 per gallon. Development of man-

[8]See pp. 585, 591, 592 for Tillinghast's part in the Army program.

ufacturing methods for production of octanes rapidly followed recognition of their value as a component of aviation fuels.

Recognition of the importance of the rich mixture properties of aromatics was a product of the supercharged engine. The United States was slow in recognizing this importance but did so in time to make use of the large wartime available supplies of such fuels.

Actual use of water-alcohol supplementary injection was slow but was not developed and put into use until the possibilities of the available hydrocarbon fuels in use in wartime had been exhausted.

Effect of High PN Fuels on Development of High-Power Engines

The development of high PN fuels and of engines for such fuels does not appear to have been expensive in light of the results obtained. Any real figure for the costs is, in the author's opinion, impossible to obtain, and judgment of the cost must be based upon an approximate appraisal of the amount of effort involved. High PN fuels can be conservatively credited with having doubled the power of engines of a given size (cubic capacity). For instance, the Liberty engine of World War I of 1,650 cu in. capacity, developed about 400 hp on 40 PN fuel; the Rolls Royce Merlin of World War II, also of 1,650 cu in. capacity, developed over 2,000 hp on fuel of about 150 PN, and something less than half the 400% increase in power can be credited to fuel development. If fuel had stayed at 50 PN it would appear that development of engines to produce over 2,000 hp for single-engine fighters and up to 3,500 hp per engine for engines used in bombardment aircraft would have cost a great deal more than the development of the current engines and of the fuels to go with them. Apart from the question of cost there is considerable doubt whether a 3,500 hp piston engine suitable for use in aircraft could be produced at all with 50 PN fuel. In the absence of high PN fuels it is improbable that a single-engine fighter equipped with a 2,000 hp piston engine would be effective for military purposes. Discussion of 2,000 hp single-engine fighters is currently, of course, of little

significance since single-engine jet fighters developing 8,000 hp are almost commonplace.

It is difficult or impossible to estimate what would have been the course of aircraft engine development if high PN fuels had not been produced. It does not seem that the Diesel engine would have been the answer and it likewise does not seem that the gas turbine of jet or propeller type would have been developed much earlier than it was.

Process of Development of Engines and Fuels

Development of engines and fuels has not been what the layman would call a scientific process; it has rather been a process of cut and try. In the case of the engine the process has been one of trying things, with the good ones accepted and the ineffective ones discarded. In the case of fuels, despite the brilliant work of the organic chemists in synthesizing hydrocarbons, which are theoretically possible but which hitherto had been unknown, the process has been one of finding out what happens with very little increase of knowledge of why things happen. Knowledge of the actual physics and chemistry of combustion in the engine cylinder has not increased in proportion to the improvement in engine performance. Lack of knowledge of why things happen is no reflection on the physicists who in the main will be responsible for determining why. The major difficulty in determining why things happen is that the reactions involved occur in almost infinitesimally short periods. Lack of knowledge of why things happen, in the opinion of the author, has not limited the effective application of the knowledge of what happens.

While the development of fuels has been a process of cut and try in the main, nevertheless a very considerable amount of high-grade scientific work was necessary in the later stages of development before it was even possible to try. As discussed above, the cut and try process has been one of making fuels and trying them in engines. The really effective trying has involved pure hydrocarbons, and this is what has produced the sound state of knowledge of fuel performance which exists. Producing laboratory quantities of these pure hydrocarbons involved scientific work which has had far-reaching effects. The published work of Ricardo[9] and co-workers was responsible for the general interest in the knocking properties of individual hydrocarbons. Ricardo may not have been the first to make such studies and some of his conclusions were misleading but, nevertheless, he was the first to publish his findings and thus focus attention on the problem. It is fortunate that men such as Ricardo and their sponsors were willing to undertake early publication. That some of the findings were later upset merely illustrates the fate which is usually met by the courageous and effective pioneer who is willing to take the risk of having his work shown to be in error.

From the time of publication of the findings of Edgar in regard to the branched chain paraffins, effective studies of the knocking properties of fuels have been increasingly concentrated in the United States which is now far in the lead. It used to be justly said that the United States had the petroleum but that the Europeans understood its composition and technology. Fuel knocking properties have continued to be the happy hunting ground of those who deal in magic. Magic is, however, being increasingly replaced by knowledge, and the octane number scale has been by far the biggest factor in this process.

It is probably fortunate that neither the aircraft engine industry, the engine users, nor the petroleum and associated industries realized the tremendous complexity of the joint fuel-engine problem when the effort to improve engine-fuel performance was initiated. If the complexity had been realized, it is possible that the problem would have been backed away from on the grounds that any effective solution was extremely unlikely. As it is, it may be said that knowledge of piston engine-fuel behavior is currently almost complete in respect to being able to predict what will happen even if knowledge of how and why things happen is exceedingly limited. There are many authorities who predict the almost immediate demise of the piston engine for any important aircraft use. It is somewhat ironical that almost complete knowledge of the behavior

[9]Harry Ralph Ricardo, "Influence of Various Fuels on the Performance of Internal Combustion Engines; an Experimental Investigation into their Behavior," *Automobile Engineer* 11, February-May, 1921, pp. 51-54, 92-97, 130-133, 169-175.

of piston aircraft engine fuels should be achieved only shortly before such fuels possibly cease to be used. While the almost immediate demise of the piston engine is freely predicted the author believes that the funeral will not occur for at least ten years. For extremely long range, e.g., the B-36 bomber, the piston engine, and particularly the compound piston engine (i.e., piston engine compounded with a gas turbine), appears to have a considerable future because of the extremely low fuel consumption which it offers and which potentially at least is subject to considerable further improvement.

The joint development of fuels and engines was not a planned program. It could hardly be a planned program since more than one country was involved. The end result was an exceedingly creditable one and it is difficult to be sure that an elaborately planned (in the sense of the current use of the term) program of development would have produced a better or a quicker answer. In fact, it is the author's belief that the success of the development was in no small part due to an entire absence of the attentions of the professional planner who sets up elaborate programs dealing with subjects of which he is entirely ignorant. The development was, in the main, initiated by governments (United States and Great Britain) but industry and technical workers outside governments were the major contributors. The development drew upon a very wide variety of industries and technical specialties. In no small measure the success was due to imagination which drew upon the existing knowledge of industries and skills which were almost entirely foreign to the aircraft industry.

The professional (and technically uninformed) planner is quite capable of glibly stating "that here we draw upon two million dollars' worth of imagination," and it would be interesting (but very costly) to watch the planner implementing this statement. The importance of imagination in a development such as that of fuels and engines is often underestimated, and much of the progress has been due to straightforward inventing. Thought control as practiced by the Japanese has no place in development although some of the government planners in the United States think that planning can be carried to such detail that it becomes thought control in effect.

A planned program would have taken almost supernatural intuition in regard to some phases of the development.

For example, manufacture of aviation fuel, consisting only of straight-run gasoline and lead, can be a self-sustaining operation which requires only markets for the other products of the refinery in order to be economically justified. The moment synthetic components such as octanes are used, aviation fuel (in peacetime at any rate) becomes a handmaiden of the production of motor gasoline. The hydrocarbon gases used as raw materials for the manufacture of octanes are mostly by-products of motor gasoline manufactured from petroleum crude oil and from natural gasoline hydrocarbons. The gases can be produced from coal at great cost, but any nation forced to do so currently would hardly be in a position to obtain military security.

Future Possibilities

It may be emphasized that the relatively enormous improvement in the performance of spark ignition piston-type aircraft engines, which has been the product of improved fuels, is unlikely to be achieved with most other types of aircraft engine. Such improvements appear to be largely limited to the spark ignition (Otto) type of engine and particularly so to the supercharged spark ignition engine. The use of 100 PN fuels in automobile engines has been recently shown to produce increased fuel mileage of almost 50% by the use of high compression ratio without supercharging. It should not be inferred that high compression ratio can produce any such improvement in the range of aircraft.

It does not appear that the gas turbine engine for aircraft will be able to obtain any very considerable improvements in performance by means of developments in fuel.

The Diesel engine does not appear likely to have a useful future for aircraft propulsion, and discussion of improvements in performance as a result of fuel development is therefore largely without significance in respect to aircraft. The Diesel engine can only burn about 70% of the air it takes in, and this handicaps it in comparison with a spark ignition engine which

burns all the air it takes in (or at least does so at high power). This means that for an equal weight of air effectively burned the Diesel engine has to have about 40% (actually greater than 40% for reasons too detailed to discuss here) greater cylinder capacity than the spark ignition engine. If the Diesel engine has any place in aircraft propulsion in the future, it would appear that it will find this place as part of a compound unit embodying a gas turbine where the high air consumption is actually an advantage. However, it may be pointed out that there is no sign that development of Diesel fuels is going to produce the startling improvements in engine performance that have occurred with spark ignition aircraft engines. There is no sign that fuel development will result in a Diesel engine of any type producing twice as much power from an engine of a given size. Prior to the development of high PN fuels for spark ignition engines, some very competent development of aircraft Diesel engines had been accomplished and the engine type seemed likely to advance. A.H.R. Fedden (then of Bristol), who was responsible for some of this development, has stated[10] that it ceased to be of interest after the advent of high PN fuels. The aircraft Diesel engine (without compounding) currently is only a matter of interest to largely uninformed inventors and promoters. The Diesel engine without compounding appears to have as little place in aircraft propulsion as would gasoline engines in a 6,000 hp freight locomotive.

The rocket-type aircraft engine appears to be likely to be susceptible to improvements in performance as a result of fuel development which can be expected to exceed those which have occurred with the piston-type aircraft engine.

In discussing the possibilities of the future the author is very well aware of the dangers of prophesy. The technical literature dealing with mechanical propulsion in the various forms of transportation is replete with both radical and conservative prophesies which the authors would now like to forget. However, revolutions can still occur in mechanical propulsion in transportation as witnessed by the gas turbine (jet and propeller) in aircraft propulsion and the Diesel-electric locomotive

[10]Sir A. H. Roy Fedden, *Aircraft Power Plant — Past and Future* (London, Royal Aeronautical Society, 1944), p. 54.

on American railroads. Many will object to terming the Diesel locomotive a revolution but it is well to consider that 15 years ago railroad experts were predicting that 100 years from now the steam locomotive would still be the major form of railroad traction. In considering the possibilities of revolutionary advances in aircraft propulsion resulting from improvements in fuel it may be well to bear in mind that very large gains are relatively easy in the early stages of an art but become increasingly difficult as the art gets older. Most of the possible advances with hydrocarbons as an aircraft fuel appear to have been performed, and revolutions due to fuel are likely to have to depend upon atomic energy or some other source almost entirely foreign to hydrocarbons.