CHAPTER III

Early Investigation of the Effects of Fuel on Aircraft Engine Performance, 1915-1928

Introduction

Development of the piston-type aircraft engine, which was used exclusively in all self-propelled aircraft until jet propulsion came into limited service toward the conclusion of World War II, was remarkably accelerated by fuel development which was initiated in the middle 1920's and which began to pay big dividends in increased performance in the early 1930's. During World War I little was known about the effects of fuel upon aircraft engine performance. It was known that gasolines from different parts of the world could increase or reduce engine output and fuel consumption. In fact, when the United States entered World War I and became the principal supplier of aviation gasoline to the Allies, engine performance was noticeably affected for the worse in comparison with that which had been obtained from the Borneo, Java, and Sumatra gasolines previously in service. In World War I gasoline which existed as such in the crude oil (straight-run gasoline) was used exclusively, and synthetic fuels largely consisting of compounds which do not naturally occur in crude oil were not used. In fact, the production of such gasolines was in its infancy and the gasolines produced were quite unsuitable for the then current aircraft engines. In World War I, if the use of a given gasoline resulted in unsatisfactory engine performance, the only generally known method of improving it consisted in adding benzol produced from coal tar. Benzol was in short supply so that its general use in aviation fuel was not possible.

The first serious attempt to improve performance of aircraft engines by use of synthetic fuel was made during World War I in the United States by Thomas Midgley and C. F. Kettering[1]

[1] See p. 579.

who used a mixture of benzol with a compound manufactured from benzol, this work having started as a result of rumors (proved later to be unfounded) that the Germans were using the compound manufactured from benzol.

Knocking as an Early Problem in Aircraft Engine Development

Knocking in piston engines as a significant problem in limiting the power output and the useful work delivered per unit of fuel was known quite early in the history of engine development. For instance, by 1905 the builder of motor cars realized that knocking was a limitation with available fuels and engines. Before World War I the builder of aircraft engines was not concerned with fuel knock since he was much too busy with trying to make the engines light enough and of sufficient mechanical reliability to stay together for a flight of a few hours. In addition, he had great difficulty in cooling air-cooled engines and by 1914 had realized that the fuel he used and particularly the amount he used had a bearing on engine cooling; he found that by using a very rich mixture, the cylinders would not become visibly red hot, but they would do so if he used a leaner mixture. He also found that when the cylinders became overheated, knocking would start which rapidly increased cylinder temperature and resulted in engine failure.

In late 1915 Major F. M. Green, then Chief Engineer of the Royal Aircraft Factory (later and currently Royal Aircraft Establishment or RAE), secured the services of Professor A. H. Gibson (then Lieutenant Gibson of the Royal Artillery) for the purpose of investigation of the general problem of aircraft engine cooling and performance. Green considered that cooling of aircraft engines was in a very backward state and would not progress until more basic knowledge replaced the hunches of the designer. Gibson was then a distinguished engineer-physicist in the field of hydraulics and had also accomplished original work in the field of cooling large gas engines burning city gas. At the RAE Gibson rapidly obtained a number of water-cooled and air-cooled cylinders and set

them up on single-cylinder engines. He proceeded to determine their operating characteristics and with air-cooled cylinders developed the technique of finding the leanest mixture on which they would operate without overheating. In many cases knocking occurred when leaning the mixture, and this knocking could be reduced or eliminated if benzol was added to the gasoline. Gibson also found that the better the cooling of an air-cooled cylinder the higher the compression ratio that could be used on the standard gasoline of about 50 PN then being used and mostly being obtained from the Dutch East Indies. If benzol was used in the fuel supplied to a very well cooled cylinder, the compression ratio could be still further increased with improvements in both power and fuel consumption.

Rating Knock Properties of Fuels

The use of a standardized technique for rating the cooling performance of air-cooled cylinders in terms of their behavior in respect to the leanest mixture they would operate on without overheating or knock led to the use of this technique in reverse for rating the knock properties of fuels. If a given cylinder was used with the standard fuel and with the leanest mixture which could be used before knock developed, other fuels could then be tested to determine whether they were better or worse than the standard; this testing resulted in a technique for rating aviation fuels which persisted for many years and for some years after it had become misleading.

The Burton Cracking Process

The Burton cracking process in which gasoline was made from heavier oil by subjecting it to heat and pressure had come into use in the United States in 1915 and led to experimental work on similar lines in England, and experimental fuels were tested by Gibson and his staff. One such cracked fuel made by Sir Oliver Lodge was found to be much better than the standard fuel in respect to knocking properties when tested in a water-cooled engine but no better or worse than the standard when tested in an air-cooled engine. Skepticism regarding these findings led to retesting a year later when it was found that the cracked fuel was no longer better than the standard in the water-cooled engine. Gibson and his staff did not appreciate the significance of these findings and that the loss of knock properties was due to instability of the cracked fuel. Instability of cracked motor gasolines later became a serious problem to the oil industry of the United States in the early 1920's. Variation of knocking properties in air-cooled and water-cooled engines was not appreciated at all until 1928 and later.

Problem of Knocking in World War I

When the United States became the source of supply of aviation gasoline to the Allies in 1917, it supplied fuel of 40 PN or less. This resulted in a serious increase of knocking difficulties in engines tested at the RAE, and the importance of fuel knock properties became increasingly appreciated. After the United States took over the supply of aviation gasoline to the Allies in 1917-1918, the French approached the British with a proposal that all aviation gasoline from American sources be redistilled to improve its volatility. The Lorraine-Dietrich (French) water-cooled engines were breaking crankshafts, and it had been determined that if the gasoline was redistilled to remove part of the higher boiling materials the crankshaft breakage was eliminated. The difficulty appears to have been due entirely to bad distribution producing rough running and not to knocking. In any case, the British turned the proposal down. This appears to be the first definite proof that bad distribution could cause mechanical failure of an engine. It was known earlier than this at the RAE that bad distribution could cause an engine to run very roughly and that it could cause loss of power. In the United States aviation gasoline was then produced in two grades, namely, Domestic Aviation Grade and Fighting Grade, and it is not known which of these caused the trouble with the Lorraine-Dietrich engine. On the whole it appears that the French were even more ignorant than the British regarding aviation fuels and their engine effects.

Specifications

The United States, after entry into the war, set up specifications for Domestic Aviation Grade (hereafter DAG) and

Fighting Grade aviation gasolines, the Fighting Grade being the more volatile and being dyed red for identification. It is believed that the dyeing of Fighting Grade for identification is the first use of dyed gasoline. Apart from the fact that these two grades were clean and fairly sweet smelling materials, they were poor aviation fuels and sufficiently bad in knocking properties to cause difficulty in combat service. At this time in the United States there was a general tendency to appraise gasoline quality in terms of the lower the specific gravity (i.e., the fewer the pounds per gallon) the better. This method of appraisal gave Pennsylvania gasoline, which might be as low as 30 PN, a higher value than the fuels from California which had 50 PN to 55 PN and which were similar in this respect to gasolines from the Dutch East Indies.

Knock Properties of California Gasolines

The excellent knock properties of the California gasolines appear to have been generally unrecognized although they were known and appreciated by Midgley and Kettering who were then working on the knock properties of aviation fuels in connection with the Liberty engine program. Midgley developed a fuel consisting of 20% benzol and 80% cyclohexane (manufactured from benzol) and tested this in a high compression Liberty engine which performed considerably better than the standard Liberty. Midgley's fuel could not have been produced in any quantity but appears to be the first serious synthetic aviation fuel. For quite a number of years, however, the lesson taught by this fuel was disregarded in the United States.

First Engine Specifically to Test Knocking

During World War I in England H. R. Ricardo was investigating the joint fuel-engine problem in gasoline engines and turned his attention to aviation engines as well as other types. Ricardo's investigations were supported by the (British) Shell interests, and he designed and developed the first engine specifically produced for investigation of the knocking properties of fuels. After the war Ricardo developed two methods of assigning ratings to the knocking properties of fuels. His engine (Ricardo E-35) was designed so that the compression ratio could be varied while the engine was operating; to test a fuel the compression ratio was varied until the fuel just produced knocking and this compression ratio was called the "Highest Useful Compression Ratio." This procedure suffered from lack of reproducibility from place to place and engine to engine.

Toluene Number Scale

Ricardo also established a fuel scale consisting of the aromatic toluene as the upper end and a low PN gasoline as the lower end. Blends of these two fuels could be made up to match the knocking characteristics of any then available fuel it was desired to test. The scale had several disadvantages, among which was the fact that successive batches of the gasoline were not entirely alike and would not have been suitable for an international standard. Likewise, toluene was prone to preignite before it knocked and therefore was not an ideal upper end of the scale. The toluene number scale, however, appears to have been the first established fuel scale which had any chance of being reproducible.

Studies of Hydrocarbons

With continued Shell sponsorship Ricardo's program was expanded and H. Tizard and D. R. Pye carried out studies and fundamental investigations of engine combustion at Cambridge University. Ricardo studied the knocking behavior of the various types of hydrocarbon which were present in gasoline and of individual hydrocarbons of each type. Aromatics, paraffins, and naphthenes were studied; only the aromatics and naphthenes were available in any reasonable purity and the paraffins were derived from petroleum and were mostly of very low purity. Some studies were also made of olefins, alcohols, and anesthetic (diethyl) ether. From these studies it was concluded that aromatics were the best, paraffins the worst, and naphthenes intermediate. This was in error in respect to the conclusion that aromatics were the best fuel component, and this was notably so where air-cooled engines were concerned. The conclusions were also in error in regard to the paraffins being bad as was later shown by Graham Edgar's

work. Edgar, of course, worked with synthetic paraffins but Ricardo, Tizard, and Pye failed to observe the very excellent knocking properties of isopentane, a paraffin found in crude oil.[2] The study which led to the conclusions was, however, an important landmark in the development of spark ignition engine fuels.

British Appraisal of Knocking Quality

This work had a pronounced effect on the thought of the British in regard to aviation fuel which was almost entirely evaluated in terms of aromatic content, a good fuel to many British aviation engineers being one with 38% aromatic content. As a result of the work of Ricardo, Tizard, and Pye, elaborate methods of determining the aromatic, naphthene, paraffin, and olefin contents of aviation and motor gasolines were set up in both England and the United States and knocking quality was appraised in terms of these analyses and without engine test. Thus British aviation was more fuel conscious than that of any other country until about 1930.

Kettering's Program of Knock Investigation

In 1911 Kettering of Dayton Engineering Laboratories Company (hereafter Delco) had become interested in the problem of knock since his system of battery ignition was commonly blamed for producing knock in automobiles which was said to be absent when the magneto, hitherto largely used as a standard for automobile ignition, was employed. (A magneto generates the electrical energy required for ignition whereas in battery ignition the energy is derived from a battery.) Kettering was able to demonstrate that the source of the spark had no influence upon knock but this did not kill the prejudice. Kettering was also troubled with knocking problems with the air-cooled farm lighting engines (Delco) he was building. These engines operated on kerosene and would knock on Pennsylvania kerosene, then considered the best produced in the United States and would not knock on California kerosene which was considered an inferior product as regards use in stoves and lamps.

[2]See p. 616.

Kettering interested his employee, Midgley, in the problem and a vigorous program was started. Midgley was a mechanical engineer by training and of a very decidedly original turn of mind but had to that date been exposed only slightly to chemistry. Midgley was assisted by T. A. Boyd in the investigation, which soon showed that the addition of small quantities of either elements such as iodine or chemical compounds to a fuel could profoundly affect its knocking properties for the better or the worse. Compounds or elements improving knocking properties were called antiknocks and those making them worse were called proknocks. This was the first evidence that antiknocks could affect combustion in an engine. Benzol and grain alcohol had hitherto been known to reduce knock in an engine, but the quantities required were enormous in comparison with the compounds discovered by Midgley and his associates.

Antiknocks had been thought to exist previously, and relatively small additions of moth balls (an aromatic) were claimed to have greatly reduced knock, but such claims were without foundation and were the result of inadequate testing technique. The most important antiknocks discovered by Midgley and his group were aromatic amines (compounds resulting from the addition of ammonia to an aromatic) and tetraethyllead. During the investigations of the Midgley group it was found that two compounds might have identical composition but differ vastly in knocking properties depending upon the way the atoms comprising the fuel molecule were arranged. Thus, anesthetic (diethyl) ether and butyl alcohol each contain four carbon atoms, ten hydrogen atoms, and one oxygen atom, but Midgley and co-workers found the two compounds to differ vastly in knocking properties.

Military Investigation of Fuels

Following the Armistice in 1918 the Army Air Force sporadically investigated aviation fuels. DAG fuel delivered to McCook Field[3] was often found to be so bad in respect to knock

[3]McCook Field was the predecessor of Wright Field as the center of Army development of aircraft engines.

that a benzol addition of about 20% was necessary to suppress knock in even the Liberty engine. W. S. James and Stanwood Sparrow at the National Bureau of Standards investigated various fuels in high compression Liberty single-cylinder engines and showed that considerable improvements in engine performance could be obtained. The Army investigated various methods of determining knock including the use of quartz windows in the cylinders which enabled the color of the flame to be determined. The Army also became aware of the excellent knock properties of the California gasolines but nothing was done about obtaining such fuel for service use.

Neglect of the California fuels was largely due to the fact that the knock problem did not seem to be sufficiently important in service operation. The Liberty engine did fairly well on the current DAG (although later use of better fuels showed that some of the mechanical difficulties occurring with DAG had been the result of knocking), the Curtiss D-12 engine did a magnificent job with DAG of less than 40 PN, and the Wright E 180 hp (Hispano) engine also appeared satisfactory in training and other low duty service on DAG. Part of the reason for neglect of the California gasolines lay in procurement difficulties; the Army specifications were supposed to conform to those of the Federal Specification Board. The Army and the Navy could make minor changes in Federal Specification Board requirements and the Army did add a chemical test in order to improve the knock properties of DAG, but this test proved almost totally ineffective and fuel of as low as 35 PN continued to be supplied. No method of procuring California gasoline by means of engine performance specifications was known, and attempts to procure gasoline by geographical location of crude supplies seemed impossible.

In 1920 or thereabouts the Army procured barrel quantities of the aromatic amines discovered by Midgley, and these were intermittently employed in DAG up to 1926 for special flight use and work in the laboratory where knocking occurred with DAG. In 1921 or 1922 the Army obtained samples of lead from Midgley and carried out tests in a single-cylinder Liberty engine. The tests now seem very unintelligent but represented thought which persisted in some military circles until as late as

1932. This thought was based on the view that military aircraft must be able to operate on the worst available motor gasoline in order to ensure supply in time of emergency. Accordingly, the Army tested lead in motor gasoline of very poor knock properties and used about 16 cc lead per U. S. gallon, this concentration being 265% of that which has ever had service use and 350% of that which has ever had very large-scale service use. Tetraethyllead is not used alone in the material now known as tetraethyllead antiknock compound, and the other materials in the compound supplied for the Army's first tests were experimental and unsuitable. In any case, the first tests of lead gave very unsatisfactory results and the matter was dropped for about two years.

Early Army Use of Aromatic Amines

In 1924 or 1925 the Type M air-cooled cylinder (see Schlaifer above, p. 180) was undergoing development tests; DAG was found to be inadequate and DAG plus benzol was employed. Shortage of benzol led to the use of aromatic amines which suppressed knock but produced difficulties with rubbery deposits in the cylinder. Tests were also made with lead, this time in reasonable concentration in DAG, and showed control of knock but produced the valve and spark plug difficulties which were later to prove major problems.

Navy Use of Leaded Fuels

From the foundation of the Bureau of Aeronautics in 1921 the Navy began to take an interest in aviation fuel and was the first of the military services to procure fuel to a specification requiring determination of knocking properties in a standardized single-cylinder engine. Due to earlier adoption of air-cooled engines for service use on a larger relative scale by the Navy (see Schlaifer above, Chapter VII), the Navy was in definite service difficulty with knocking at an earlier date than the Army and in 1926 began the use of lead in operating squadrons. The early Navy use of lead involved carrying cans of the lead compound in the aircraft and adding this to the gasoline when the airplane was refueled. This practice continued in the

Navy on a general scale until about 1933 but was used only on a very limited scale by the Army.

Army Use of Leaded Fuels

In 1927 the Army began to encounter serious knocking difficulties in service with its large air-cooled engines, i.e., Wasp, Cyclone, and Hornet. Captain T. E. Tillinghast, then Chief of the Power Plant Section at McCook Field, considered that the use of lead was the most feasible way out of the difficulties and began the addition of 3 cc lead per U. S. gallon on a limited service basis. He followed this in 1928 by initiating a systematic investigation of the aviation fuel problem as a whole and of the effects of fuel knock quality upon engine performance in particular.

Founding of the Cooperative Fuel Research Committee

In 1919-1920 the automobile industry as a whole became dissatisfied with the quality of motor gasoline available to the public and was particularly disturbed by the wide variation of available supplies in respect to: ease of starting, distribution, boiling of fuel in the carburetor and other parts of the automobile fuel system, and knocking. It was realized that there was an almost complete lack of means of defining the properties of motor gasoline in respect to effects upon these difficulties. The automobile and petroleum industries realized the necessity for a joint attack upon the problem since it involved fuels, engines, and automobile fuel systems. There was at this time a fear of shortage of crude oil supplies; in view of this fear it appeared important to determine what could be done to fuels and automobiles so that an increased proportion of the crude oil could be made available as suitable motor gasoline.

Sponsoring and Financing of the Cooperative Fuel Research Committee

The Cooperative Fuel Research Committee (hereafter CFR) was evolved in 1921 as a result of discussions within the Society of Automotive Engineers (hereafter SAE), and the leaders of these discussions appear to have been David Beecroft (automotive), Coker Clarkson (Manager of SAE), B. B.

Bachman (automotive), and R. E. Wilson (then a Professor of Chemical Engineering at Massachusetts Institute of Technology but later of the petroleum industry). C. F. Kettering (automotive) and H. L. Horning (automotive), once the CFR was agreed upon, became prime movers and vigorously supported and pushed its work. The CFR was sponsored and financed by the SAE and the American Petroleum Institute (hereafter API). At the time of the formation of the CFR there were no accepted means of defining the properties of a gasoline in respect to: ease of starting, boiling in the fuel system, and the rapidity with which the engine became fully operable after starting and which is now known to be related to distribution as affected by both engine and fuel. Midgley and Boyd, and Ricardo, as a result of their extensive studies of the knocking properties of fuels, had stimulated interest in measurement of knock properties, and Ricardo had produced the E-35 engine as a standard means of measuring knocking properties. While studies of knocking properties of fuels were in progress, the situation was chaotic since the engines and the means of determining knock used in the United States were different in almost every laboratory. Likewise, there was no common means of expressing the knocking properties of a gasoline. One laboratory might express it in terms of an engine function and another in terms of the amount of benzol which had to be added to the fuel under test to make it equal to a particular commercial gasoline or the amount of benzol which had to be added to the commercial gasoline to make it equal to the fuel under test. The commercial gasoline was assumed not to vary in knocking properties.

Bureau of Standards Studies of Fuel

The United States Government, as a user of gasoline, was interested in the determination and control of its essential properties and the National Bureau of Standards had in the main conducted such studies for the various interested government agencies. The Bureau of Standards was represented on the original CFR and was chosen by the CFR as an impartial research organization to carry out studies of the effects of gasoline properties upon engine behavior and vice versa. The

studies at the Bureau of Standards were in part financed by the CFR and in part by the government.

The CFR Standard Engine — A Joint Product of Two Industries and the Government

The CFR fairly soon decided that a standard engine was necessary for measurement of the knocking properties of fuels, and this decision ultimately led to the evolution and development of the CFR engine which was (and in 1949 is still being) produced by the Waukesha Motor Company and which soon became an international standard. H. L. Horning was then head of the Waukesha Motor Company and made available the facilities of this company for the design and manufacture of the CFR engine which was then distributed to the cooperating CFR laboratories for test and evaluation. The CFR engine and the necessary operating conditions for evaluating motor fuels were the products of cooperative work by the *oil industry* and the *users of gasoline* in the form of the automobile industry *with the government as both a user and an impartial arbiter interested in means of setting and maintaining standards.* The CFR, after considerable exploration of means of expressing and recording knocking behavior by means of a system of standard fuels, adopted the octane number scale. It later standardized the benzol-octane scale in which benzol was added to octane as a means of measuring fuels better than octane, but this was abandoned after Wright Field established a test method which showed benzol to be considerably inferior to octane.

Investigation of Fuel Scales

In 1926 Graham Edgar of the Ethyl Gasoline Corporation (now Ethyl Corporation) was investigating fuel scales as a means of expressing fuel knocking quality. The original work of Kettering, Midgley, and Boyd with lead for General Motors resulted in the foundation of the General Motors Chemical Company for the purpose of manufacturing and distributing lead in the form of "Ethyl Fluid." The method of manufacture was difficult and costly, and Standard Oil Development Company (Standard Oil Company of New Jersey subsidiary) employed Professor C. A. Kraus, then of Clark University, to study improved methods of synthesis. Kraus discovered the method of synthesis which was employed for many years. The situation was that General Motors had developed the product and controlled the patent situation, and Standard Oil Company of New Jersey had a greatly improved and patentable commercial process of manufacture. General Motors and Standard Oil Company of New Jersey pooled their interests and jointly formed the Ethyl Gasoline Corporation which marketed the product and carried out research in the use of the product but did no manufacturing. E. I. duPont de Nemours & Company, with its very extensive experience in the manufacture of organic chemicals, undertook to build plants for the manufacture of lead and for many years was the sole manufacturer on the North American Continent. The duPont company currently produces and sells lead in competition with the Ethyl Corporation. The Ethyl Gasoline Corporation required oil companies marketing gasoline containing its product to maintain a minimum standard of knocking quality. Edgar was not satisfied with the toluene number scale of Ricardo since this scale used a gasoline as the lower end of the scale and this gasoline obviously could not be kept constant in knocking properties. Edgar chose benzol as the upper end of his scale and decided that a paraffin which could be synthesized in high purity would be most suitable for the low end. He chose the octane later used in the octane scale as the most suitable for reasonably cheap synthesis. On engine testing the octane Edgar found it to be of much higher knock quality than any available gasoline and adopted it as the upper end of the scale. Since the octane that he had hoped to use for the lower end of his fuel scale turned out to be unsuitable for this use, Edgar sought another suitable paraffin for the lower end of the scale.

He selected the heptane currently used in the octane scale and chose this on the grounds that it was of the type of paraffin known to exist in gasoline. This heptane was also chosen since it was known that it could be extracted in high purity from the oil of the Jeffrey pine which grows in California at altitudes of 8,000 ft and higher. Heptane did not then seem suitable for cheap synthesis but was later synthesized and sold for $25 per gallon although it is currently extracted from petroleum and

sold for less than $1 per gallon. At that time octane also cost about $25 per gallon, and this cost with that of heptane limited the use of these materials in fuel testing. Commercial gasolines which had been calibrated in terms of heptane and octane were generally used for fuel testing and engine testing, and this use resulted in confusion and misleading conclusions. There are nine possible heptanes and eighteen octanes. Edgar's group prepared all the heptanes including triptane[4] and a number of the octanes. These were engine tested by General Motors and the results published later.[5] Since octane had considerably better knocking properties than any available gasoline and heptane much worse than any known gasoline, and the two compounds were essentially the same in all respects except knocking properties, Edgar proposed in 1927[6] that they be used to form a fuel scale. This proposal was later accepted and standardized by the CFR.

Up to this time equations were in use which rated the knocking properties of a gasoline in terms of its chemical composition and which gave the lowest rating to a fuel consisting completely of paraffins. Prior to Edgar's work Midgley, Kettering, and Boyd had shown, as we have already seen, that the manner in which a given number of atoms of carbon, hydrogen, and oxygen were arranged might have a profound effect upon knocking properties; but this fact was not generally appreciated, and in any case there was no sign that similar findings might apply to paraffins. The discovery of the excellent knocking properties of octane and other branched chain paraffins had an outstanding effect upon the development of aviation fuels. The use of branched chain paraffins and the use of lead (see work of Midgley, Kettering, and Boyd above) have been to date the most important methods of obtaining high PN fuels. For current types of piston aircraft engine the branched chain paraffins become increasingly important as PN exceeds 100 by increasing margins. Marked change of piston engine charac-

[4]See pp. 618-619.

[5]W. G. Lovell, J. M. Campbell, and T. A. Boyd, "Detonation Characteristics of Some Paraffin Hydrocarbons," *Industrial and Engineering Chemistry* 23, January 1931 p. 26.

[6]Graham Edgar, "Measurement of Knock Characteristics of Gasoline in Terms of a Standard Fuel," *Industrial and Engineering Chemistry* 19, January 1927, pp. 145-146.

teristics might change the relative order of importance of branched chain paraffins, but they would still remain a major factor in obtaining PN's of the order of 130 and higher. The use of the octane scale has had a very considerable influence in clarifying understanding of the aviation fuel problem as a whole.

Edgar's work represents one of those happy accidents of research and development where an investigator attempts to achieve a given objective and fails but ends up with an entirely different finding of vastly greater importance than his original aim.