CHAPTER V

Government and Business Relationships in the Development of Aviation Fuels, 1932-1939

CFR-AFD PROGRAMS

LATE in 1932 or early in 1933 a new phase of joint engine-fuel development, which has been mentioned briefly, began in the form of cooperative activity by the CFR. An Aviation Fuels Division (hereafter AFD) was formed by the CFR and a subcommittee was set up to produce a program of tests of sensitive and insensitive fuels in complete aircraft engines of severe and mild types. *This subcommittee consisted of representatives of the government, engine manufacturers, and the oil industry. The engine manufacturers provided engines and test work gratis; the CFR supplied fuels gratis for the tests and partly financed engine tests at the National Bureau of Standards. The participants in the program realized that the problem was a joint one for the petroleum industry, the engine manufacturer, and the fuel user, and that no one of the three could solve it alone.* The major aim of the test program was to determine the relative behavior of widely different types of fuels in complete aircraft engines with a view to developing more satisfactory laboratory engine methods for appraisal of knocking quality so that such improved methods could be used in specifications for the procurement of fuel which would give satisfactory and reasonably uniform behavior in service.

This program was the first of many undertaken by the CFR-AFD, covering many other phases of the aviation fuel problem besides knocking properties. Vapor locking due to both gasoline and the airplane fuel systems and storage stability of fuels are important items of the cooperative program carried out by AFD-CFR and which was still in progress in 1949. The results of the first series of tests of knocking properties were

published in 1936[1] and another program was immediately drafted.

AVAILABLE COMPONENTS FOR PRODUCING FUELS

The work at Wright Field had shown that there were then only two commercially available components for producing fuels of high PN for use in severe engines: straight-run gasoline of about 50 PN and lead. Addition of benzol to these components produced a fuel which was found to be inferior in a severe engine to the same components without benzol. This finding was in part due to continued and unjustified use of the method of rating which descended from Gibson's work. Wright Field wished to raise PN beyond values which could be obtained with high PN gasoline and lead, and the octane used in the octane scale seemed to be the most promising compound for addition to leaded high PN gasoline to achieve a further increase.

THE ROLE OF ISOOCTANE IN PRODUCING SUPERIOR FUELS

Octane seemed most promising since in blends with gasoline it responded sharply to the addition of lead whereas blends of benzol and gasoline responded poorly. Octane also seemed desirable since it was not sensitive and seemed therefore admirably suited to use in severe engines. Several engine tests of the pure octane then used only as a reference fuel in the laboratory knock test engines and costing $25 per gallon were planned at Wright Field but were abandoned because of engine breakdown difficulties. The tests were to have been carried out in one cylinder from a complete aircraft engine. The cylinder[2] would stand supercharging to a power output which was four times as great as that which it developed as part of the complete aircraft engine. The tests were to have been carried out on the straight octane and would have demonstrated the remarkable gains in performance which could be achieved by increasing PN from 76 to 100. At this period, however (1930-1932),

[1]C. B. Veal, "Rating Aviation Fuels in Full-Scale Aircraft Engines," *SAE Journal (Transactions)* 38, May 1936, pp. 161-175.
[2]Immediate ancestor of the Hyper No. 1 cylinder; see Schlaifer above, p. 268.

risking $125 worth of fuel for 30 minutes of testing seemed like a very rash step and it was some years before opinion became reconciled to such testing. In any case, a specification for 100 octane fuel was written on the basis of laboratory knock test engine investigations of octane plus California gasoline plus lead, but a year or two passed before preparation began for a full-scale test of 100 PN fuel in a complete aircraft engine of highly supercharged type.

In the meantime there was no source of octane except the reference material used in the octane scale which was produced and sold by Rohm & Haas Company at $25 per gallon. Rohm & Haas was an experienced manufacturer of synthetic organic chemicals and had undertaken to supply octane at the request of the Ethyl Gasoline Corporation. Rohm & Haas secured its raw material from Standard Oil Company of New Jersey (hereafter Jersey) which it then subjected to additional processing and to elaborate purification. In consequence of the very limited supply of octane[3] Wright Field gave thought to methods of obtaining it on a considerable scale.

Proposed PWA Project

At this time Public Works Administration funds were being allotted to government agencies for construction of permanent or semipermanent plants which would produce employment of skilled personnel. There was a chance of Wright Field's securing such funds and three-quarters of a million dollars was tentatively allotted for such a plant by Wright Field in the event that such funds became available to it. The plant would have employed the methods evolved by Edgar, Calingaert, and Standard Oil Development Company (subsidiary of Jersey) for the production of the semifinished material which Rohm & Haas had worked up into finished octane. It was contemplated that the plant would be built and operated under contract by a chemical manufacturer or an oil refiner since such operation was quite outside the province of Wright Field. PWA funds did not become available for the plant, however, so the project was dropped without going beyond the visionary stage.

Efforts at Wright Field to Increase Further Fuel PN

In the meantime Wright Field was carrying on development of the Wasp engine in conjunction with Pratt & Whitney and was endeavoring to obtain considerable increase of power by means of a high degree of supercharging in an engine with improved cylinder cooling. This engine suffered from power limitation due to knocking with fuel of 76 PN so a fuel of about 93 PN was made up from a small stock of gasoline of California type; this gasoline had the highest PN of any then known to Wright Field. This gasoline, when blended to about 93 PN by means of an excessive amount of lead, enabled the Wasp to develop about 900 hp for short periods without knocking or overheating. (The test periods were kept short since the mechanical strength of the engine was feared — at this period, 1932 or early 1933, the Wasp was rated at only about 600 hp.) Despite the 900 hp output of the Wasp on 93 PN fuel, it does not appear that Wright Field had realized the gains in power output which might be achieved in a supercharged engine by improving fuel from 76 PN to 100 PN; it does not appear that anyone else had realized the possibilities either. The PN scale had not then been evolved,[4] and fuels were discussed in terms of their octane

[3]Isooctane is, as has been stated above, a branched chain paraffin for which the full technical name is 2,2,4-trimethylpentane. It was first made by Graham Edgar and G. Calingaert by treating the commercially available tertiary butyl alcohol with sulfuric acid, this treatment producing the olefin diisobutylene. This reaction for the production of diisobutylene had been known for many years but was of only academic interest since it had never been commercially used. When hydrogen is added to the olefin diisobutylene, it becomes paraffin isooctane, and it is believed that this step of producing the paraffin had not previously been accomplished. The hydrogen is added by heating the olefin and supplying hydrogen under pressure and in the presence of a catalyst. While Edgar and Calingaert made their first batch of isooctane from tertiary butyl alcohol, successive larger batches were made from diisobutylene which was produced by Jersey from the gases which result when crude oil is cracked (see Burton process above as an example of cracking) to produce motor gasoline. These gases are a mixture which contains some isobutylene which can be selectively removed by treatment with sulfuric acid, the result of the treatment being either tertiary butyl alcohol or diisobutylene as desired. Alkylate, which is a mixture of octanes, is produced by the addition of isobutylene to isobutane forming octanes without the necessity of the step involving the addition of hydrogen. The Appendix on Hydrocarbons shows the steps involved in the production of isooctane.

[4]The PN scale was not introduced until about 1943 although the British had for some years used a crude version of it based on a 100 octane number commercial gasoline (Grade 100/125). The PN scale was introduced after the Army and Navy specified fuel with a lean rating of 100 octane number and a rich mixture rating (see rich mixture ratings, below) equal to isooctane + 1 cc lead (Grade

(Footnote continued on next page)

numbers. Wright Field expected about 10% more power from 100 octane number fuel (100 PN) than from 91 octane number (76 PN).

Late in 1933 O. Chenoweth, Assistant Chief of the Power Plant Branch at Wright Field, started a program to investigate 100 PN fuels made with octane. He secured approval for funds to purchase octane and to carry out tests in one or more highly supercharged engines. Since Rohm & Haas was the only source of octane and Wright Field could not, in compliance with procurement regulations, ask this firm what an impure grade would cost in a 1,000 gallon batch, the author requested Edgar to make unofficial inquiries of Rohm & Haas. Edgar

100/125). The personnel responsible for fuel in the Navy and in the Army were confronted with the problem of repeatedly explaining to admirals and generals that it was not possible to assign an octane number to isooctane + 1 cc lead. Operating personnel in the supply and maintenance divisions of the Services arbitrarily started to assign octane numbers to the new fuel and so to mark fuel servicing trucks. There was no uniformity in such assignment, and the fuel might be described as 104 octane number on one field and as 108 octane number on another. This state of confusion could, of course, result in a pilot's landing his aircraft on a field and requesting that it be refueled with 108 octane number. On being informed that only 104 octane number was available the pilot would probably refuse it as unsafe for his aircraft.

Such a state of chaos could not be allowed to persist and the Navy, the Army, and the British Air Commission representatives decided that fuels of 100 octane number and higher should be described by PN. The PN scale was based on 100 octane number (isooctane) as permitting 100% power in a supercharged engine, 130 PN permitting 130% of the power available on 100 octane number. The relation between permissible power and various concentrations of lead in isooctane (which, of course, had been the rating scale previously in use) was derived by averaging a large amount of full-scale engine and laboratory single-cylinder engine data. Performance Numbers below 100 were not evolved until later and have never come into use in fuel specifications.

Performance Numbers below 100 originated as a result of a handbook on aviation fuels and their effects on engine performance. The Army had requested the Ethyl Corporation to prepare such a handbook on contract since the Army personnel who knew the fuel-engine problem were so busy with both routine and research work that producing a handbook was impossible. The Ethyl Corporation submitted a bid of $1 for 25,000 copies of the handbook which later became a joint Army-Navy document with the Navy securing 5,000 copies for $1 (printing costs alone being $45,000). The author was responsible for writing the handbook (subject, of course, to official approval) and was confronted with the problem of explaining engine performance in terms of octane numbers below 100 for the benefit of personnel who were essentially laymen as regards fuels and fuel-engine problems. The author informed the Army and Navy representatives that he found it impossible to explain engine performance in terms of octane numbers but could do so in terms of Performance Numbers and was told to prepare a set of Performance Numbers for octane numbers below 100. This Army and Navy agreement made it possible to complete the fuel handbook, which was entitled "Aviation Fuels and Their Effects on Engine Performance" (NAVAER-02-1-511; U.S.A.A.F. T.O. No. 06-5-4).

obtained a tentative price of $4,000 for the batch and this figure was provisionally budgeted for in the test program.

"Army Method" 100 PN Fuel

At a somewhat later date personnel of Shell Oil Company, Inc., had orally discussed with a CFR Committee a possibility of manufacturing octane of slightly lower purity than the reference grade produced by Rohm & Haas. Shell had indicated that its proposed grade would be much cheaper than the reference grade. Shell had not proceeded with manufacture when it was informed of the Wright Field plans by the author who had then left the government service. Shell explored the situation at Wright Field and when the proposal was circulated for 1,000 gallons of octane, Shell was the low bidder and obtained the contract. The octane was blended with California gasoline and lead was added to the mixture, the blend being adjusted to give 100 PN by a laboratory engine test method evolved by Wright Field and known as the "Army Method." The "Army Method" used a special cylinder designed by Wright Field, made by Waukesha Motor Company, and fitted to the CFR engine. The "Army Method" also used Prestone cooling, was quite severe, and had been evolved to supersede the methods which had used the Ethyl engine. The 100 PN fuel made with octane was tested in the Pratt & Whitney Wasp and in the Wright Cyclone and was compared with 76 PN and 93 PN fuels made from conventional (but high PN) California type gasolines and lead. The 100 PN fuel, depending upon the engine and engine conditions, permitted power output to be 15% to 30% higher than with the 75 PN fuel. The results were published by Lieutenant F. D. Klein[5] early in 1935 and made a marked impression on both foreign and domestic engine manufacturers and upon the oil industry. Before the presentation of the paper one member of the oil industry who knew that Wright Field was working on 100 PN fuels but did not know of the engine results, expressed the opinion that the staff at Wright Field responsible for such nonsense were, or

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

should be, candidates for admission to mental institutions but quickly changed his mind when shown the engine data.

Also immediately following the publication of Klein's paper, Wright Aero began to formulate plans for development of an engine to take full advantage of 100 PN fuel. By August, 1935, the test program was under way and results were presented before the SAE in January, 1936.[6]

While the Army work demonstrated the large increases of power which 100 PN fuel made possible, Wright Aero chose to demonstrate mainly the possibilities of the fuel in regard to improving fuel consumption. A special 1820 "Cyclone" engine was built with high compression ratio (about 8 to 1) and with a supercharger which gave only a moderate manifold pressure (thus absorbing little power and producing a minimum of mixture heating). This engine at an output of about 425 bhp attained the abnormally low fuel consumption of 0.34 lb bhp hr. This was a test bed consumption which could not be attained in flight and was obtained with relatively low engine output. Nevertheless it was at least 15% lower than had ever been obtained with a complete air-cooled[7] aircraft engine on the test bed. This fuel consumption was the product of a special engine type of possibly limited usefulness; in any case, as a type it was not pursued and the best test consumption of recent military or airline engines (air-cooled or liquid-cooled) is of the order of 0.37 lb bhp hr (as of 1949).

The Young paper showed the possibilities of 100 PN fuel in regard to abnormally low fuel consumption and corresponding increase of range. The Wright work was very strong support for the Army case for 100 PN fuel and can be considered as one of the important landmarks in the development of 100 PN.

Production of 100 PN

The Army started plans to procure service test quantities of 100 PN fuel which put a load upon the oil industry since new plants had to be built from the ground up to put into practice a

[6]Raymond W. Young, "Air-Cooled Radial Aircraft-Engine Performance Possibilities," *SAE Journal (Transactions)* 38, June 1936, pp. 234-256.

[7]The Napier water-cooled engine for the Schneider Trophy races (see p. 554) of 1927 had attained a fuel consumption of 0.32 lb per bhp hr with 10 to 1 compression ratio.

process which had previously been used only on a laboratory scale. Jersey and Shell were the companies which took the program most seriously and were the mainstay of the early stages of the program. J. H. Doolittle (later Lt. General, USAAF), then Aviation Manager of Shell, in particular risked his future by persuading Shell to go heavily into plant expansion for the production of 100 PN fuel. The risk taken by Doolittle was shown when the Wright Field plans for service test of 100 PN fuel were opposed by the Army General Staff, and for some time the purchases by the Army were not sufficient to keep the plants newly installed by the oil industry operating at anything like capacity.

Conflict of Army General Staff and Wright Field over 100 PN

The Army General Staff was slow to appreciate the advantages of 100 PN fuel and, in addition, was disturbed about the possibility of insufficient supply in time of emergency. Wright Field battled the General Staff for about two years over the question of standardizing 100 PN fuel for all combat aircraft. The battle was won in part by Wright Field's resorting to publication of its data. Publication of data as a means of forcing the hand of a conservative General Staff may seem to be a questionable move but may be considered in the light of the fact that the improved performance due to 100 PN could not have been kept secret and, furthermore, that foreign governments were liable to standardize 100 PN for combat use. Had the General Staff been able to foresee that the daily consumption of fuel of 100 PN and higher would be about 20,000,000 gallons by the combat forces of the United States alone during World War II, Wright Field would doubtless have lost the argument. The General Staff at this time was thinking of about 3/4 million gallons per day as a maximum wartime demand. However, if the General Staff had been able to foresee that over 20,000,000 gallons per day of 100 PN would be produced at a cost of approximately 16 cents per gallon, the General Staff would probably have agreed with Wright Field earlier than it did. The controversy with the General Staff was essentially but not entirely concluded with the standardizing of 100 PN by the Army Air Forces in the middle of 1936.

Development of Methods of Producing Octane

Following Army procurement of service test quantities of 100 PN fuel, the oil industry carried out vigorous research and development in methods of manufacturing octane. The first quantity production of 100 PN fuel by Shell and Jersey involved production of octane by the cold acid process which essentially was the method used by Edgar for the first known production of this compound. Of the eighteen octanes the one used in the octane scale and three others have similar knocking properties. The cold acid process used as starting material a single gaseous hydrocarbon found in the gases produced in the manufacture of motor gasoline by cracking of oil. The cold acid process was followed by the hot acid process which used three gaseous hydrocarbons as starting material and promptly doubled the potential production. The hot acid process was followed by the phosphoric acid process which, at some sacrifice in knocking quality, can more than double the potential yield of the cold acid process when working on the same three gases used by the hot acid process. The hot acid and phosphoric acid processes produce a mixture of the four octanes referred to above and the mixture is superior in rich mixture properties (see below) to the cold acid process.

Testing of Fuel Components

The Army, in order to amplify the potential production of 100 PN, sought the advice of Jersey through R.P. Russell, then Vice President, Standard Oil Development Company. Russell made a survey of potential components other than octane for 100 PN fuel. The survey included not only materials in production by Jersey but experimental compounds which were still in the laboratory stage. Russell submitted for test a number of aromatics which Jersey was producing in quantity by high pressure hydrogenation of oil (this being Jersey's development of the Bergius process for producing oil from coal used by the Germans). None of these aromatics were found to be suitable although they and others were later found to be of considerable value during World War II when used in conjunction with

octanes. Russell also submitted diisopropyl ether which Jersey had investigated some time previously. Ricardo had tested diethyl (anesthetic) ether and had found it to be of very low PN; this finding resulted in the general assumption that all others had poor knocking properties.

Diisopropyl Ether

H. E. Buc of Jersey, in the face of considerable skepticism, had refused to accept the view that all ethers must have poor knocking properties because anesthetic ether was bad. Buc investigated branched chain ethers and found that diisopropyl ether was of about 100 PN and that it responded strongly to additions of lead. Diisopropyl ether has about 15% less heat energy per pound than does octane, a significant disadvantage for an aviation fuel component. Diisopropyl ether can be made from propane, a constituent of natural gas which is available in large quantity, and also from a constituent in the gases produced in making motor gasoline by cracking. The materials necessary for the manufacture of diisopropyl ether seemed at that time to be much more widely available than that necessary for the production of octane by the cold acid process. It seemed therefore that the ether was worth exploring extensively despite its deficiency in respect to available energy per unit of weight. The laboratory engine test methods for determination of knocking properties then in use did not penalize a fuel for low energy content, and by these methods diisopropyl ether was found to be equal to cold acid octane for blending in 100 PN fuels. Tests in complete aircraft engines were carried out comparing a 76 PN fuel with 100 PN fuels made with both octane and diisopropyl ether. The deficiency in energy content of the ether showed up in these tests but the ether blend was still clearly superior to the normal 76 PN fuel. Buc and E. E. Aldrin delivered a paper covering the results of the engine tests before the SAE.[8] The audience had no knowledge of the contents of the paper before its delivery and was decidedly startled. Diisopropyl ether, during manufacture, combines very readily with oxygen from the air and this ruins the knock-

[8] H. E. Buc and Edwin E. Aldrin, "A New High-Octane Blending Agent," *SAE Journal (Transactions)* 39, September 1936, pp. 333-340.

ing properties. The combination with oxygen during manufacture or later can be easily prevented by a simple precaution. Buc was aware of the precautions to be taken in respect to oxygen but several other laboratories which had engine-tested diisopropyl ether were not and consequently had rated the material as possessing very poor knocking properties.

Jersey subsequently made a considerable number of branched chain ethers in small quantity and evaluated them in small laboratory engines. Because of the engine test methods then in use Jersey failed to detect that one of the ethers it tested was considerably better than diisopropyl ether for use in an aircraft engine fuel. Shell, using improved engine test methods at a later date, determined that the compound in question, namely methyl-tertiary butyl ether, was much superior to diisopropyl ether. Because of rapid development of methods of manufacturing octanes, the discovery of the knocking properties of the ethers proved to be of little practical importance since diisopropyl and other ethers have been little used in aviation fuels and where used at all the concentration has been low. While the Jersey and the Shell work found little or no practical application, neither company suffered significant financial loss in the matter since neither had installed anything but small-scale facilities for production of ethers. Buc's discovery, however, may be said to be the last really important one concerning groups of compounds. Since the finding regarding the ethers, individual compounds of a group have been shown to be outstanding but no new group has been shown to be important. Thus, Ricardo had largely (but not entirely) defined the quality of aromatics, and Edgar had completely upset the views on paraffins and had defined their value. Buc's work with the ethers, while of much less significance than that of Edgar's with paraffins, nevertheless had almost as devastating an effect upon the current state of knowledge. At the time of Buc's work the knowledge concerning naphthenes and olefins was far from complete but was devoid of any gross misconceptions. (For further details on types of compounds see the Appendix on Hydrocarbons.) Buc's work had a very salutary effect in respect to basing conclusions either on limited data or on fuel compounds of doubtful purity.

Although departing from chronological sequence in discussion, the development of the alkylation process can logically be dealt with here. It has been seen that the hot acid and phosphoric acid processes followed the cold acid process and about doubled the potential yield. These three methods were all two-step processes in which a liquid having approximately the boiling point of water was produced from gases as the first step. As a second step the liquid was made to combine with hydrogen by a process known as hydrogenation. The hydrogenation step was expensive, and in addition the oil industry sought methods which would still further increase yields from a given quantity of available raw material. Several American companies and one British oil company were working simultaneously on this problem and all arrived completely or in part at the same conclusion, so that pooling of patents was necessary. The process known as alkylation avoids the hydrogenation step and produces at least four times as much product from a given amount of the usually available raw material as does the cold acid process. The development of the alkylation process resulted in putting 100 PN fuel on a firm basis from the standpoint of potential production in time of national emergency, and if any single process of refining can be said to have been the keystone of production of 100 PN fuels during World War II, alkylation would unquestionably merit the title. Alkylation gives a product known as alkylate, which is inferior to octanes produced by the three acid processes, but this disadvantage is more than made up by the much greater possible production.

Octane and Heptane in Full-Scale Engine Testing

When the second CFR program of tests in complete aircraft engines was drafted, it was decided that the confusion which resulted from using commercial aviation gasolines as full-scale reference fuels should be avoided by adopting the octane used in the octane scale. It was planned to use somewhat lower purity than required by the reference grade of octane. With the cooperation of Shell and Jersey a batch of about 70,000 gallons of 97% purity material was jointly manufactured by these two companies. This batch cost about $40,000 and production was financed by CFR. This was a decidedly daring step at this time when it had not been appreciated that the cost of reference fuels was a relatively minor item in the total cost of running fuel tests in complete aircraft engines. While the cooperating agencies were willing to pay about 55 cents per gallon for octane as a reference fuel for aircraft engine testing, they failed to appreciate that heptane at about $5 per gallon was equally desirable and should be used instead of a very low PN gasoline. The use of heptane as a full-scale aircraft engine reference fuel was not accomplished until 1946 when this material was produced by Phillips Petroleum Company (hereafter Phillips) at a cost of less than $1 per gallon. The second series of CFR aircraft engine tests included commercial 100 PN fuels, and the tests were of great value in further establishing the important technical advantages of such fuels. From the time of publication[9] of the second series of CFR tests in 1938 the CFR has continued to sponsor tests in complete aircraft engines of new types of fuels or new potential components of aviation fuels.

The use of high PN fuels by the airlines made relatively slow progress since airline officials were in general inclined to judge fuels by their cost per gallon rather than on a basis of the overall cost of a given operation, which might be more cheaply carried out with an expensive fuel than with a cheap one. It would appear that for the domestic airlines (operating over land) using the current aircraft, 100 PN fuel would have increased operating costs. Pan American Airways, however, had long been convinced that low fuel consumption in long-range over-ocean operation was worth a considerable increase in fuel cost and put Boeing flying boats into transatlantic service with special high compression Wright R-2600 engines using 115 PN fuel. The high compression engines with 115 PN fuel reduced fuel consumption by about 5% in comparison with the same type of boat with standard R-2600 engines and 100 PN fuel.

[9]H. K. Cummings, "Rating Aviation Fuels in Full-Scale Aircraft Engines," *SAE Journal* (*Transactions*) 43, December 1938, pp. 497-503.

Fuel Behavior at Rich Mixture and Lean Mixture

Prejudice Against Aromatics

The advent of 68 PN fuel in the United States coincided with a period of intense development of air-cooled engines, and the demand for more and more power at times resulted in engines which operated at excessive cylinder temperatures and which were consequently suited best by insensitive fuels. The general line of thought was to regard the fuel which would stand the most abuse in the forms of high cylinder temperature and hot mixture supplied to the cylinders by a supercharger as being superior to a fuel which did not stand this abuse but which was better under milder conditions. The use of California type gasolines plus lead for 68 and 76 PN fuels was supplemented by selected mid-continent gasolines plus lead, and the latter were even less sensitive than the California type blends. Among the engine manufacturers there were some who had suffered severe difficulty and limitation of development of air-cooled engines as a result of use of benzol blends, and these manufacturers viewed with suspicion any fuel containing any appreciable amount of aromatics. As it turned out, the insensitive 68 and 76 PN fuels were a fortunate accidental choice for the period of preliminary development of large air-cooled engines. The appraisal of fuels, however, in terms of their insensitivity represented a tendency to try to have your cake and eat it too and also started a blind prejudice against aromatics which has persisted and which produced an unfortunate controversy during World War II.

British Preference for Sensitive Fuels

The British adopted 68 PN fuel shortly after it was adopted by the United States. As a result of a number of factors, the British preferred considerably more sensitive fuels than those used in the United States. The most important factors were: (1) their major source of aviation gasoline was the Dutch East Indies, which produced highly aromatic gasolines, (2) their greater interest was in water-cooled engines, and (3) their tendency was to emphasize maximum power rather than economy and engine cooling under cruising conditions as was the habit in the United States. The British found that the more sensitive fuels permitted greater maximum power than did the less sensitive types. Both sensitive and insensitive fuels were assigned equal Performance Numbers in the standard laboratory test by which they were blended and accepted. The standard laboratory test appraised the fuels at lean mixture which is used in the complete aircraft engine for the cruising condition. The aircraft engine at maximum power, however, which is used at take-off and full power combat, usually uses rich mixture (this being particularly true of supercharged engines). Thus, specifications were appraising fuels in terms of their lean mixture or cruising performance whereas their performance at rich mixture or the take-off condition, which might be more important than the cruise condition, was not appraised.

Rich Mixture Performance

In any case, the British became convinced of the importance of specifying PN under both lean and rich mixture conditions, and included such requirements in their specifications late in 1938 or early in 1939. When the British adopted 100 PN fuel for the RAF they found that it might be quite variable in rich mixture PN and, as a result, set up a standard for rich mixture behavior. In the United States the importance of rich mixture performance was overlooked until the British evidence put the matter beyond question. Actually, the evidence in regard to rich mixture behavior was available in the United States at least as early as it was in England. In retrospect it is possible to consider numerous tests in the United States which showed rich mixture effects but which were misconstrued as being the inevitable differences which arose between mild and severe engines.

It was ultimately determined that sensitive fuels had good rich mixture performance, i.e., their Performance Numbers increased as the mixture became richer. Insensitive fuels, on the other hand, had poor rich mixture performance; in fact, their Performance Numbers in extreme cases were reduced at rich mixture. Thus, while rich mixture performance is merely

another manifestation of the effects of engine temperature upon PN, it was not so recognized in the United States until demonstrated beyond doubt in Europe. The Germans were aware of rich mixture effects about as early as the British and produced fuels with very excellent rich mixture performance.[10] The British findings in regard to rich and lean mixture behavior resulted in acceptance of the idea of controlled sensitivity of aviation fuels which constitutes an important landmark.

Catalytic Cracking Process

The work at Wright Field and the first series of CFR tests in complete aircraft engines had shown that cracked aviation fuels which were similar to cracked motor fuels except that they were more volatile, were not attractive for high Performance Numbers. Eugene Houdry started work in France about 1924 with a catalytic cracking process which produced gasoline from an oil fraction similar to kerosene by means of moderate temperature and pressure in the presence of a catalyst. This was in contrast to cracking processes (known as thermal cracking) then in use which produced gasoline by subjecting oil of kerosene and less volatile types to a combination of high temperature and high pressure. Houdry's process was taken up by the Socony-Vacuum Oil Company, Incorporated (hereafter Socony), and Houdry came to the United States and continued development. The Sun Oil Company (hereafter Sun) later took over the development which then began to accelerate rapidly and culminated in a successful commercial process. This process was publicly described by Houdry, Socony, Sun, and E. B. Badger and Sons Co. late in 1938[11] and aroused great interest in the oil industry. Unexpectedly it turned out that the Houdry process could produce an avia-

[10]The Germans did not, however, use rich mixture in their engines at maximum power and this was not understood in the United States until the middle of World War II when it was found that rich mixture reduced the permissible power of the German engines equipped with fuel injection.

[11]Eugene Houdry, Wilbur F. Burt, A. E. Pew, Jr., and W. A. Peters, Jr., "Catalytic Processing of Petroleum Hydrocarbons by the Houdry Process," American Petroleum Institute, *Proceedings* 19, Sec. 3, 1938, pp. 133-148.

Also in *National Petroleum News* 30, November 30, 1938, R570-572, 574, 576-580.

Also as "The Houdry Process" in *The Oil and Gas Journal* 37, November 24, 1938, pp. 40-43, 45, 48.

tion gasoline of 58 PN without lead and which with lead was better than the available straight-run gasolines. This finding made Houdry aviation gasoline a very attractive potential component of 100 PN fuel since less alkylate or other octanes were needed than with the straight-run gasolines then used in 100 PN fuel. Jersey and a group of other oil companies with experience in the use of catalysts in oil refining, and particularly in respect to cracking, had pooled their patents and experience as a means of producing a catalytic cracking process competitive to that of Houdry. This pooled effort resulted in the Fluid catalytic cracking process to which Jersey contributed the idea of a powdered catalyst which flows like a liquid and can thus be readily circulated.

Isopentane

In the manufacture of aviation gasoline it is desirable from the standpoint of cost and supply to use, as far as possible, materials which exist in the crude oil and which can be readily separated from it. Straight-run gasoline, of course, exists as such in the crude oil and is readily separated. Straight-run gasoline has a PN of up to 55 (up to 82 when lead is added) and consists of components both better and worse than 55 PN but which are not readily separated. R. C. Alden of Phillips was responsible for pointing out that isopentane, which exists in both crude oil and natural gas and is fairly readily separated from either, is a usable component of aviation fuel. Isopentane has a PN of 76 without lead and about 115 with lead and is thus a very useful component of 100 PN fuel. Isopentane boils at about 85 F and the amount which can be used in aviation gasoline is limited by the boiling point to about 20%. In addition to occurring naturally, isopentane can be produced in considerable quantity by the Houdry and Fluid catalytic cracking units (hereafter cat crackers). Since the work of Phillips with isopentane, this component has become an important constituent of fuel of 100 PN and higher and is universally used in such fuels at the time of this writing.

Research in Pure Hydrocarbons

Publication[12] of the Army work with 100 PN fuel showed the importance of synthetic hydrocarbons such as the octane used in the octane scale as means of making high PN fuels. Before publication of the Army 100 PN data, General Motors had been carrying out studies of pure hydrocarbons, and in 1934 W. G. Lovell, J. M. Campbell, and T. A. Boyd published data[13] covering the PN's of a number of paraffin hydrocarbons, some of which were shown to be much better than the octane of the octane scale. The Army work showed that hydrocarbons which had been little more than laboratory curiosities might soon become important components of aviation fuels. The work of Lovell and co-workers was not only of interest in regard to the best hydrocarbons to include in high PN aviation fuels but also in respect to the hydrocarbons which should be excluded. Interest in the knocking properties of pure hydrocarbons led to a good deal of work covering the synthesis and engine testing of pure compounds. This was a wasteful and inefficient proceeding since several laboratories might all produce the same compound whereas the total knowledge would be more usefully extended by avoiding such overlapping.

Projects of the API

The oil industry is fiercely competitive and, in addition, has a healthy respect for the Sherman Act. The competition is equally as vigorous in technical development as it is in sales, and the competition in technical development is most vigorous in development of manufacturing methods. Knowledge of the properties of a particular hydrocarbon which can occur in petroleum or which can be produced from petroleum is usually of little or no competitive value unless a method of producing the compound is available. The oil industry wisely decided that both it and its customers would benefit from a cooperative attack on the problem of synthesizing hydrocarbons which can be included in gasoline. Accordingly, the API founded the

[12] Klein, op. cit.

[13] Wheeler G. Lovell, John M. Campbell, and T. A. Boyd, "Knocking Characteristics of Hydrocarbons," *Industrial and Engineering Chemistry* 26, October 1934, p. 1105.

Pure Hydrocarbon Research Project (currently API Research Project 45) in 1939. The purpose of Research Project 45 was the synthesis and purification of hydrocarbons which can be included in gasoline and determination of their knocking and other properties. The magnitude of the problem undertaken can be seen when it is understood that *motor gasoline can contain as many as 6,000 different hydrocarbons and aviation fuel as many as 300.* The API had previously sponsored and financed for many years API Research Project 6, which has been devoted to separating and identifying the hydrocarbons present in crude petroleum as it is produced. These and other API Research Projects are excellent examples of the valuable results of corporate cooperative basic research. The findings of these projects are published as soon as possible and become freely available to all. Not all API corporate members contribute to the projects and the contributors only have prior knowledge of the results up to the time of publication. The API is, of course, carrying on the research projects with a view to benefiting the oil industry and the projects constitute an example of highly intelligent selfishness which redounds to the credit of American industry.

Triptane

Before the foundation of API Project 45, the National Advisory Committee for Aeronautics (hereafter NACA) had maintained a project at the National Bureau of Standards for the synthesis and test of pure hydrocarbons which might be used in aviation fuel. The NACA interest in fuels began at a relatively late date and this interest in the main was the result of the full-scale work with isooctane. While the NACA did not develop an early interest in pure hydrocarbons, it had, at an early date, explored combustion in engine cylinders by high-speed photographic methods and had sponsored combustion research at the National Bureau of Standards and elsewhere. With the formation of Project 45 the NACA project was coordinated with it to avoid overlapping. Lovell and co-workers in 1934 had shown triptane (see Appendix on Hydrocarbons) to be a great deal better than the octane of the octane scale.

Further tests of triptane in small laboratory engines of somewhat different type and having different operating conditions from those used by Lovell showed triptane to be only slightly better than octane. In 1938 a quantity of triptane sufficient for test in a supercharged engine of laboratory type was made and tested by the Ethyl Corporation and gave the same answer as found by Lovell; from this time triptane was regarded as the last word in high PN aviation fuels. Further work on triptane is discussed below in approximate chronological order.