CHAPTER II

Essential Properties of a Fuel for Aircraft Engines

A FUEL for an aircraft engine is a material which will produce mechanical energy, and it is almost essential that it produce a maximum of energy per unit weight. For this reason fuels for aircraft engines consist almost exclusively of compounds of carbon with hydrogen, known as hydrocarbons. Hydrocarbons of suitable type containing small amounts of impurities and relatively small additions of nonhydrocarbon materials have constituted more than 99% of all aviation fuel used up to 1949. During World War II wood and grain alcohols mixed with water were used to considerable advantage as supplementary fuels but were carried in a separate fuel system and were not mixed with the regular hydrocarbon fuel until they were added to the air going into the engine. Ethers similar to anesthetic ether are the only nonhydrocarbon materials which appear to be capable of completely replacing hydrocarbons as aircraft engine fuels, but the use of ethers would involve a significant increase in the weight of fuel which would have to be carried.[1]

[1]The introduction of the chemistry of fuels into the discussion seems unavoidable since understanding of this chemistry has been the major cause of advancement in aviation fuels. The author, having only an elementary high school training in chemistry, thoroughly understands the mental confusion of the layman when confronted with hydrocarbon (organic) chemistry. Aviation fuels made practically no progress until the engineer began to have an elementary understanding of their chemistry. Before this time the fuel chemist who unquestionably understood fuel chemistry (although not nearly so well as he thought he did) also thought that he understood engines. The fuel chemist has continued to think that he understands engines, a belief that is perhaps correct in the case of 0.1% of the chemists involved.

The engine development engineer has been partially successful in restraining the fuel chemist from appraising aircraft engine fuels in decrepit washing machine engines or in model aircraft engines. The engine development engineer in the early stages of his exposure to fuel chemistry is just as much of a layman in this respect as is an accountant. When the engine development engineer is in the stage where he has to listen in a state of frightened silence to the fuel chemist, little progress is made. When the engineer and the chemist each acquire an elementary knowledge of the other's arts (and they are mostly arts rather than sciences) they can then successfully jeer at each other and the march of progress is on. While

(*Footnote continued on next page*)

An aircraft engine, like an automobile engine, produces power by means of the expansion of heated air, and other things being equal the power produced will be proportional to the weight of air which is taken in, heated, and expanded.

Heating of the air so that it can be usefully expanded is accomplished by mixing hydrocarbons with the air taken in. The hydrocarbons when mixed with air are converted from liquid to gaseous form. The mixture of air with hydrocarbon gas is readily ignited by means of a spark. Ignition greatly increases the temperature of the mixture of air and fuel, and the increase of temperature considerably increases the pressure. The pressure is used to push a piston which thereby converts the heat energy in the fuel into mechanical work. While the heat energy in the fuel produces work, the air is an equally important part of the process since the energy in the fuel cannot be made available without air. The gas turbine aircraft engine used for both jet propulsion and propeller turbines also produces mechanical energy by the expansion of heated air.

Piston-type aircraft engines have, up to 1949, almost exclusively used a carburetor to mix the fuel and air, in this respect being identical with automobile engines. German military engines during World War II used a fuel injection system (see Schlaifer above, p. 538) which had a pump for each individual cylinder and injected the fuel into the cylinder head. A limited number of Wright R-3350 engines which had fuel injectors were built for the B-29 bomber, and it is understood that these engines were used in the bombing of Hiroshima and Nagasaki. Wright R-3350 engines equipped with fuel injection are now in fairly extensive use in both airline and military service.

The five most important properties of a fuel for an aircraft engine of the current piston type are as follows:

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there is nothing more amusing to the author than watching a chemist attempt to develop pistons, he is well aware that the engineers' understanding of chemistry is equally amusing to the chemist. The author, having suffered the labor pains involved when one tries to understand the elements of fuel chemistry and still being very much of a layman, has included in Technical Appendix B a discussion of hydrocarbons for the layman if he has sufficient curiosity to wish to go beyond the text of the main discussion (pp. 693-705).

1. Volatility

Volatility is a term defining the ease or otherwise with which the fuel vaporizes or assumes the gaseous form. Ease of vaporization is directly related to the boiling point of the fuel. Mixing fuel with air causes the fuel to boil and assume the gaseous form, the blend of fuel and air being known as "mixture." Gasoline is a mixture of compounds of low, medium, and high boiling points. The compounds present in aviation fuel boil at temperatures varying from 85° F to about 350° F. Material boiling above 275° F is usually present in less than 10% concentration. The low boiling materials promote ease of starting but cannot be present to an excessive amount without causing the fuel to boil in the fuel system before it reaches the carburetor. The amount of high boiling material is limited by the necessity for having almost all the fuel in vapor form by the time the spark occurs. The time between the instant when the fuel leaves the carburetor jet as it is sprayed into the air until the spark passes in the cylinder usually occupies a period of less than 1/16 second, and any fuel still in liquid form at the time the spark passes will be wasted and in addition may damage the engine.

The mixture is transferred from the carburetor to the cylinders by a system of pipes known as the induction system. The mixture in the induction system usually contains some unevaporated or liquid fuel, and if because of low fuel volatility, low mixture temperature, or unsuitable design of the induction system, the amount of liquid fuel received by various cylinders varies widely, engine performance is seriously penalized and the engine is said to have bad distribution. Other factors being equal, the more volatile the fuel the better the distribution.

Volatility is given the most important place among the properties of an aviation fuel, since if the fuel is not sufficiently volatile to form a mixture which will burn, the other properties are unimportant. Obviously, correct volatility will be unimportant if the other properties result in wrecking the engine.

2. Knocking Properties

The automobile driver is usually acquainted with the knock or ping sometimes emitted by his engine when he "steps on it" at low speed. Knock in an automobile is rarely more than an inconvenience to the driver but, if very heavy, is an indication that the fuel is limiting the power output of the engine. Knocking also occurs in aircraft engines but is much more serious than it is in automobile engines. Knocking cannot be allowed to persist in aircraft engines for more than very brief periods since it causes mechanical damage and also causes the temperature of the cylinders and pistons to reach unsafe limits. Knock may be described as combustion of the fuel-air mixture which has become uncontrolled. There is another form of uncontrolled combustion which occurs in both automobile and aircraft engines and which is known as preignition from the fact that the fuel-air mixture in the cylinder spontaneously ignites before the passage of the spark. Preignition is not an important problem in automobile engines but in aircraft engines is very destructive and dangerous.

The Combustion Process in Engines

For even a very elementary discussion of knocking a discussion of the manner of burning fuel in an engine appears to be necessary. All important aircraft engines operate on the four stroke or "Otto" cycle which requires four strokes of the piston in the cylinder (two up and two down) to complete the combustion process. Most modern aircraft engines have a top operating speed of about 3,000 rpm which means that in any one cylinder the combustion cycle is completed 25 times per second.

In the four-stroke cycle the piston moves outward from the cylinder head, filling the cylinder with mixture through the open intake valve. The intake valve then closes and the piston moves toward the cylinder head, compressing the mixture which is ignited by the spark plug just before the piston reaches its closest point of approach to the cylinder head. The piston then moves away from the cylinder head, being pushed by the high pressure hot mixture. Just before the piston reaches its

greatest distance from the cylinder head the exhaust valve opens and the hot gases at a pressure of between 50 and 200 psi start to escape from the cylinder to the atmosphere. The piston reaches its outermost position and then starts to return toward the cylinder head, and when it reaches its innermost position in the cylinder the exhaust gases have been expelled, completing the fourth piston stroke, the exhaust valve then closes, and the cycle starts over again.

Compression Ratio

When the piston compresses the mixture on the second stroke, it does so into a space known as the clearance volume. If the clearance volume is 20% of the volume displaced by the piston, the ratio:

$$\frac{\text{piston volume} + \text{clearance volume}}{\text{clearance volume}} \text{ is } 6 \text{ (or } \frac{1 + 0.2}{0.2}\text{)}$$

and is known as the compression ratio. If the clearance volume is 10% of the volume swept by the piston, the compression ratio becomes 11 to 1. The higher the compression ratio, the greater the tendency for knocking with a given fuel. The general public is well acquainted with the term "high compression" as applied to automobiles.

The pressure of the air in the induction system has a marked effect on the tendency to knock. In the automobile engine the maximum pressure which can exist in the induction system is a slight vacuum whereas in military service aircraft engines a pressure of 30 psi is used and this pressure is produced by a supercharger (see Schlaifer below, pp. 668-671). The power of an engine is proportional to the weight of air burned, and increasing the pressure in the induction system from a slight vacuum to 30 psi results in the production of almost four times as much power. In general, the tendency to produce knocking varies almost in proportion to the pressure in the induction system.

The knocking properties of aviation gasolines have varied very widely, and gasoline used in World War II was nearly four times as good in this respect as the gasoline used in World War I.

The problem of controlling and describing the knocking properties of fuels is a very complex one. No satisfactory method of determining knocking properties without the use of an engine has ever been evolved. Added to the difficulty and complexity of the problem is the fact that two fuels of equal knocking property in one engine operated with a given engine condition may be quite different in knocking property when the engine conditions are changed. Fortunately, a basic standard in the form of a system of standard fuels has been available for measuring and expressing knocking properties, and by the use of this standard in conjunction with a suitable engine and appropriate engine conditions fuels for aviation engine use can be satisfactorily specified and manufactured.

While it is not possible to express the knocking property of a fuel without an engine, the use of an engine alone to rate the fuel in terms of some engine function (such as the amount of compression ratio or induction system pressure that the fuel requires to produce knocking) does not suffice. A given engine will vary from day to day and place to place, and two ostensibly identical engines will give different answers in the same place and on the same day. By the use of standardized engines with standardized engine operating conditions, however, and a system of standard pure chemicals which can be blended into fuels having the same knocking tendency as the fuel being tested, it is possible to express the knocking property of any fuel in terms of the pure fuels and the engine conditions in such a manner that variations of engines with time and place become largely unimportant. The standard fuel system consists of blends of heptane and isooctane expressed as octane numbers; the general public is familiar with octane numbers of automobile gasolines. For fuels which have knock properties too high to rate in terms of octane number, isooctane plus tetraethyllead is used. Heptane, isooctane, and tetraethyllead will be discussed in more detail later as the development of aviation fuel is explored.

Neither octane numbers nor ratings in terms of isooctane plus tetraethyllead are direct measures of engine performance; therefore Performance Numbers, which are almost a direct measure of engine performance, will be used hereafter for ex-

pressing fuel knocking properties rather than ratings in terms of octane number and isooctane plus tetraethyllead (hereafter lead). Examples of the relation of octane number, lead in isooctane, and Performance Numbers to engine performance may be quoted to show why Performance Numbers (hereafter PN) are used rather than the other ratings. Consider fuels having ratings of 72 and 100 octane number and isooctane + 1 cc lead and isooctane + 6 cc lead.[2] These fuels have Performance Numbers of 50, 100, 125, and 161 respectively. In a supercharged engine the 40% increase of octane number from 72 to 100 permits a 100% increase in power. In the case of the fuels with ratings of isooctane + 1 cc lead and isooctane + 6 cc lead, a 500% increase in lead content permits only a 30% increase in power. Doubling the PN, i.e., from 50 to 100, will permit the compression ratio to be approximately doubled if the manifold pressure is kept constant. Doubling the compression ratio will increase the power by approximately 25% and reduce the fuel used per horsepower by approximately 20%. Knocking properties have been and will be further extensively discussed since it is this property of aviation fuels which has changed most with the passage of time, and it is the property which has been most responsible for engine development.

3. Energy Content

The performance of aircraft is always limited by the maximum permissible weight of the aircraft at which flight can be sustained. Thus, the weight of fuel which must be carried to accomplish a given mission is obviously important. Possible fuels for aviation use vary greatly in the amount of heat energy they contain per unit weight. Thus, the hydrocarbon fuels which are best in this respect contain about twice as much energy per unit weight as does wood alcohol and almost twice as much per unit volume. A bomber can carry out a specified mission carrying 10 tons of good hydrocarbon fuel and 10 tons of bombs; it would need 20 tons of wood alcohol to fly the same

[2]Lead concentrations in cubic centimeters tetraethyllead per U.S. gallon; this is the usual abbreviation in the United States. The British and the Canadians also abbreviate to cc lead but in this case the Imperial gallon is involved.

distance and thus could carry no bombs so that the mission would be useless.

Hydrocarbon fuels vary somewhat in their energy content. While this variation among hydrocarbons which can be used is less than 10%, it is nevertheless significant. In considering the energy content of fuels it is important that this property be compared for fuels of equal PN since a fuel of very low PN, such as the heptane used in the octane scale, would be unable to turn its high energy content effectively into mechanical work.

4. Stability

The stability of a fuel is a term covering maintenance of its properties as originally manufactured with the passage of time. For instance, an unsuitable hydrocarbon fuel may be partially converted from a liquid to a solid, may have its PN very greatly reduced, and may develop a most unpleasant and sickening odor. Synthetic rubber is composed of unstable hydrocarbons which readily turn from liquids to solids.

An unstable fuel may wreck an engine because of low PN or may stop operation by plugging the induction system with rubbery materials.

5. Freezing and Carburetor Icing

The temperature at which a fuel freezes (i.e., starts to form solids as the temperature is lowered) is important since the fuel may be cooled to a temperature below −60° F on the ground and still lower atmospheric temperatures may be encountered in flight. As a result of these requirements, fuel for aircraft engines is generally required not to start freezing at a temperature above −76° F. Benzol is the outstanding example of a fuel which is limited for aviation use by its freezing point. Pure benzol freezes at about +40° F and not more than about 20% can be blended in gasoline if the blend is to meet a freezing point requirement of −76° F.

In the 1920's and earlier a considerable amount of trouble was encountered with formation of frozen material in the air passages of aircraft engine carburetors. This frozen material resembled ice but was quite often considered to be frozen fuel,

and when benzol was blended in the fuel the solid material at times did contain some benzol. Accumulation of ice in carburetors proved to be exceedingly dangerous in flight since it often caused engine stoppage and a forced landing or a crash.

In the early 1930's an epidemic of carburetor freezing experienced by the Army, which temporarily grounded a large number of aircraft, resulted in proving that freezing of the fuel in the carburetor was not the cause of the difficulty. It was found that the ice resulted from freezing of water in the ingoing air and that this trouble could be at its worst in the early summer when the amount of moisture in the air was much higher than in winter. When mixed with the air, the fuel evaporates and in so doing lowers the temperature of the air. The more volatile the fuel, the more rapidly it evaporates and the more rapidly it cools the air. If the fuel is very volatile, it will be completely evaporated in the carburetor and thus produce the maximum tendency to carburetor icing. If the fuel is less volatile, it will be only partly evaporated in the carburetor and evaporation will be completed after the fuel-air mixture has left the carburetor; in many cases this delayed evaporation avoids ice formation of a type which will cause trouble. The Army trouble was cured by use of less volatile gasoline, and since that time aviation fuel specifications have contained a requirement that fuel shall not be too volatile. The first known Army difficulty with very volatile gasoline led the author to think that the trouble was due to fuel boiling in the fuel system. As a result of this thought a Reid vapor pressure requirement was added to the specification, this being the first time such a requirement had been embodied in an aviation fuel specification. Wide service use of very volatile gasoline of controlled Reid vapor pressure by the Army resulted in repetition of the earlier trouble which was finally found to be due to carburetor icing rather than to fuel system boiling (vapor lock). The author still regards this faulty diagnosis with considerable amusement, even though the addition of a Reid vapor pressure requirement proved to be desirable and is now a standard feature of all aviation fuel specifications.

When the carburetor freezing epidemic was encountered by the Army, aircraft engine carburetors were basically similar to those then and currently used on automobiles. As a result of difficulty with freezing of these carburetors in both civil and military aircraft, nonicing carburetors were developed in the early 1930's (see Schlaifer above, Chapter XVIII) and largely eliminated freezing due to evaporation of fuel. Choking of the carburetor and induction system with ice due to flight under conditions which form ice on the wings and other external parts of the aircraft structure can still occur with nonicing carburetors. This type of induction system icing can be avoided in most aircraft by picking up the carburetor air from a spot on the airplane where the air has been separated from the ice-forming constituents.