EO 45-5A-2

(FORMERLY EO 45-5-2)

ROYAL CANADIAN AIR FORCE

RCAF FUELS SPECIFICATIONS USE & DISPOSITION

ISSUED ON AUTHORITY OF THE CHIEF OF THE AIR STAFF

20 JUN 53

LIST OF RCAF REVISIONS

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FOREWORD

This Engineering Order has been prepared to provide information concerning the more important properties of RCAF fuels, and covers in particular those properties which are of most interest to the user Units.

The discussion largely deals with the effects of fuel properties on engine performance. The effects of engine design and engine operating conditions on fuel behaviour are also covered briefly.

Detailed discussion concerns only aviation fuels and engines except in the rare cases where other types of fuel and engine are specifically mentioned.

CROSS-REFERENCED ENGINEERING ORDERS

EO 45-1-2	SPECIFIED AND ALTERNATE GRADE FUEL AND OIL FOR AIRCRAFT ENGINE COMBINATIONS
EO 45-1-4	RCAF PETROLEUM AND ASSOCIATED PRODUCTS WITH US AND BRITISH EQUIVALENT

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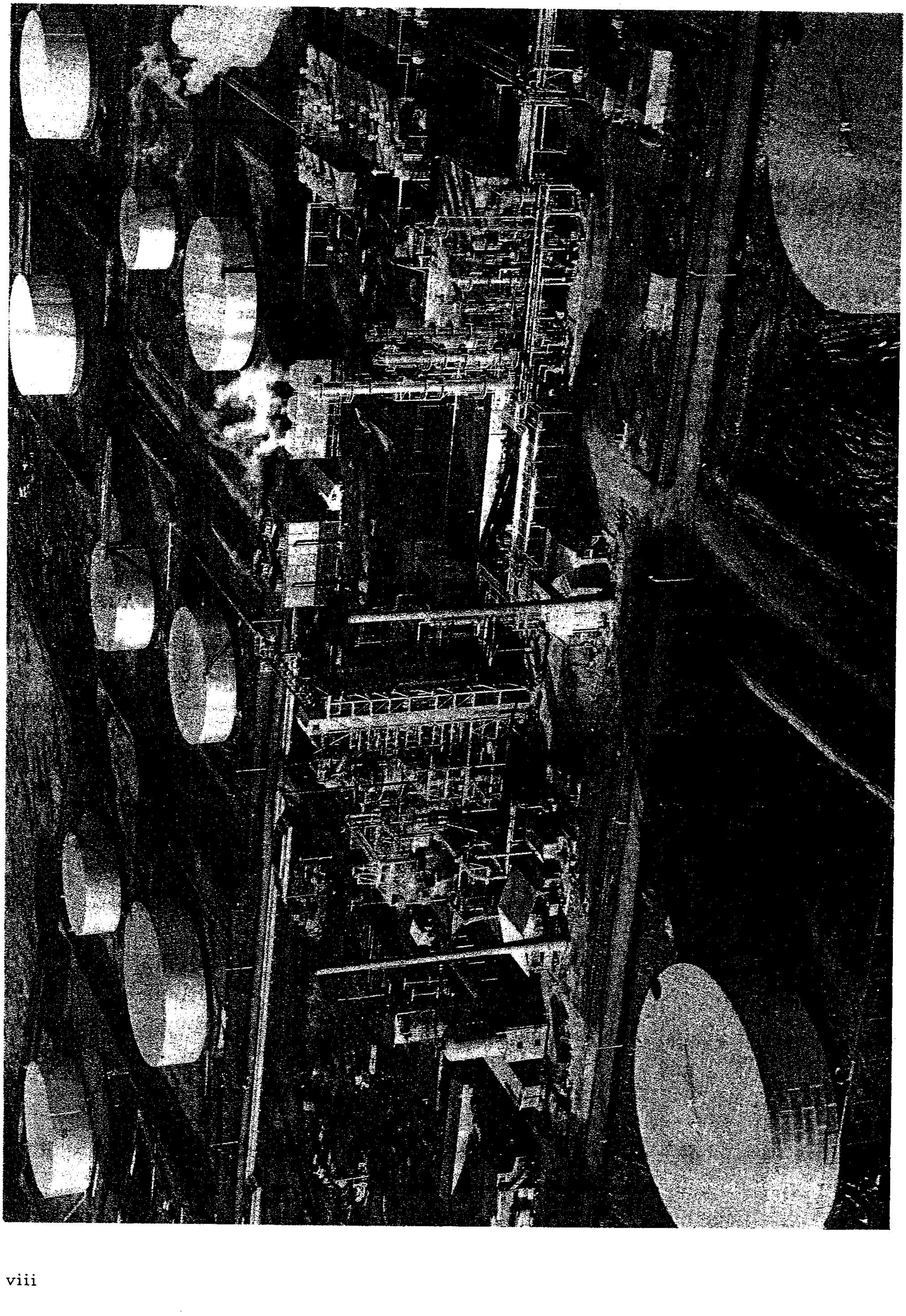


AERIAL VIEW - MONTREAL REFINERY
SHELL OIL COMPANY OF CANADA LTD., MONTREAL

PART 1

AVIATION GASOLINE

COMBUSTION

1 Combustion or burning, in a chemical sense, is the combination of one or more elements with oxygen which results in the formation of oxide of the elements, accompanied in all cases by the liberation of heat. The heat produced is the result of a chemical reaction which converts the potential (stored up) energy in the fuel heat which, in turn, can be utilized inside a closed cylinder and be partially converted into kinetic energy (energy of motion). Energy may be transferred and transformed in many ways, but it is never created or destroyed. Fuel must evaporate first before it will burn.

OXYGEN

2 Oxygen (O), essential to combustion, comprises approximately 20 percent of air by volume. The remaining 80 percent is chiefly nitrogen, a very inert gas, which does not enter chemically into the process of combustion Oxygen, a very active gas, will combine with a great number of elements and compounds; in each instance, the amount of heat liberated depends on the chemical nature of the substance involved. Hydrogen and carbon, alone or in any of their various combinations, produce large quantities of heat when burned and constitute our most important fuels for the production of heat and power.

HYDROGEN

3 Hydrogen (H) is a very light and highly inflammable gas. When mixed with air and ignited, it combines with oxygen to form the oxide H_2O (water). The combustion of pure hydrogen is a very rapid process which, if confined, may produce a very high pressure.

CARBON

4 Carbon (C) is a solid existing in three forms: the familiar carbon present in soot or lampblack, graphite, and the diamond. Although differing in physical properties, these are all pure carbon and, under proper conditions one form could be converted into another without any change in chemical structure. At a very high temperature, carbon will pass from the solid into the vapour state. Carbon in its natural state does not exist as a liquid. When ignited in a plentiful supply of air or oxygen, carbon burns with a clear flame to form carbon dioxide (CO_2), an inactive and harmless gas. However when the supply of oxygen is insufficient (rich mixture), a certain quantity of carbon monoxide will also be produced. Carbon monoxide is a poisonous gas which may cause death when present in the air to the extent of only four parts in 10,000 (0.04 of one percent) by volume. The gas is colourless and odourless; thus it gives practically no warning of its presence.

5 As fuels, hydrogen and carbon are seldom available in their natural state; they occur in combination with each other, to form compounds known as hydrocarbons (CH group). Many thousands of these compounds exist, and all are classed as fuels. These hydrocarbons are present in large quantities in coal and petroleum as solids, liquids, and gases.

6 Crude petroleum, because of its abundance and the many products which may be extracted from it, has become our most important source of hydrocarbon compounds for internal-combustion engine fuels and lubricants. Although crude samples from different production fields usually vary in composition, all crudes are made up of a great number of hydrocarbon compounds arranged in groups. The paraffin series is the most common in North America. The chemical nature of petroleum is so complex that complete analysis rarely is attempted. However, the crude may be separated into fractions by distillation to produce the desired commercial products, including gasoline, kerosene, and lubricating oil.

AVIATION GASOLINE

Gasoline is a blend or mixture of hydrocarbon liquids ranging in boiling point from approximately 32° to 218°C (90° to 425°F). No exact limits are established for this mixture range. Because of the latitude in boiling point and various other characteristics, it is impossible to list the detailed specifications of gasoline but a general composition of fuel is shown in Figure 1-2. Any sample must be subjected to a number of tests before its exact properties can be determined. Only after such testing can a gasoline be pronounced satisfactory for use as a fuel in a particular type of internal-combustion engine.

PRODUCTION PROCESSES

8 Of the many methods employed for producing gasoline, three are sufficiently important to warrant a brief description of the apparatus and procedure involved. These are the fractional distillation process, the cracking process, and the absorption process, described in the following paragraphs.

9 The fractional distillation process, the first to be developed, produces what is known as "straight run" gasoline. By this process the crude is heated to a moderate temperature in a retort to vapourize progressively the various hydrocarbon liquids. The lighter and more volatile compounds are first vapourized, followed in order by those of progressively higher boiling points. These vapours are then led through condensers, which return them to a liquid state. By proper regulation of the vapourization and condensation, the hydrocarbons are separated into various "fractions" or component parts (such as gasoline, fuel oil, lubricating oil, etc.), although further treatment and purification are often necessary. The fractional distillation process is accomplished at atmospheric pressure and during the process no effort is made to change the chemical nature of any of the fractions.

10 The cracking process is employed principally as a means of increasing the yield of gasoline from a given amount of crude. Petroleum fractions which are neither suitable for gasoline nor lubricating oil very often may be cracked, thus obtaining a considerable quantity of gasoline. The cracking process is a form of destructive distillation in which the crude, or a portion of it, is placed in a sealed retort and subjected to a high temperature and high pressure. These conditions serve to break up the chemical arrangement of the heavy hydro-carbon molecules and partially convert the heavier products into cracked gasoline. The fuel thus produced often is superior to many grades of straight run gasoline in antiknock value but requires thorough refining to make it suitable for storage. The reason for this is that cracked hydrocarbons, which are chemically olefins and diolefins, produce gum on ageing. Some types of cracked gasoline may be stabilized or inhibited from gum formation by the addition of a small quantity of a suitable anticatalyst. A high percentage of the total gasoline production at present is the result of the cracking process.

11 The absorption process is the most common method of obtaining a fuel of comparatively high volatility, known as casing-head or natural gasoline, from natural gas. The gasoline is extracted from certain compounds present in the natural gas by forcing it through a heavy oil which absorbs the liquid content of the gas. The oil is then distilled to reclaim the light fraction, which is gasoline. If properly blended with a straight-run or cracked gasoline, it is quite satisfactory as an engine fuel.

PROPERTIES OF AVIATION GASOLINE

12 There are a number of properties of gasoline which affect engine performance and design. Five of the most significant are listed below, and will be discussed in subsequent paragraphs. However, these are not the only properties of gasoline which are of significance, and the order of importance is not a hard and fast rule.

(a) Anti-knock value.

(b) Volatility

(c) Vapour locking tendency.

(d) Stability.

(e) Solvent and corrosion properties.

ANTI-KNOCK VALUE

Definition

13 The anti-knock value of a fuel is defined as the resistance the fuel has to detonation. Some gasolines have better anti-knock performance, or good detonation resisting qualities, when compared with other fuels under similar operating conditions.

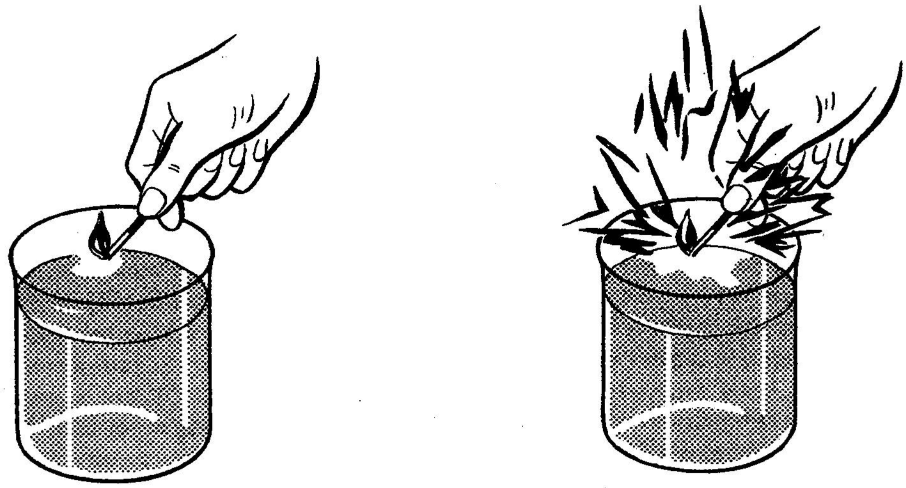


Figure 1-1 Fuel Must Evaporate To Burn

14 Detonation or "knocking" occurs when the temperature of the unburned charge of fuel is raised so high that it ignites spontaneously and combustion occurs almost instantaneously with a flame velocity near 1,000 feet per second, the normal rate of flame velocity is 60 feet per second. The cylinder walls and piston receive this hammer like blow, creating a pressure rise too great to be accommodated by the moving parts of the engine. Finally, the energy is released as heat rather than mechanical power. It has been found that detonation is similar to an explosion in the cylinder, see Figure 1-3.

ANTI-KNOCK COMPOUNDS

15 To combat this undesirable quality of some fuels, certain methods of increasing the effective anti-knock ratings of a gasoline are outlined.

(a) Choice of hydrocarbons with high anti-knock ratings.

(b) Use of additives to the gasoline which have been found to improve anti-knock performance.

(1) Metallic compounds.

(2) Aromatic Amines, (chemical combinations of aromatic hydrocarbons with ammonia).

(3) By cooling the charge in the cylinder, (water injection).

TETRAETHYL LEAD

16 The metallic compound additive commonly used to improve the anti-knock rating of gasoline is tetraethyl lead (TEL). The mixture added to Aviation Gasoline is called Ethyl Fluid, which consists of TEL, ethylene dibromide, dye, and an inhibitor (against gum formation), see Figure 1-4). The ethylene dibromide is added to prevent the formation of lead oxide, which not being volatile, tends to deposit on the combustion chamber, valves, and spark plugs of the engine.

17 The effect of this addition is that during the combustion of leaded fuel, the ethylene dibromide combines with the lead oxide to form lead bromide which is volatile at the combustion

temperatures. Thus, most of the lead is carried away in the exhaust gases in the form of lead bromide. Ethylene dichloride is sometimes used in place of ethylene dibromide in motor fuels. Ethylene dibromide and ethylene dichloride or referred to as a "scavenger". They are added to ethyl fluid in the exact amounts theoretically required to combine with all the lead in TEL.

18 One of the main difficulties with tetraethyl lead and ethylene dibromide scavenger is their different vapourization points. At low charge temperatures, ethylene dibromide is vapourized with the more volatile fractions of the fuel, while TEL remains with approximately ten per cent of the fuel, which is less volatile, and collects as liquid droplets on the induction pipe. Although gases may be distributed evenly between the cylinders, liquids are not. Therefore, certain cylinders receive greater quantities of this TEL liquid fuel and only the normal distribution of the scavenger. This excess of TEL in some cylinders creates plug fouling, the excess of the scavenger in the other cylinders results in exhaust valve corrosion. To overcome this condition, an investigation to develop alternate lead scavengers, such as tricresly phosphate, with a vapourization point nearer to that of TEL is promising. At any temperature above 40°C (104°F) there is no liquid fuel present in the induction pipe.

19 TEL content in fuel is expressed in millilitres per Imperial Gallon, in the abbreviated form mls./IG TEL can only be added to gasoline in limited quantities. The first millilitre added improves the octane number by a certain amount, the second a smaller amount and so on, see Figures 1-4, 1-5, 1-6 and 1-7. Therefore, there is a limit to the amount of TEL which can usefully be added to a gasoline, this is known as lead response. Some types of impurities, such as sulphur, present in gasoline decrease its lead response.

20 Other metallic anti-knock agents have been used with less effect than TEL. These are iron and nickel carbonyl, which are unstable and unsuitable for long term storage.

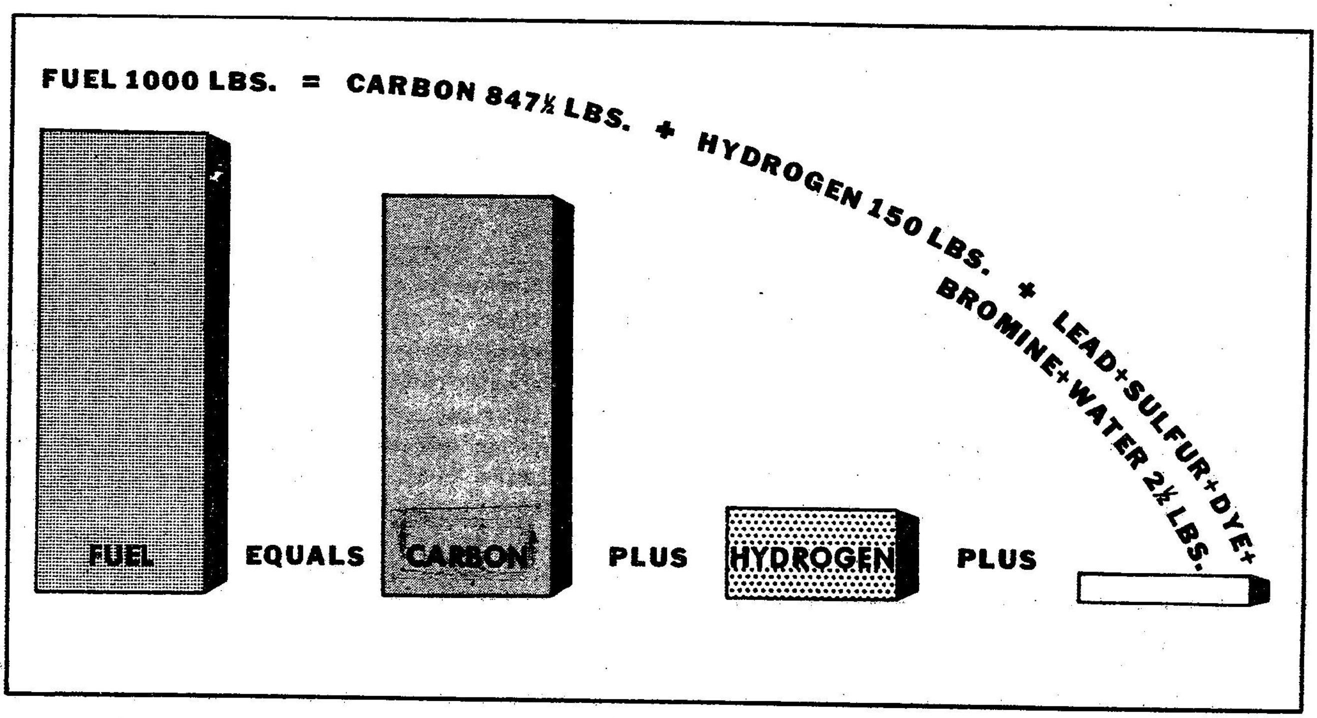


Figure 1-2 Fuel Composition

OCTANE AND PERFORMANCE NUMBER RATINGS

21 "Octane" and "Performance Number Rating" are terms universally used to designate the anti-knock value of the fuel mixture in an engine cylinder. Modern aircraft engines of high power output have been made possible principally as a result of the blending of fuels of high octane rating. The use of such fuels has permitted increases in compression ratio and manifold pressure, with resultant improvement in engine power and efficiency. However, even the high octane fuels will detonate under severe operating conditions or if certain engine controls are improperly operated.

22 Both the power output and the reliability of an aircraft powerplant depend to a great extent on the use of a fuel of sufficiently high anti-knock value or octane rating. The substitution of an inferior fuel, while permissible in certain emergencies, see EO 45-1-2, is attended by serious danger of detonation unless the engine is operated at reduced throttle. The cylinder temperature and the charge temperature on certain high powered engines are under the control of the operator within certain limits; neither reading should be permitted to exceed the maximum value specified for a particular engine.

23 Unfortunately, the whole problem of knock is exceedingly complicated and much has yet to be learned concerning it. However, in spite of the large number of unknowns, the problem in RCAF aircraft is under reasonably good control provided that the aircraft is operated on the grade of fuel which is specified or on a higher grade, and that engine operating conditions are held within the limits which are known to be safe, and which are covered by -1 Engineering Orders.

24 Aircraft engines in military use operate over a wide variety of conditions. One of the most important of the variables is the amount of fuel which is added to a given quantity of air. Under long range cruising conditions only six pounds of fuel may be added to each 100 pounds of air (lean mixture) whereas at take-off or War Emergency Rating eleven pounds of fuel per 100 pounds of air may be used (rich mixture). This relation of fuel to air is known as the fuel-air ratio and,

$$\frac{\text{60 lbs. fuel per hour}}{\text{100 lbs. air per hour}} = 0.060 \text{ Fuel/Air Ratio.}$$

25 At a given engine speed of, say 2400 RMP, it may be possible to safely take nearly twice as much power out of the engine at 0.11 fuel-air ratio as it is at 0.06 fuel air ratio because the rich mixture has less tendency to knock, see Figure 1-7, Some other factors having an influence on the tendency to produce knock are: engine speed, manifold pressure (boost), fuel grade, atmospheric temperature, spark advance, cylinder compression ratio, cylinder temperature (this can be directly determined in the case of air cooled engines, but in the case of liquid cooled engines can be judged only from the coolant temperature), grade of lubricating oil and oil consumption. In addition, the type of spark plug may markedly affect the tendency towards preignition.

26 Fuels vary extensively in octane and performance number rating and ability to produce power is more or less dependent upon this rating. When the fuel grade is 100 or less, this number indicates "octane number". If the number is 100 or above, it indicates the relative power that the engine can develop safely with equal knocking tendency and is known as Performance Number, see Figure 1-9. When the grade includes two numbers, such as Grade 100/130 or Grade 91/98, the first number indicates the rating at lean mixture conditions and the second the rating at rich mixture. Thus, Grade 100/130 indicates a lean mixture rating of 100 Performance Number (also 100 octane number) and the rich Performance Number indicates that the engine will develop 130 percent (1.3 times) as much power on this fuel under rich mixture conditions as it would on a fuel having a rich Performance Number of 100. Both the first and second figures in Grade 91/98 refer to octane numbers. It is unfortunate that the method of designating grade should shift from one scale to another. That is due to the fact that an octane number scale with an upper limit of 100 was sufficient until 1941; now fuels with ratings of more than 100 octane number under rich mixture conditions are in general service use, and a suitable method of designation was devised.

27 The following table lists the approximate rating ranges of the most common fuels.

(a) High output engine grade 115/145.

(b) Medium output engine grade 91/98 and 100/130.

(c) Low output engine grade 73 and 80.

AROMATIC AMINES

28 The action of the aromatic amines is similar to that of TEL although very much greater concentrations are required. However, since aromatic amines are basically fuels, and the products of combustion are non-corrosive, the quantities blended with gasoline have no deleterious effects.

29 Chemical combination of aromatics with ammonia produces substances known as "aromatic amines". A large number of such substances are known and some of them are powerful anti-knocks, whereas others are pro-knocks (the reverse of an anti-knock).

30 Aniline is the simplest of the aromatic amines and is an effective anti-knock but is not used since it is not soluble in current aviation fuels at low temperature. Two aromatic amines, namely xylidine and monomethyl aniline, were both used in limited military service in World War II but were never used in general service. Grade 100/150 fuel containing monomethyl aniline was used in the campaign against the German V-1 (buzz) bombs and permitted additional engine performance which enabled fighter aircraft to catch and shoot down the bombs. The same fighter aircraft could not catch the bombs when using Grade 100/130 fuel. Since the end of World War II fuels containing both xylidine and monomethyl aniline have been in limited military service use. Xylidine is produced by a chemical process which essentially consists of adding ammonia to xylenes. There are six possible xylidines but only five of these are present in commercially produced material. The properties of aniline, xylidine and monomethyl aniline are shown in Table 6. Three per cent of xylidine will increase the rich Performance Number of Grade 100/130 fuel by about 15%, namely, it will raise it to Grade 150. The addition of xylidine (or of monomethyl aniline) slightly reduces the lean rating and in the production of

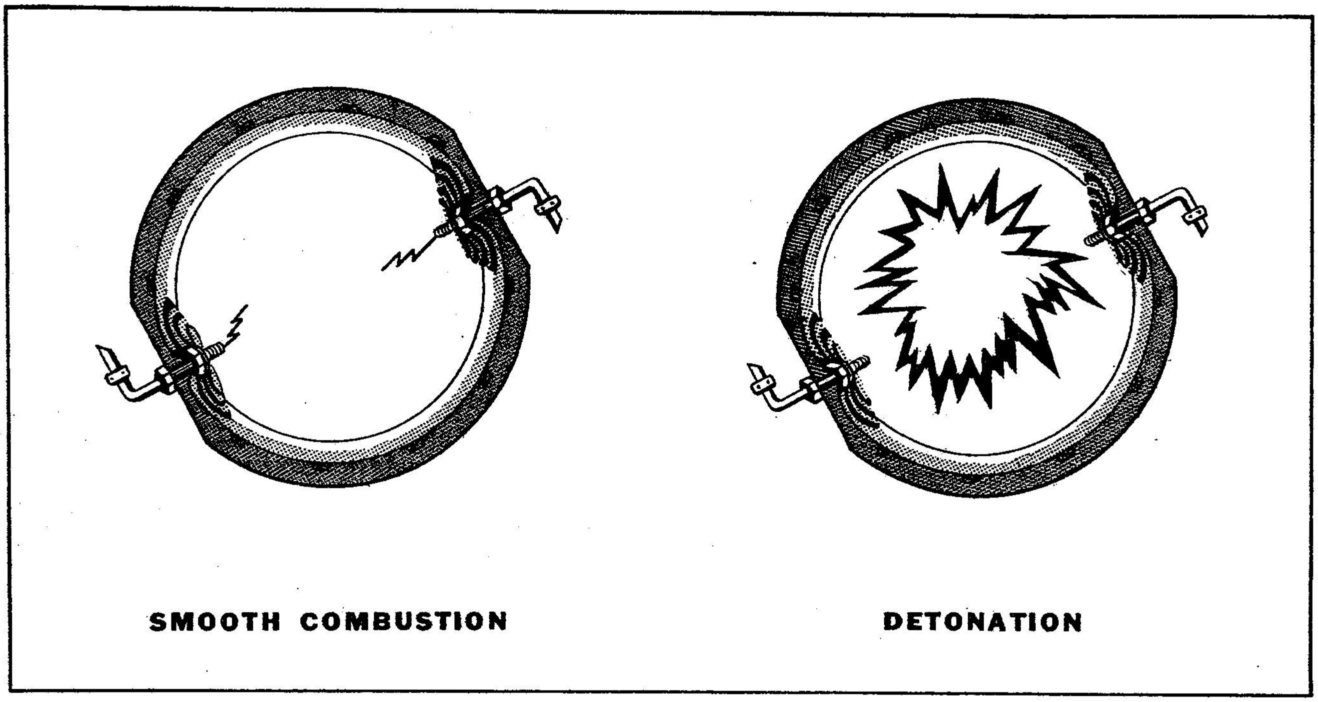


Figure 1-3

Grade 100/150 (not a common grade) containing 3% xylidine it was considered necessary to increase the lead from 4.6 to 6.0 ml. While it was considered necessary to add additional lead to restore the lean rating, it appears that this was only necessary as regards performance of full-scale aircraft engines. While Grade 100/150 will have 100 Performance Number under cruise conditions and 150 Performance Number under rich mixture conditions in some engines, there are some which will rate it at 150 Performance Number at lean cruise. It is commonly considered that aromatic amines are only effective anti-knocks at rich mixture but this is not the case. While, when added to Grades 100/130 and 115/145, thev are pro-knocks at the lean condition and anti-knocks at the rich condition, this pro-knock effect is due to the severity of the lean test method. When aromatic amines are added to some of the grades lower than 100/130, they do not produce a pro-knock effect at the lean condition. If the lean Performance Number of the grade is low enough the amines (xylidine and monomethyl aniline) then become effective anti-knocks and are so indicated by the laboratory knock test methods. Two and a half per cent of monomethyl aniline produces the same anti-knock effect as 3% xylidine. Both xylidine and monomethyl aniline produce "sensitive" fuels (namely, a large difference in lean and rich Performance Numbers). Since both xylidine and monomethyl aniline are materials of high boiling point they tend to aggravate distribution difficulties. Both xylidine and monomethyl aniline sharply increase the rich Performance Number of any fuel to which they are added, but at the same time they increase the preignition tendency. Thus, it often occurs that full advantage cannot be taken of the improved Performance Number of such blends since the increased engine output causes the cylinders to run hotter and results in preignition occurring before the knock limit of the fuel is reached. Use of such blends therefore generally requires modification in the engine installation and particular attention must be given to the spark plugs.

31 Both xylidine and monomethyl aniline are much more powerful solvents than any other components at present used in aviation fuel. This solvent action is particularly noticeable with rubber and synthetic rubber used in fuel system parts, and special rubber compounds may be needed for such parts.

EFFECTS OF FUELS ON RUBBER

32 Throughout the discussion above, ref erence has been made to the solvent effects (fuel components on rubber parts in the fue system of the aircraft. During World War the solvent effect of fuels on rubber fuel syster parts caused very severe difficulties whic resulted from the solvent effect causing th parts to swell so that they either became in operative or in some cases actually disinte grated. The difficulties were almost entirel due to a relatively high concentration of aroma tics. The troubles were most pronounced wit Canadian equipment since high aromatic con tents had not previously been in use in Canada The British and the Germans had previousl used fuels with up to 40% aromatics and conse quently had developed suitable rubber com pounds for use with such fuels. Subsequent t the end of World War II it has been found tha shrinkage of rubber parts may be a very seriou problem with fuels of low solvent power. Thus rubber parts which have been developed to avoi excessive swelling in a highly aromatic fue may shrink and cause leakage when used with fuel having a very low aromatic content, such fuel consisting almost entirely of paraffins The problem of rubber shrinkage causing leak age has proved to be particularly serious whe rubber is alternately exposed to fuels of hig and low solvent powers. Since the end of Worl War II the majority of the fuels of Grade 100 130 and Grade 115/145 have had very low aro matic content (in some cases below 5%) an most fuel used for civil use is of this type. T obviate the shrinkage difficulty some militar gasoline has been purchased with a minimur aromatic content of 10%. This has caused a increase of cost since the necessary aromatic cost more in peacetime than suitable paraffins In some cases aromatic amines have been adde to gasoline which were almost free of aromatic as a means of obtaining sufficient solvent powe to avoid rubber shrinkage. It has been foun that the paraffins vary significantly in thei effects in producing rubber shrinkage, iso octane being worse than normal heptane.

33 All fuel components have some effect (swelling, shrinkage or solution) on rubber but in some cases the concentration of the com ponent is too low to produce any significar effect. Rubber would be seriously affected b the bromine constituent of the lead anti-knoc compound if exposed to the straight compound

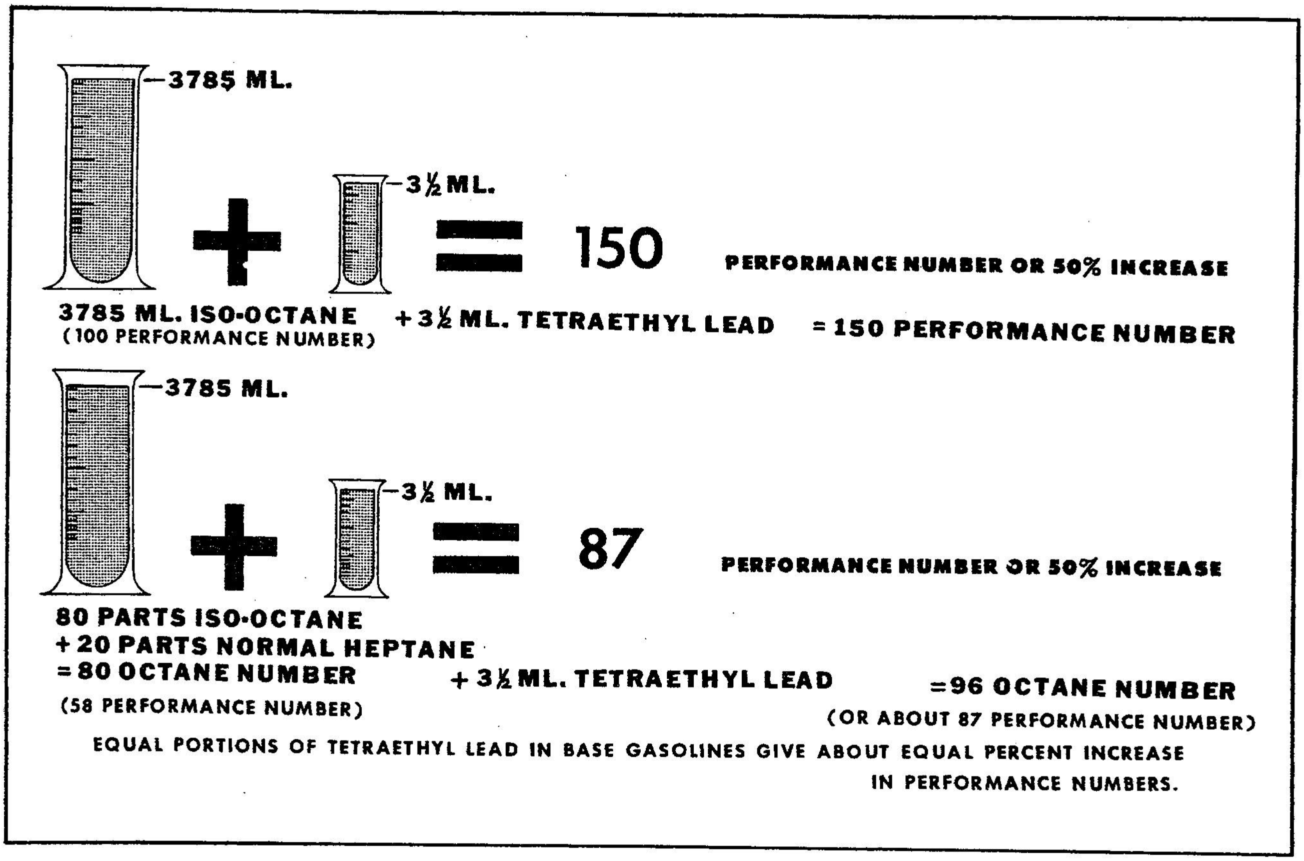


Figure 1-4 Performance Number Increase Due to Lead

but when the compound is diluted to the small concentration used in aviation gasoline, no effect is experienced.

34 Turbine engine fuels have the same general effects on rubber as gasolines, namely, shrinkage and swelling. There is some evidence that the rubber problem with turbine fuels may be more complex than it is with aviation gasolines, since the turbine fuels contain a greater variety of classes of chemical compounds as well as a much greater number of compounds of each class.

35 The problem of rubber parts exposed to fuels is exceedingly difficult. The rubber must neither shrink nor swell excessively when exposed to a wide variety of fuels such as low aromatic and high aromatic concentrations or blends containing aromatic amines. Rubber parts in the RCAF must withstand temperatures from -54°C to at least +74°C (-65°F to +165°F) without damage or loss of plasticity at the lower range.

Definition

36 Liquid fuels, that are used in internal combustion engines, must always be converted into a vapour state before combustion occurs. This property of a liquid which enables it to change readily into a vapour is known as "Volatility", a characteristic which may be determined by a distillation test and vapour pressure test.

VOLATILITY TESTS

37 In the distillation test, the gasoline is heated and vapourized at a constant rate. The boiling temperatures are recorded as the various percentages of fuel are recovered. These temperatures determine the volatility range between the initial and end boiling points of the fuel under test, see Figure 1-11.

38 The vapour pressure test is accomplished by sealing a sample of the fuel in a bomb equipp-

ed with a pressure gauge. The apparatus then is immersed in a constant temperature bath and the indicated pressure is noted. The higher the corrected vapour pressure obtained from the fuel under test, the more susceptible it is to vapour locking. Aviation fuels have a Reid Vapour Pressure of seven psi (maximum).

39 The volatility of a fuel is quite important in determining whether or not an engine can be started when cold. In this connection, it is well to know that gasoline is not combustible in its liquid form, principally because the molecules of the liquid will not readily mix with the oxygen of the air. However, gasoline vapour unites quite readily with oxygen resulting in very rapid combustion. Therefore it is quite evident that an engine fuel should be sufficiently volatile to form combustible vapour at low atmospheric temperatures.

VAPOUR LOCKING TENDENCY

Definition

40 Excessively volatile gasolines are ve troublesome, because they promote a conditi known as vapour lock. This condition is due vapour formation in the fuel lines which re stricts the liquid flow, resulting in a lean mi ture and the possibility of engine failure.

Causes

41 Another contributing factor to vapo locking is that atmospheric pressure decrease with altitude. Therefore, when an aircra climbs, air and fuel vapour tend to evolve fro the fuel in the tank due to decrease in pressure Reduction in temperature of the fuel decrease this evolution of vapour, but when an aircra climbs rapidly, very little cooling of the gaso line occurs by conduction and radiation to th surrounding air. Therefore an aircraft ma

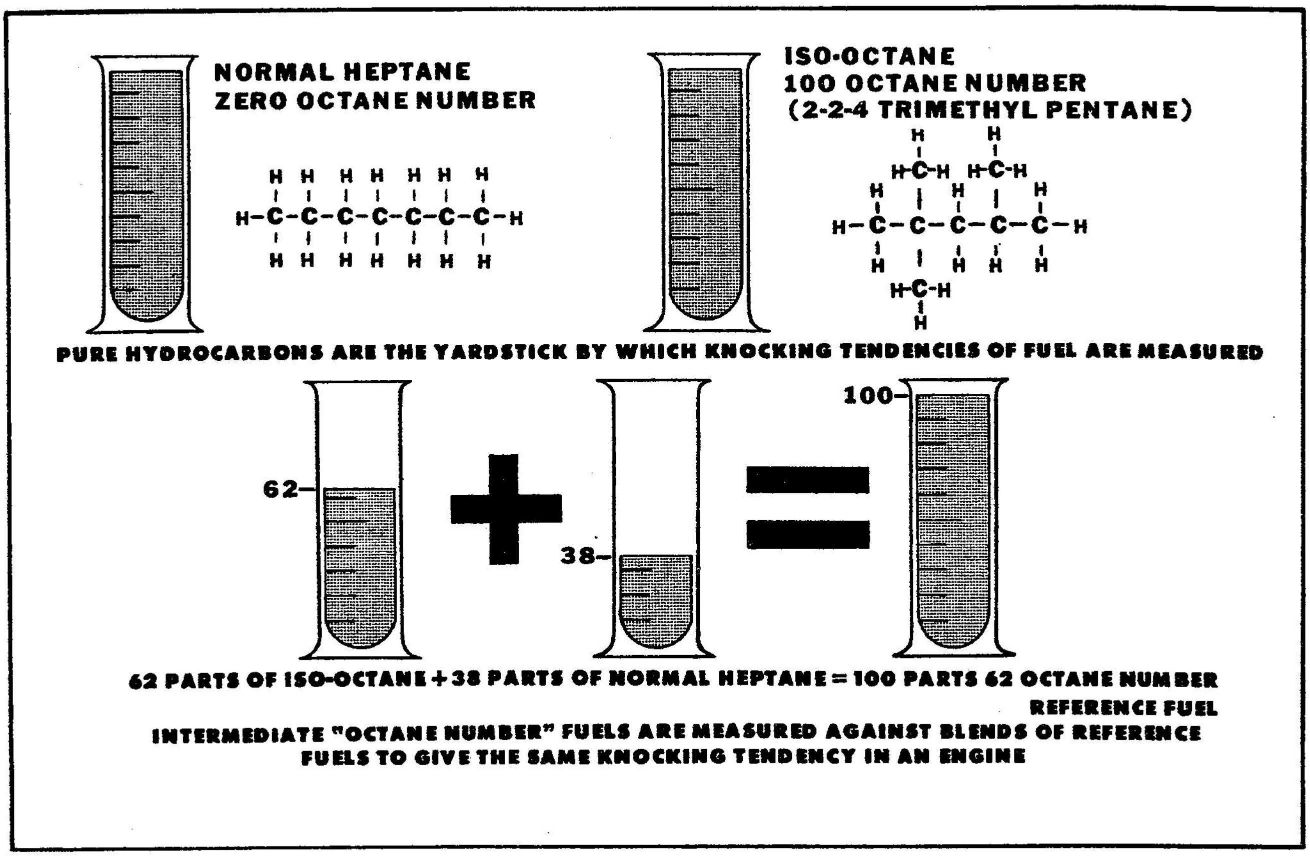


Figure 1-5 Matching Reference Fuels

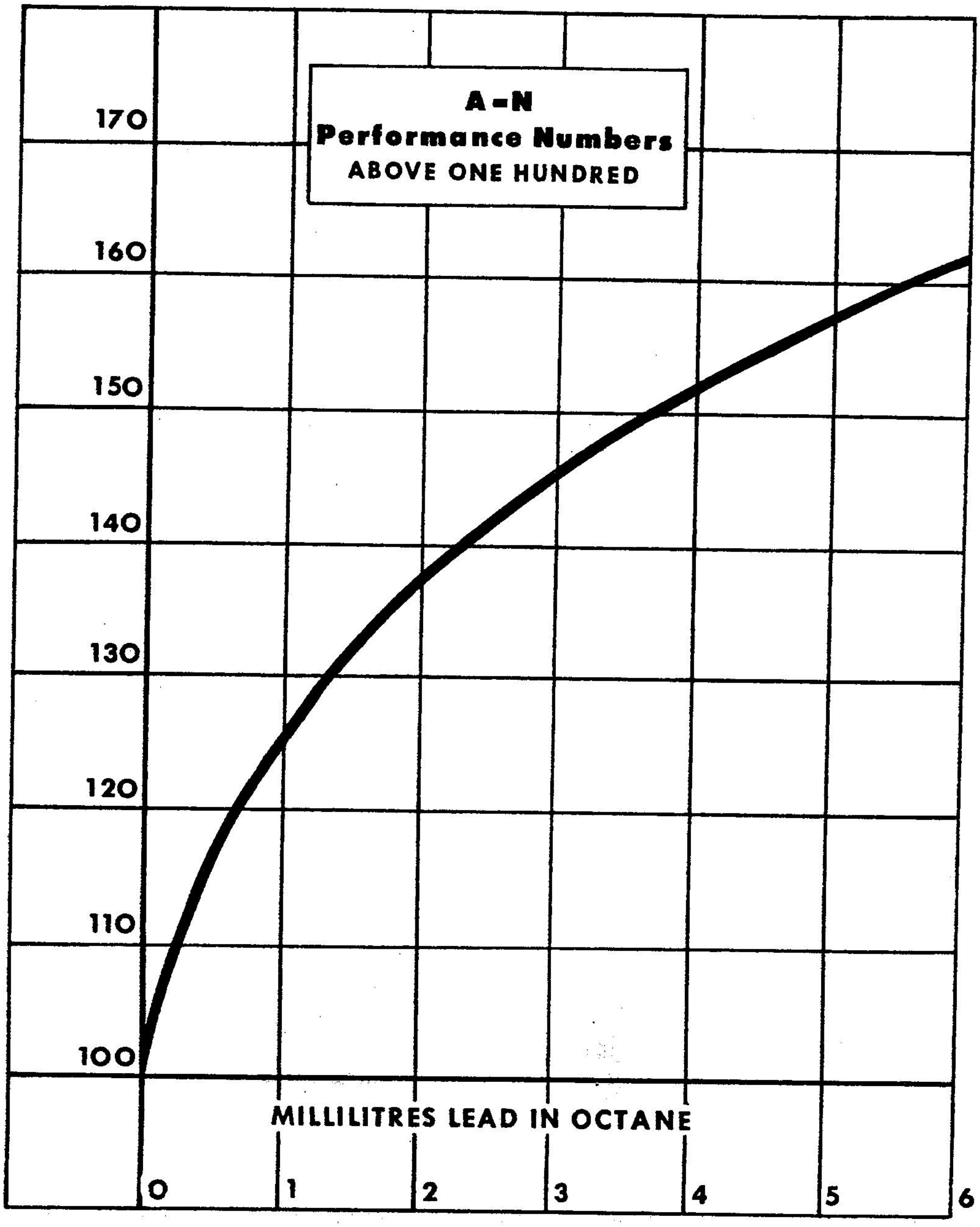
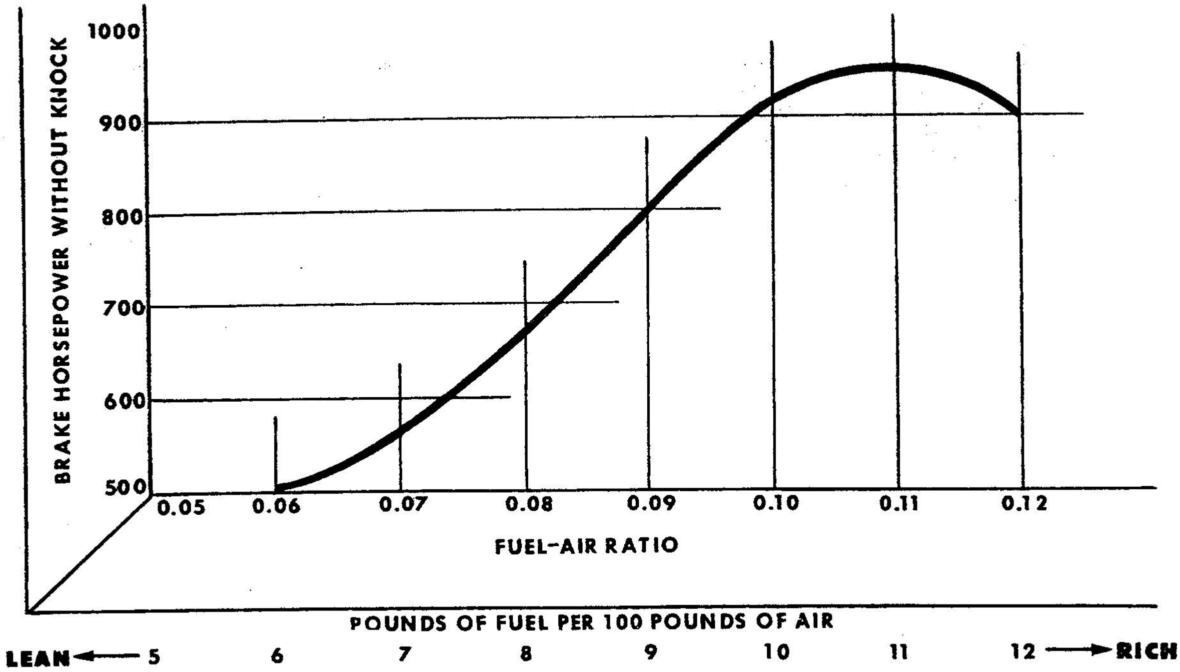

A-N
Performance Numbers
ABOVE ONE HUNDRED
170
160
150
140
130
120
110
100
MILLILITRES LEAD IN OCTANE
0
1
2
3
4
5
6

Figure 1-6



Under otherwise constant conditions such as: RPM, COOLING AIR TEMPERATURE, ETC., **the richness of the mixture determines the power an engine will develop without knock on a given fuel.**

Figure 1-7 Fuel-Air Ratio Curve

be flying at 35,000 feet with the fuel contents temperature near that at ground level.

42 In many cases vapour locking can be almost eliminated by the design of the fuel feeder system to the engine. This entails avoiding a suction head to the fuel pump, sharp bends in the fuel lines, and by design of the fuel pump with sufficient excess capacity so that it can deal with vapour.

STABILITY

Definition

43 Storage stability depends on the tendency of fuel to form gummy products in various types of bulk and container storage. "Gum" as referred to here applies to a colourless or yellowish deposit which is sometimes left as residue when gasoline is completely evaporated. It may cause deposits in the intake manifold and cause sticking of the inlet valves and any moving parts in the fuel system. Aviation gasoline fresh from the refinery usually contains negligible amounts of gum. When the gasoline is stored gum may form; the degree of gum formation depending on the nature of the gasoline and the conditions of storage. High atmospheric temperatures and exposure to air hasten gum formation, which is more rapid in small containers like tins and drums than in large storage tanks, owing to the greater ratio of surface area to volume in the former case. Exposure to light may cause gum to form more rapidly in a gasoline. The formation of gum is due to oxidation and polymerization of unsaturated hydrocarbons in the fuel.

44 Unsatisfactory storage stability may also appear in the form of white compounds in the fuel. This is precipitation of a lead compound of the TEL. This condition, if not excessive, is not dangerous, but usually indicates that something else is wrong. This white powder, if it causes sneezing after drying, is very poisonous and should be kept wet with kerosene or oil while it is being removed. The powdery deposit has only a slight effect on the properties of the fuel.

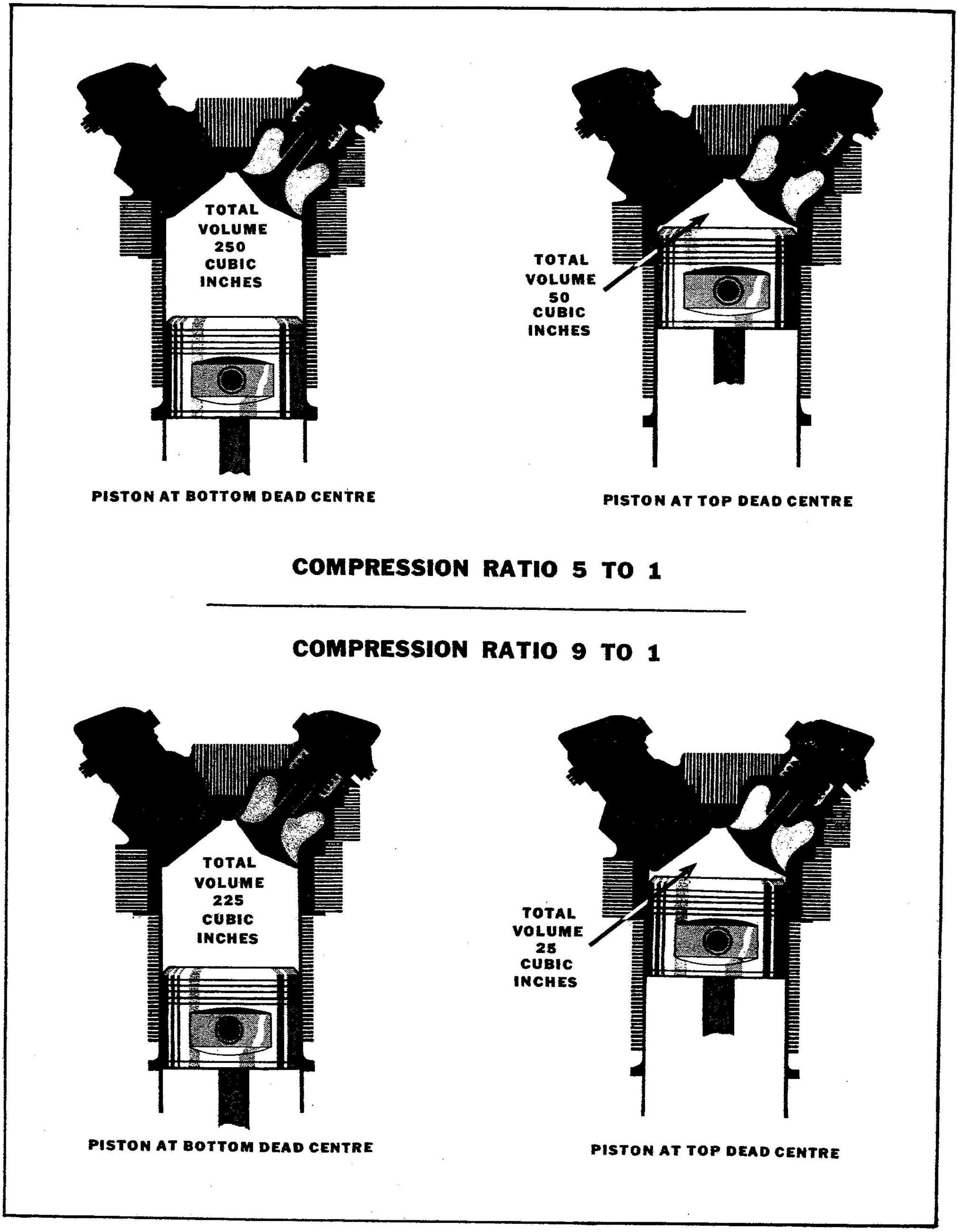


Figure 1-8 Compression Ratio

CHANGE OF FUEL COLOUR

45 Another form of instability is usually evidenced by change of fuel colour and the presence of considerable quantities of white, insoluble powder. This type of instability is to a large extent associated with storage of leaded fuels in galvanized drums which have accumulated small quantities of water in the interior. At present it is known that this type of instability may remove up to 75% of the bromine present in the gasoline. Loss of bromine will produce a tendency to much more rapid spark plug fouling, but does not render the gasoline unusable provided one part of it is mixed with at least three parts of gasoline of the same grade but not showing white sediment or loss of colour. Gasoline stored in black iron drums may contain rust which is fairly easily removed by filtering. It was thought until recently that storage in black iron drums eliminated the loss of bromine which occurs with galvanized drums. It is now known that bromine is lost in black iron drums if storage conditions are sufficiently severe. This loss is, however, much smaller than that occurring with galvanized drums. It has been found that loss of bromine in both galvanized and black iron drums can be eliminated by change of the type of bromine compound used in the lead anti-knock compound.

46 When these conditions occur, the fuel is to be quarantined and not used until the gasoline has been tested and permission for its use has been granted by AMCHQ.

TESTING FOR STABILITY

47 Specifications safeguard stability by requiring that a sample of the gasoline shall be exposed to 100 pounds pressure of pure oxygen in a sealed container which is heated to the boiling point of water 100°C, (212°F). Heating is continued for 16 hours after which the bomb is cooled. The gasoline is then removed and measured quantity is evaporated to determine the weight of residue left after evaporation. The residue is not permitted to exceed one pound in 1500 gallons (4-1/2 tons). This oxygen bomb stability test is only applicable to fuel at the time it is manufactured at the oil refinery, Gasoline after storage, shipping, and particularly when in drums or cans, is not required to meet the oxygen stability test requirements (accelerated ageing test) of the specifications.

48 The above "Accelerated Gum and Precipitate Test" is a truer estimate of the stora[
stability of the fuel, although quite a lot m[
be predicted by the "Existent Gum" content
the fuel when the increase of gum for a certa
length of time is known.

CORROSION PROPERTIES

Corrosive Constituents

49 The corrosive property of fuel is caus[
chiefly by sulphur compounds which atta[
tanks, fuel lines, pumps, exhaust systems, et
While it would be very desirable to elimina
sulphur completely from the fuel, the cost
refining would be prohibitive. However, t[
lead content is held to definite limits becau[
of its deleterious effects on lead respons[

50 The presence of naphthenic acids in avi[
tion turbine fuels is highly undesirable wh[
the fuel system contains a component utilizi[
indium-coated lead surfaces. At high rates
fuel flow experienced in jet aircraft, micr[
scopic (5-10 microns) insoluble particles m[
erode the protective metallic coating over t[
lead surface. Lead is extremely sensitive
naphthenic acids and a slight trace of this ac
can cause a fuel pump to fail within a few hou[
of operation.

51 While sulphur compounds in turbine fue
do not at present seem to produce any seriou
corrosive or other effects resulting from the
products of combustion, certain types of sulph[
compounds can have undesirable effects on fu
system parts. Mercaptans have a very unple[
sant odor (the combat weapon of a skunk is
mercaptan) and have been shown to attack ca[
mium plate on fuel system parts and also
produce deterioration of rubber type packin[
in the fuel system. Mercaptans are fairly read
ly removed from petroleum products in t[
refining process but at added cost, and the
removal will somewhat reduce the availab
supply in times of national emergency. Me[
captans should be limited to a relatively l[
value in aviation turbine fuel.

ALCOHOL AND BENZENE

Types

52 Although the petroleum fractions kno[
as gasoline have been employed almost excl[
sively for internal combustion engine fuel[
other liquid fuels have been investigated a[
used to some extent. Ethyl (grain) alcohol a[
benzene appear to be preferred at present, s[

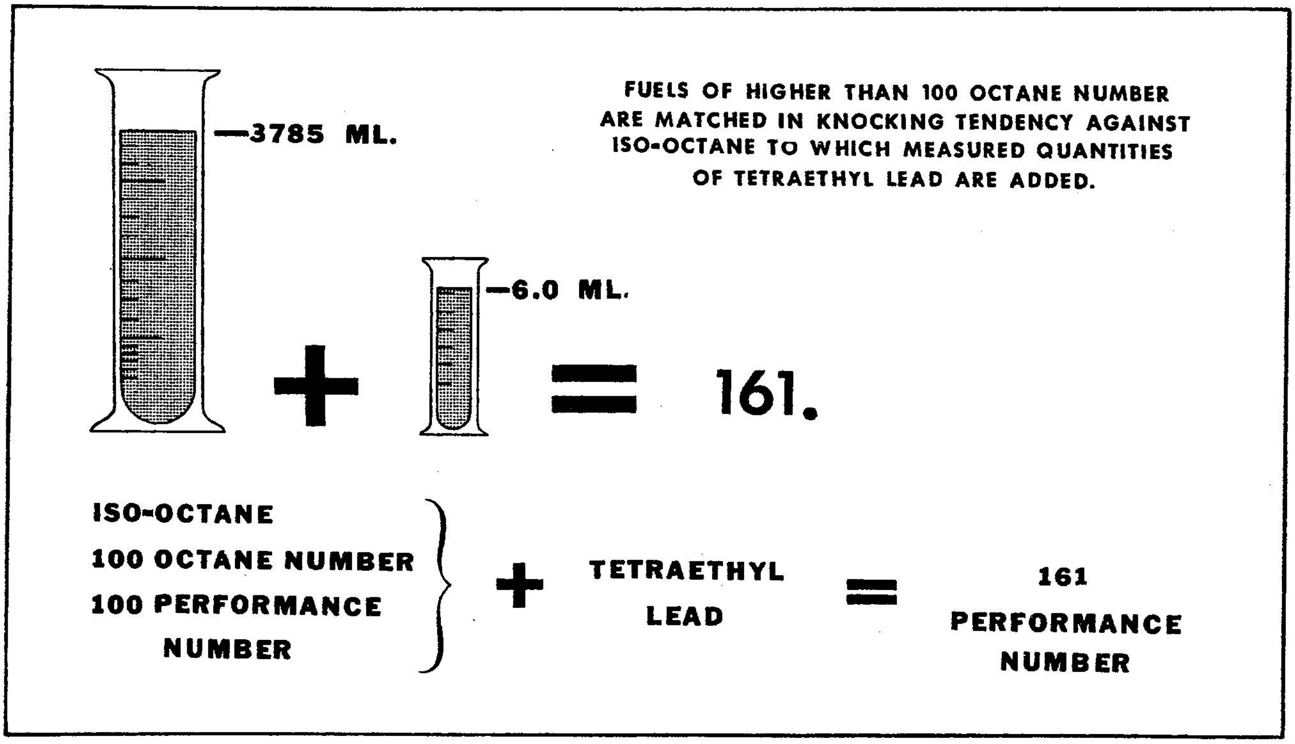


Figure 1-9 Octane Rating

Table 6.

ETHYL ALCOHOL

53 Ethyl alcohol is a compound of hydrogen, carbon, and oxygen, which may be prepared from any organic compounds such as grain, starch, or sugar. Its chief virtue as an engine fuel is that it will withstand a high compression pressure, which in turn promotes efficient engine operation. The particular disadvantages of alcohol as compared with gasoline are its low heat value, low vapour pressure, and a pronounced affinity for water.

Benzene

54 Benzene is a hydrocarbon compound obtained chiefly from coal. It may be compressed to a high degree, but it has a low specific heat value per pound (but more per gallon than gasoline), slow burning rate, high freezing point, and greater cost, and the available supply would be urgently required by other industries in case of military emergency. It has been successfully blended with gasoline as an anti-knock compound; however, when used in this manner, it is inferior to such anti-knock compounds as tetraethyl lead, iso-octane, and iso-pentane. Largely because its use would raise the freezing point excessively, benzene is not utilized in aviation gasoline.

THE TURBINE ENGINE AND ITS FUELS
FACTORS CONTROLLING CRUISING
FUEL ECONOMY

55 A considerable number of factors control the minimum specific fuel consumption or economy which can be attained. Some of these factors are built into the engine and are not under the control of the pilot or flight engineer, others are characteristic of the aircraft and may or may not be subject to control by the crew; some engine factors can be considered as operating variables and are under definite control by the crew.

56 In considering the question of obtaining the lowest specific fuel consumption from the engine, it should be pointed out that the practical application is really that of using the minimum weight of fuel per mile flown at a given airspeed. This minimum weight of fuel per mile flown may not always coincide with the

conditions which give the lowest specific fuel consumption in the engine. For example:

57 To avoid overheating with very lean mixture it may be necessary to use an excessive opening of the cowl flaps; this setting may reduce engine fuel consumption but increase the fuel required per mile flown.

58 Minimum fuel consumption for a given horsepower in flight may be obtained with low engine speed and high manifold pressure. This low engine speed may require such a high pitch angle setting on the propellor that the propellor efficiency becomes unfavorable and produces greater fuel consumption per mile flown than an engine operating condition less favorable to engine economy. Detailed discussion of engine operating conditions which are unfavorable to over-all aircraft fuel economy are not a subject for this EO and information must be sought in relevent - 2 Engineering Orders.

59 The various factors which influence the specific fuel economy of the engine under cruise conditions are listed below in order of relative importance. These are discussed on the basis of the requirement of a definite and fixed amoun of power being available at the propellor hul and leave out any questions of aircraft efficiency.

FUEL AIR RATIO

60 This is without question the most important factor. Where maximum range is desirec choice of engine and aircraft operating conditions which will permit the engine to operate at a fuel air ratio of about 0.065 without knock will, in general, produce the lowest specific fuel consumption. The mixture can, however, be made too lean and specific consumption will then increase as shown in Figure 1-14. As the mixture becomes leaner than about 0.08 fuel-air ratio, the manifold pressure required for a given power at fixed engine speed will need to be increased.

ENGINE FRICTION

61 A considerable amount of power is used merely to keep the engine rotating at a given speed without any useful power being taken out at the propellor shaft. This internal power requires fuel to produce it and other things being equal the fuel required to produce a given

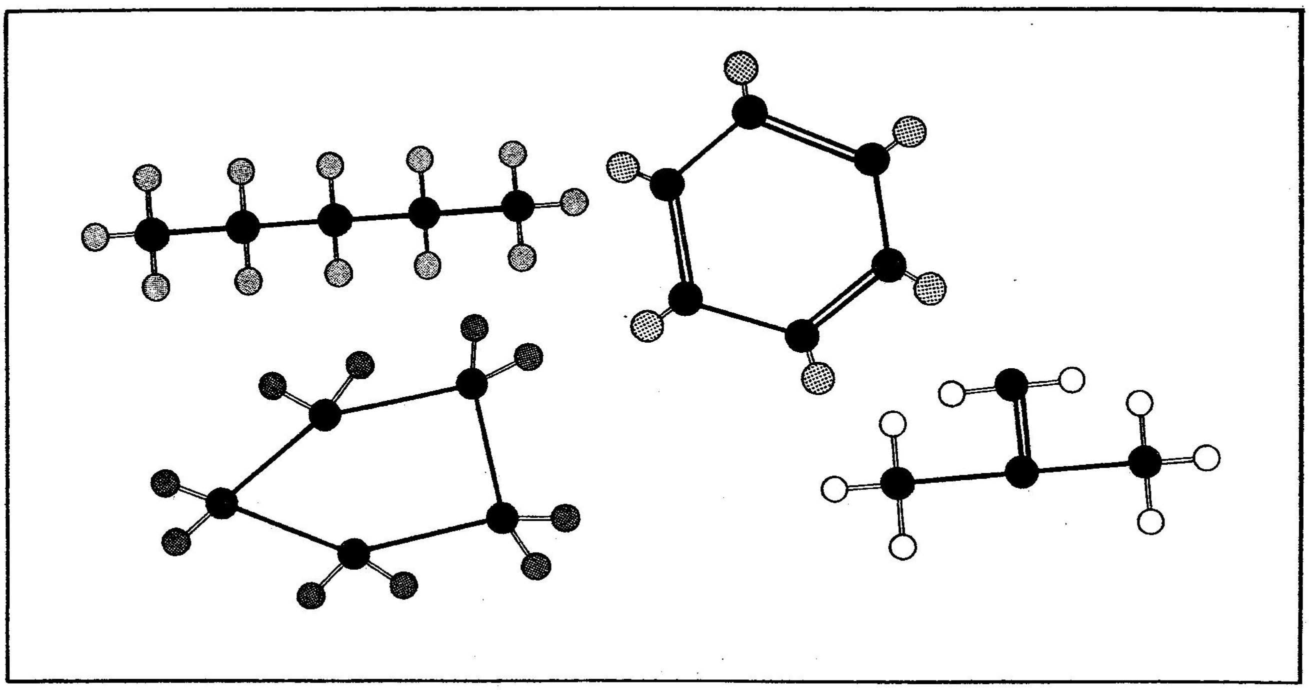


Figure 1-10 Typical Gasoline Molecules

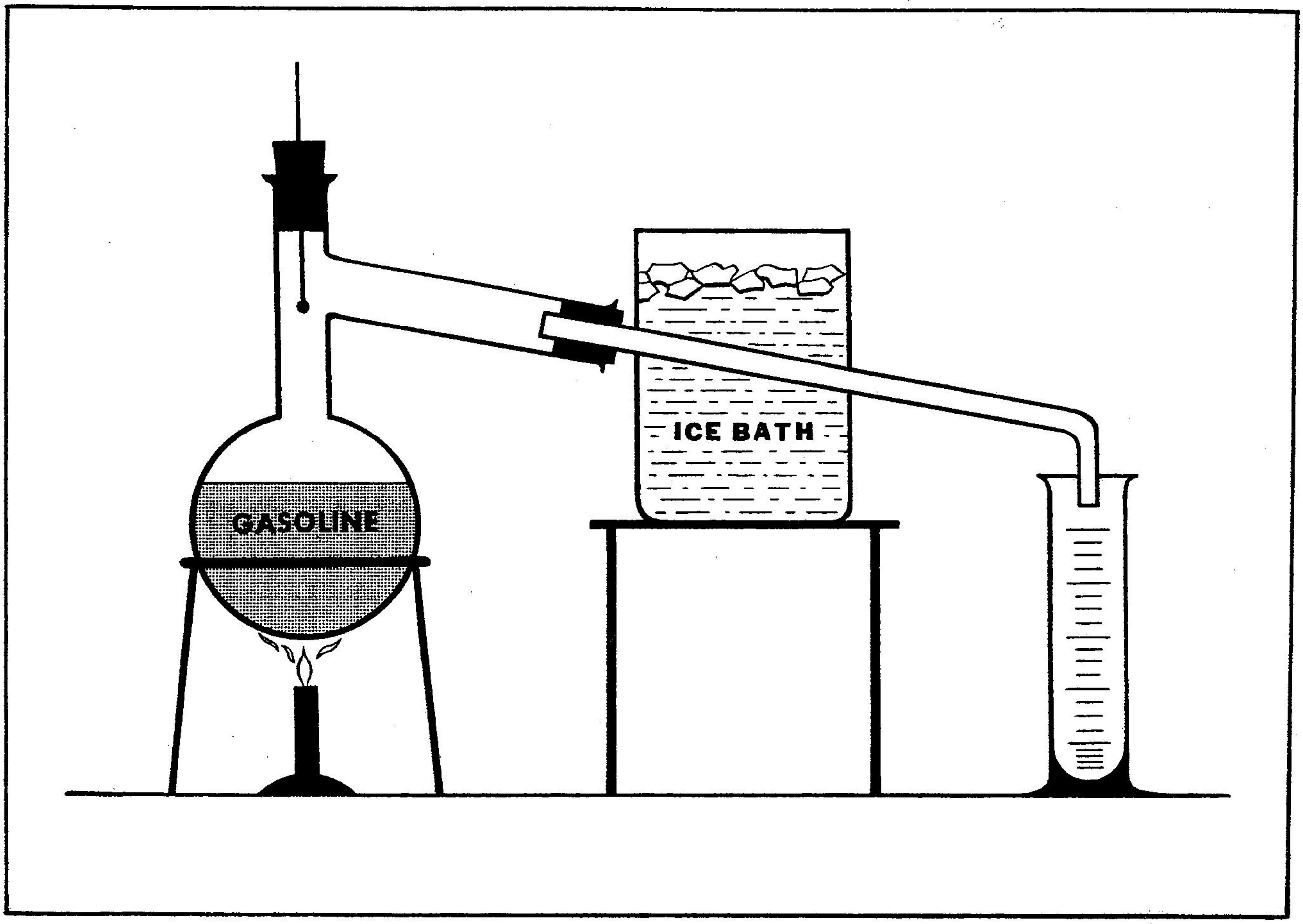


Figure 1-11 ASTM Distillation Apparatus

power at the propellor shaft will be increased as the engine friction (or internal engine power) is increased. Engine friction increases rapidly with engine speed and may easily be four or more times as great at 3000 rpm as it is at 1500 rpm. For a given cruising power, minimum engine friction and lowest fuel consumption are in general obtained by the lowest rpm and the highest manifold pressure which will allow maximum economy mixture strength to be used without knock. Maximum economy mixture strength usually corresponds (in the absence of knock) to a fuel-air ratio of about 0.065, but this may vary somewhat with the engine type.

CYLINDER COMPRESSION RATIO

62 Increase of cylinder compression ratio may have a significant effect on economy, always provided that the fuel has a lean Performance Number sufficient to permit operation without "knock" at maximum economy mixture strength and without excessive spark retard (see Spark Advance).

63 Cylinder compression ratio in aircraft engines has nothing like the favorable effect upon fuel economy that it has been shown to have in routine use of passenger car engines which normally operate at less than 10% of their maximum available output. In the case of the passenger car engine, increase of compression ratio necessitates an increased fuel Performance Number. In the case of the aircraft engine, when increase of compression ratio is considered, any accompanying increase of Performance Number is largely out of the question and a lean Performance Number of 115

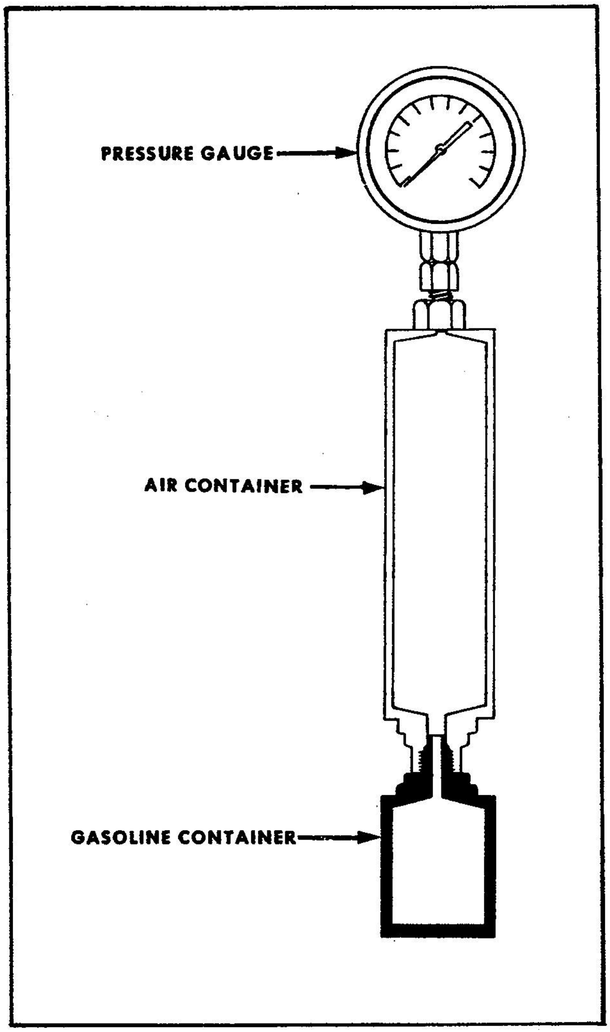


Figure 1-12 Reid Vapour Pressure Test Bomb

(Grade 115/145) must be regarded as the highest that is likely to be available for several years to come. In fact, it would seem that any considerable increase of lean Performance Number will have to come from the engine rather than from the fuel. Such increase can result from mild engines which give the fuel its rich rating under lean conditions. Assuming constant fuel Performance Number, the question of compression ratio largely resolves itself into one of increasing compression ratio for the benefit of fuel economy but at the expense of maximum available power. It is possible to compute the effects of compression ratio upon fuel economy and available maximum power with considerable accuracy. Thus, with a given fuel, increasing the cylinder compression ratio from 6 to 1, to 8 to 1 will reduce the fuel consumption (lb per horsepower hour) by approximately 10% and will reduce the maximum available power by about 20%. This would seem to be in direct contrast with the passenger car engine where increase of compression ratio improves both power output and fuel economy. The explanation for this disparity is the fact that the passenger car engine is naturally aspirated (that is, it has constant air consumption) and has an increasing Performance Number requirement with increase of compression ratio. The aircraft engine is supercharged and the air consumption (on a given fuel) is varied to suit the compression ratio.

64 The above discussion may possibly seem to infer that lowering the cylinder compression ratio of aircraft engines below present levels is desirable. The discussion, however, should not be so taken; the present compression ratio level of between 6 and 7 represents the best known compromise in regard to maximum power, fuel consumption, cylinder cooling, exhaust valve life, etc.

65 The relative effects of fuel-air ratio and cylinder compression may be considered. In Figure 1-14, which gives actual data for an engine with a compression ratio of 6 to 1, it will be noted that increase of fuel-air ratio from the maximum economy value of 0.067 to 0.08 increases the fuel consumption by 12%. It may be noted that 0.08 fuel-air ratio is the value that with gasoline, in most engines, gives the maximum power output for a given air consumption and is known as "maximum power mixture strength." In supercharged aircraft engines, much higher power is available at a fuel-air ratio of 0.10 to 0.11 than at 0.08, but at the higher fuel-air ratios less power is available per pound of air than at a fuel-air ratio of 0.080. The difference in fuel consumption between fuel-air ratios of 0.08 and 0.067 shown in Figure 1-14 is much less than can be obtained if all engine conditions are adjusted for maximum economy. In Figure 1-14 the fuel consumption at 0.08 fuel-air ratio is 0.51 lb per hp hour, and this is an excellent value for this

fuel-air ratio at 6 to 1 compression ratio. At 0.067 fuel-air ratio, the consumption of 0.455 lb per hp hour is considerably higher than the best that can be obtained for this compression ratio. The data shown in Figure 1-14 were obtained with constant spark advance, By adjustment of spark and other changes to obtain maximum fuel economy it should be possible to obtain a fuel consumption of 0.41 lb per hp hour. If an increase of compression ratio be considered which will give the same fuel consumption at 0.08 fuel-air ratio as the 6 to 1 compression ratio does at 0.067 fuel-air ratio, it will be found that a compression ratio of 8.8 to 1 is necessary. A compression ratio of 8.8 to 1 at 0.067 fuel-air ratio will give 11% lower fuel consumption than will the 6 to 1 ratio. The 8.8 to 1 compression ratio will reduce the maximum power available on a given fuel to about 78% of that available with 6 to 1 ratio. It should be emphasized that while lean mixture is a major avenue of obtaining cruising fuel economy, it is an avenue that has its difficulties. Very lean mixture emphasized difficulties of cylinder cooling, exhaust valve life and spark plug fouling.

66 High cylinder compression ratio would not appear to be a practical method of improving cruising fuel economy of aircraft engines. If considerable improvement in fuel economy is required, recovery of the energy available in the exhaust gases seems to be the most suitable method. Recovery of exhaust energy by use of a gas turbine in series with a piston engine can reduce fuel consumption during cruise by at least 15% while increasing maximum power by about 20%. These improvements are obtained in some current engines without increase of cylinder compression ratio or of fuel Performance Number.

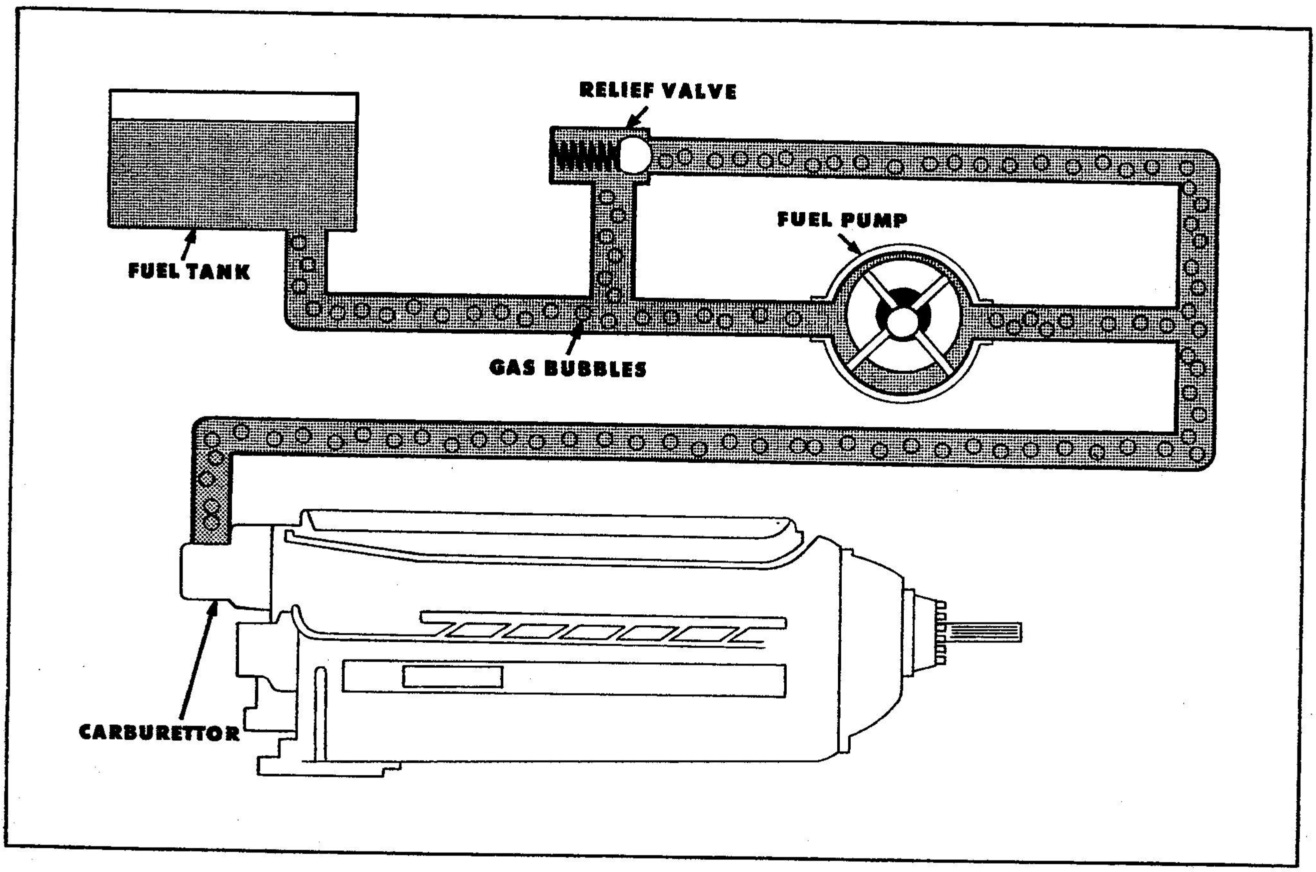


Figure 1-13 Vapour Lock

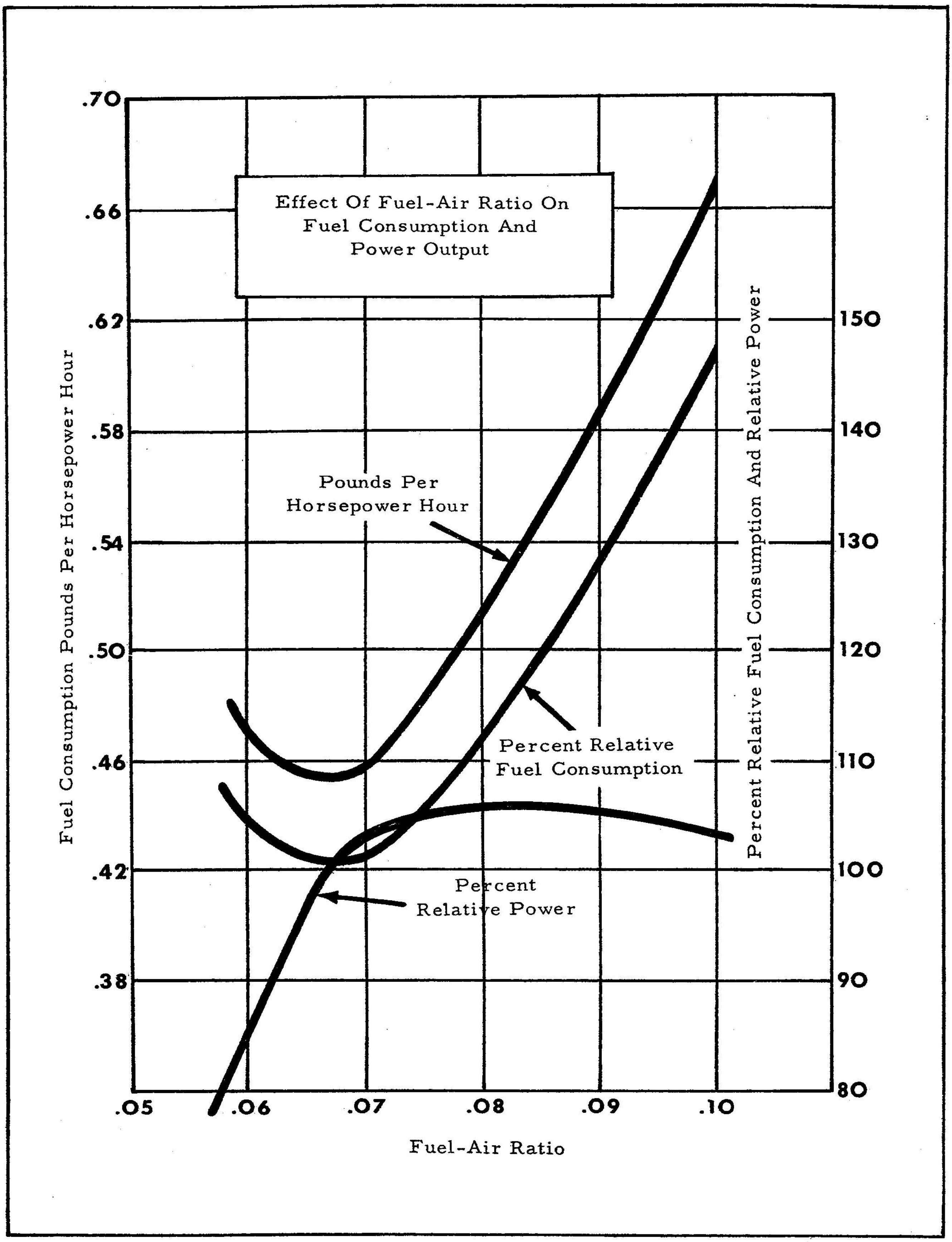

Effect Of Fuel-Air Ratio On Fuel Consumption And Power Output
Fuel Consumption Pounds Per Horsepower Hour
Percent Relative Fuel Consumption And Relative Power
Pounds Per Horsepower Hour
Percent Relative Fuel Consumption
Percent Relative Power
.70
.66
.62
.58
.54
.50
.46
.42
.38
150
140
130
120
110
100
90
80
.05
.06
.07
.08
.09
.10
Fuel-Air Ratio

Figure 1-14

WATER INJECTION

67 Where lean knock value is sufficient to permit increased compression ratio for fuel economy, the limitations of such increased compression ratio on take-off and War Emergency Rating power are now being overcome in some cases by adding water (or water and alcohol where it is necessary to prevent the water from freezing) to the fuel-air mixture. The addition of water will, in most cases, permit power increases at take-off which exceed the mechanical strength of the engine. When water or water-alcohol is used for high power operation, the fuel-air ratio is usually reduced from about 0.10, which is normal at high power, to about 0.08 at the instant the water injection is started. By this means the specific fuel consumption plus specific water consumption will be of the order of 0.70 pound per brake horsepower hour, which is no greater than the specific fuel consumption at the maximum power permissible without water injection. Water injection produces its effects by reducing the temperature of the fuel-air charge and also by direct cooling of the cylinder and piston. In some cases the cooling of the cylinder walls makes it possible to take a power output from an engine installation which would require redesign of the cooling system if equal power output was obtained by a high Performance Number fuel without water injection. The effect of injection of water or water-alcohol in permitting increased power output cannot be explained entirely in terms of mixture and cylinder cooling. For instance, water-alcohol which has less cooling effect than straight water usually permits a greater power increase than straight water. Water injection for elimination of knock is very old and was known about as early as 1880.

68 At present water injection is used in both military and civil transport service for increasing output above that possible by the use of Grade 100/130 or Grade 115/145 alone. At least with American equipment, water injection is not used with fuel grades below 100/130, although there is no reason why it should not be used. For example, it would be useful with Grade 91/96 in countries where grades 100/130 and 115/145 are not available. By the use of water injection power is increased by 15% to 25%, thus the rich Performance Number of Grade 100/130 becomes 150 to 160 instead of 130. Similarly, the rich Performance Number of Grade 115/145 becomes 168 to 182 instead of 145. While water gives the same maximum output as would a fuel with 15% to 25% high rich Performance Number, it really does much more, since the use of such fuels would mostly require revision of the engine cooling system, which is not necessary with water injection.

69 With most engines and installations, water alone cannot be used owing to freezing of the water in the tanks or in the lines either on the ground or in flight. Some engines give best results from the permissible power gain standpoint when a mixture of water and alcohol is used, in others the plain water is as good as water-alcohol.

70 Water appears to have the same type of effect as lead, inasmuch as a given addition of water produces a more or less uniform increase of Performance Number. Thus, 40 parts of water per 100 parts of fuel will permit increasing output by about 40% if the fuel-air ratio is reduced when the water is injected the gain in output is 20% to 30%.

71 In the Introduction it is stated that alcohols and other oxygen containing compounds are not used in fuel because such compounds decrease range. This appears to be in conflict with the use of water-alcohol injection and still more with injection of water alone, since the latter has zero heat of combustion. Actually there is no conflict, since water-alcohol or water when used with Grade 100/130 fuel does not involve increased weight consumption (except insofar as this is due to increased power). Furthermore, alcohol and water are only currently used under conditions of engine operation where fuel economy is of secondary importance and is not used at cruising where fuel economy is mostly of supreme importance.

72 The use of water injection, apart from its effects in permitting a great increase of power without the occurrence of knock, is of almost equal value in its effects on engine cooling. Water injection results in removing heat from the cylinders and pistons which would otherwise have to be removed by the engine cooling system. The heat removed from the cylinders and pistons is discharged by the exhaust system in the form of steam. The function of water injection in reducing the heat to be disposed of by the cooling system is similar to

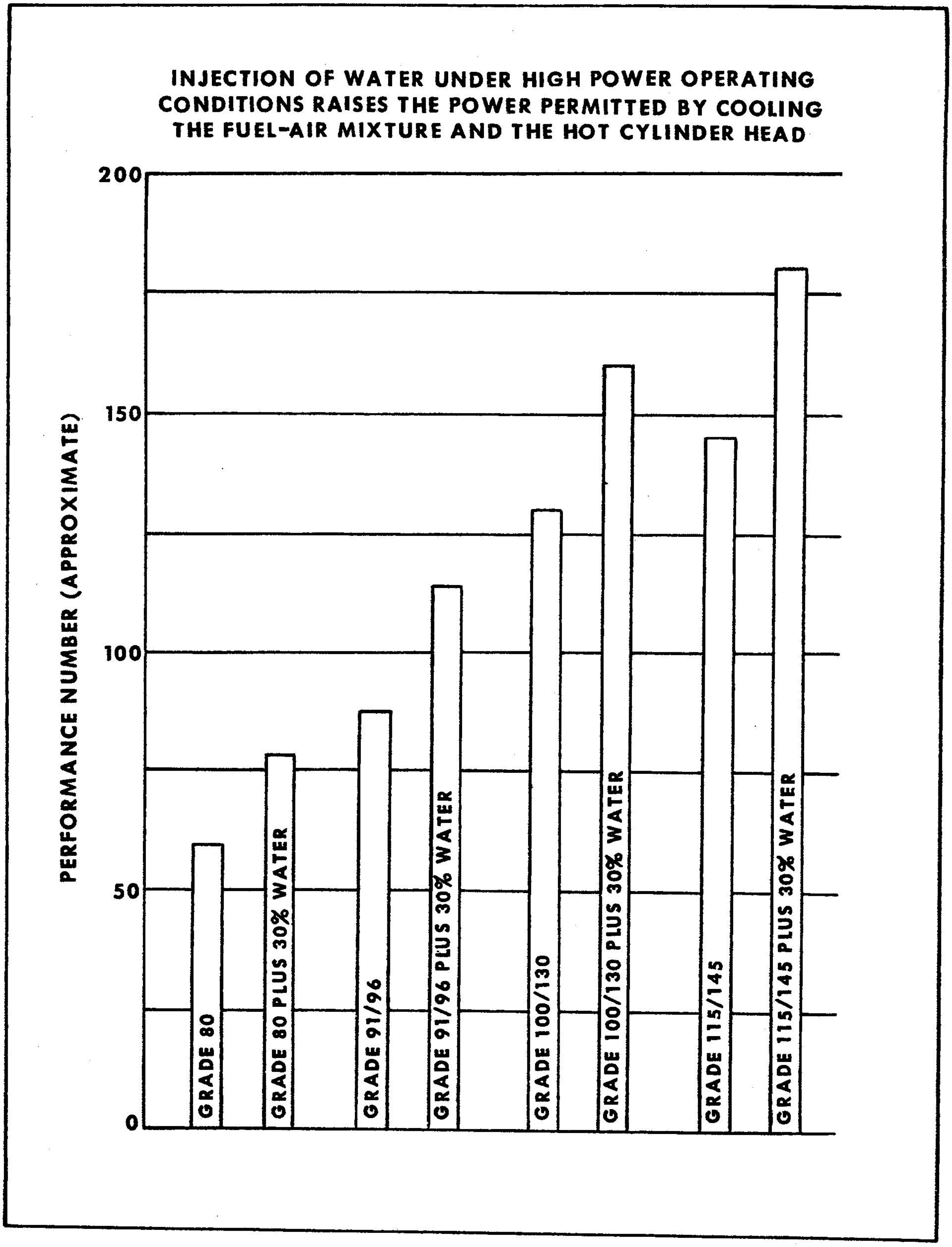


Figure 1-15 Performance Gain Due to Water

but considerably greater than that produced by rich mixture. While the use of rich mixture is of great value in reducing the tendency to knock, it is also of great value in reducing the temperature of the cylinders and pistons. If an engine is operated at lean mixture without knock and the mixture is then progressively richened without any other change of operating conditions, it will be found that the cylinder temperatures are considerably reduced as the mixture is richened. If fuels of sufficiently high Performance Number to permit operation at War Emergency Rating power with lean mixture were available, engine cooling systems would need to be considerably increased in capacity. Such increase of cooling system capacity would, in most cases, greatly increase aircraft drag. Furthermore, increase of cooling system capacity would probably not be sufficient to prevent piston and exhaust valve overheating at War Emergency Rating power with lean mixture. Thus, with presently available aircraft the use of either rich mixture or water injection has value in respect to permitting high power operation, which is not related to the value of these measures in suppressing "knock".

INFLUENCE OF MIXTURE TEMPERATURE

73 The temperature of the mixture of fuel and air in the intake manifolds has a considerable effect upon the power output of the engine. In the absence of knock a -12.2°C (10°F) increase of mixture temperature will decrease the power output by about 1%. However, increase of mixture temperature will generally increase the tendency to knock (it may not do so if the distribution is uneven at the lower mixture temperature) and as a result the manifold pressure must be reduced by closing the throttle to avoid knock. The sum of the effects of reduced charge weight due to increased temperature and of the necessity of still further reducing charge weight to avoid knock results in reducing permissible power by about 2% for each 10°F increase of mixture temperature. Thus, if mixture temperature is increased from 65°C to 120°C (150 °F to 250°F), power output will be reduced by about 20% on a given fuel grade. If, however, it is desired to keep power output constant despite the increase of mixture temperature, then if Grade 130 fuel is satisfactory for 65.5°C (150°F) mixture temperature, 130 x 100/80 or about Grade 160 will be necessary for 121°C (250°F) mixture temperature. These figures are sufficient to indicate the reason for the use of intercoolers or aftercoolers with turbo-super-chargers and two-stage geared superchargers. Some engines suffer less from the effects of mixture temperature than the figures given above and others suffer more. With sensitive fuels (i.e., those having large differences between lean and rich knock ratings), the effects of high mixture temperature can be even larger than those given above.

74 Increase of temperature of the fuel-air mixture in the manifold produces an increase in knocking tendency due to the fact that temperature of the charge in the cylinder is considerably increased at the time the spark jumps. The temperature increase at the time of the spark is several times the increase in manifold temperature.

75 The above figures (2% power decrease for each -12.2°C (10°F) increase in mixture temperature) are sufficient to explain the effects of water injection. In current use of water injection, approximately 0.2 pound water per horsepower hour (corresponding to a water-air ratio of approximately 0.03) is used and this is sufficient in some cases to reduce mixture temperature by as much as 150°F, which would explain a 30% permissible power increase. The mixture temperature in the induction system is unlikely to be reduced by as much as 65.5°C (150°F), since insufficient time is available for complete evaporation. However, even though the water is not completely evaporated by the time it passes the intake valve, the residual liquid will produce further mixture cooling effects in the cylinder.

SPARK ADVANCE

76 The spark advance used in most current engines is a compromise between the setting which will give the highest War Emergency Rating (WER) and that which will give the best cruising economy. Thus, if the spark is set for best economy at cruise, the power available at the WER will be reduced by 5 to 10%. If, on the contrary, the spark is set for maximum WER then the fuel consumption at cruise may be increased by 5%. Some engines are now in service which are equipped with automatic spark change mechanism which provides advanced spark for best economy cruise and a retarded spark for maximum power.

FUEL AIR MIXTURE DISTRIBUTION

77 If the fuel-air mixture is not equally supplied to all cylinders, specific fuel consumption will be increased. Figure 1-14 shows the effect of fuel-air ratio on: specific and relative fuel consumption and also on relative power, under conditions of constant manifold pressure in a single cylinder engine. This work of necessity has to be carried out on a single cylinder engine since distribution inequalities cannot be avoided on a multi-cylinder even with fuel injection. While a single cylinder engine has no distribution problem in the normal sense it can have effects which produce essentially the same result. It can have pulsation effects in the induction system which may result in liquid fuel surging backwards and forwards in the pipe out of time with the engine explosions. This surging of liquid fuel may result in successive cycles having varying fuel-air ratios. In a single cylinder engine equipped with cylinder head fuel injection the cycle to cycle fuel-air ratio can vary considerably from two causes. Firstly, induction system pulsations can result in a variation in the amount of air induced in successive cycles. Thus, even if the injection pump has absolutely uniform delivery per injection there will be a cyclic variation in fuel-air ratio. Secondly, while there may be cyclic uniformity of air supply, successive injections of the fuel pump can fluctuate considerably.

78 From Figure 1-14 it can be seen that maximum economy is obtained at 0.067 fuel-air ratio and that either richening or leaning to 0.077 or 0.057 will result in an increase of about 8% in consumption. Thus, if some cylinders are operating at 0.067 and others at 0.057 and 0.077, the two latter will use up 8% more fuel and the over-all economy of the engine will be reduced. If distribution is poor with the engine operating at full throttle and low rpm, engine operating conditions may need changing. Increase of carburettor air temperature and increase of engine rpm with the throttle kept wide open will increase mixture temperature and thus improve distribution. Reduction of manifold pressure by closing the throttle and maintenance of equal power by increased rpm will also increase mixture temperature and improve distribution, this is less likely to produce knock than the use of full throttle with carburettor air heat. Poor mixture distribution at lean cruise will show up principally in the form of engine roughness and in backfiring in extreme cases. Some long-range aircraft equipped with fuel flow meters and means of measuring engine power in flight (torque meters) can directly determine specific cruising fuel consumption and can thus detect the effects of bad distribution and take measures to correct it.

LEAN PERFORMANCE NUMBER OF FUEL

79 Some current combat engines could take advantage of an increase in lean Performance Number over that available in Grade 100/130. To use fuel of higher lean grade with only minor changes in current engines, adjustment of spark advance for cruise and cruising at higher manifold pressure and reduced rpm would be the most suitable modifications.

80 While higher lean Performance Number might permit improved cruise economy in some current engines, operating of engines on fuels of lower lean Performance Number than they are rated on can have very severe effects on specific fuel consumption at cruise. Thus, an engine rated on Grade 100/130 may have its cruising specific fuel consumption increased by 15% to 20% if the carburettor setting is changed for proper operation on Grade 91/96.

WEATHERING OF FUEL IN TANKS

81 While weathering (or loss by evaporation) of fuel in the tanks while in flight is not an engine function, it is obvious that all possible measures should be taken to eliminate such loss. It is obvious that it is hardly worthwhile operating the engine to obtain maximum cruise range if an avoidable 5% loss of fuel by evaporation in flight is neglected. In general, fuel handling methods and aircraft operating practices which tend to minimize boiling of the fuel in the tanks and vapor lock will also tend to minimize evaporation losses. Engineering Orders should be consulted in regard to such practices in the case of individual aircraft.

AROMATICS IN PISTON-ENGINE FUELS

82 Subsequent to the introduction of octane number scale for rating aviation fuels in 1930, aromatics were used only to a very limited extent in the United States until some time after Pearl Harbour. The British and the Germans had in the meantime used fuels containing up to 40% aromatics and had developed their equipment to use such fuels.

83 Until the middle of 1942 the highest grade

of fuel specified by the Army and Navy was of 100 octane number and only a lean rating was specified. Some of the fuel supplied to this specification was only Grade 100/100, whereas most American engines had been developed on fuel of approximately Grade 100/120. Use of Grade 100/100 fuel in engines developed on Grade 100/120 in conjunction with the more severe duty which equipment is subject to in war time caused serious difficulties in service and resulted in the almost immediate specification of a rich rating method and of Grade 100/125.

EFFECTS ON SELF-SEALING FUEL CELLS

84 When only a lean rating was specified paraffinic fuels were the most economical to produce apart from the fact that aromatics were viewed with unjustified suspicion. Self-sealing fuel cells had been developed for paraffinic fuels originally, and many of these cells were in service until 1941 and were known to be unsuitable for fuels containing appreciable quantities of aromatics. Buna or self-sealing cells are now in wide use, see EO 110-20 Series.

CAT CRACKED GASOLINE

85 With the requirement of a rich rating, aromatics became, in wartime, the economical and available component to obtain a rich rating of 125 Performance Number. Prior to 1941, Grade 100 fuel had been almost entirely produced by blending gasoline directly distilled from crude oil (straight-run gasoline) with various high Performance Number paraffinic blending agents (alkylate and similar materials) produced by means of expensive and complicated plants. By 1942, alkylate and other similar blending agents were in shortest supply, and suitable straight-run gasolines to blend with them were the next rarest component. This situation was relieved by substituting catalytically cracked (cat cracked) gasoline for the straight-run gasoline. Cat cracked gasoline was in use for motor fuel prior to 1941, and it was known that good aviation fuel could be made by this process, however, until the middle of 1941 the plants were almost exclusively used for producing motor gasoline. Cat cracked aviation gasoline largely consists of branched chain paraffins and aromatics; the proportions of these two components can be varied by changing the operating conditions of the plants. Prior to 1942, cat cracked aviation gasoline had been deliberately manufactured to a low aromatic content in view of the general American opinion of aromatics; this low aromatic content, however, reduced the amount of gasoline which could be produced.

AROMATICS SAVED UNITED NATIONS

86 With the specification of Grade 100/125 and the enormous demand for such fuel, cat cracked fuel containing 20 to 30% of aromatics was produced in the greatest available quantity by diversion of the cat crackers from motor fuel manufacture. The cat cracked fuel proved to be a life saver to the United Nations both in respect to engine performance and quantity of fuel available. Cumene (an aromatic) was also blended into Grade 100/125 and was to considerable value in relieving the critical shortage. Cumene was also of help in increasing lean rating in which respect if differs from most other aromatics. While the use of aromatics was a life saver, such fuel blends initially caused a great deal of operating trouble with equipment not designed for them. This trouble was mostly in connection with "rubber" parts of the fuel system, such parts being the linings of self-sealing fuel cells, fuel hose, carburettor diaphragms, and pump packings. These difficulties have now been largely overcome by development of suitable rubber-like parts (see Effect of Fuels on Rubber). However, in the meantime aromatics had acquired a reputation in some quarters as the cause of all ills in an aircraft, even to tail-wheel failure.

87 In the case of two fuels having equal Performance Number both lean and rich, one not containing aromatics is somewhat preferable to another containing 15% aromatics. However, the air warfare carried out by the United Nations in 1942-1945 would not have been possible without fuels containing aromatics. In some quarters it was suggested that the use of aromatics was a mistake and that expansion of production by means of increased manufacture of paraffinic blending agents should have been chosen. Great expansion of production of paraffinic blending agents was not possible for a number of reasons, the most important being the fact that it required steel which would have had to be taken from the liberty ship and destroyer programs.

88 While aromatics were of outstanding importance in obtaining rich Performance Numbers during World War II in Grade 100/130 gasoline and may again be very important in

this respect for this grade in another emergency, the situation is different in respect to Grade 115/145. The aromatics necessary to obtain rich performance in Grade 115/145 are much less readilv available than aromatics suitable for Grade 100/130. Cumene is no longer available due to a rapid increase in other important uses for benzene. As a result the only available aromatics are toluene and the meta-para xylenes. Plant capacity to produce the latter aromatics is so exceedingly expensive and requires so much steel that these aromatics are not likely to be available in sufficient quantity in another emergency. As a result monomethyl aniline or xylidine may have to be used for rich performance in Grade 115/145 and possibly in Grade 100/130. Use of monomethyl aniline or xylidine results in lowering the lean rating of blends having lean ratings of 100 and 115 Performance Numbers before the addition of the aromatic amines and this means that the concentration of paraffinic blendir agents must be increased to bring the lean rat ings back to 115 and 100 respectively. Such a increase is economical even if it means buildir additional plants, since increased plant capacit for paraffinic blending agents requires muc less steel than will the installation of plant to produce aromatics which will give the re quired rich performance. The loss of lean per formance due to the addition of aromatic amine may really be a laboratory finding rather tha a true reduction of full-scale aircraft engin performance (see Aromatic Amines - Para 28) Further experience with aromatic amines wi be required to show whether the loss shown i laboratory lean performance is reflected in th full-scale engines.

ALL-PURPOSE PISTON ENGINE FUEL

89 The question in the heading is frequentl raised. To many individuals concerned wit

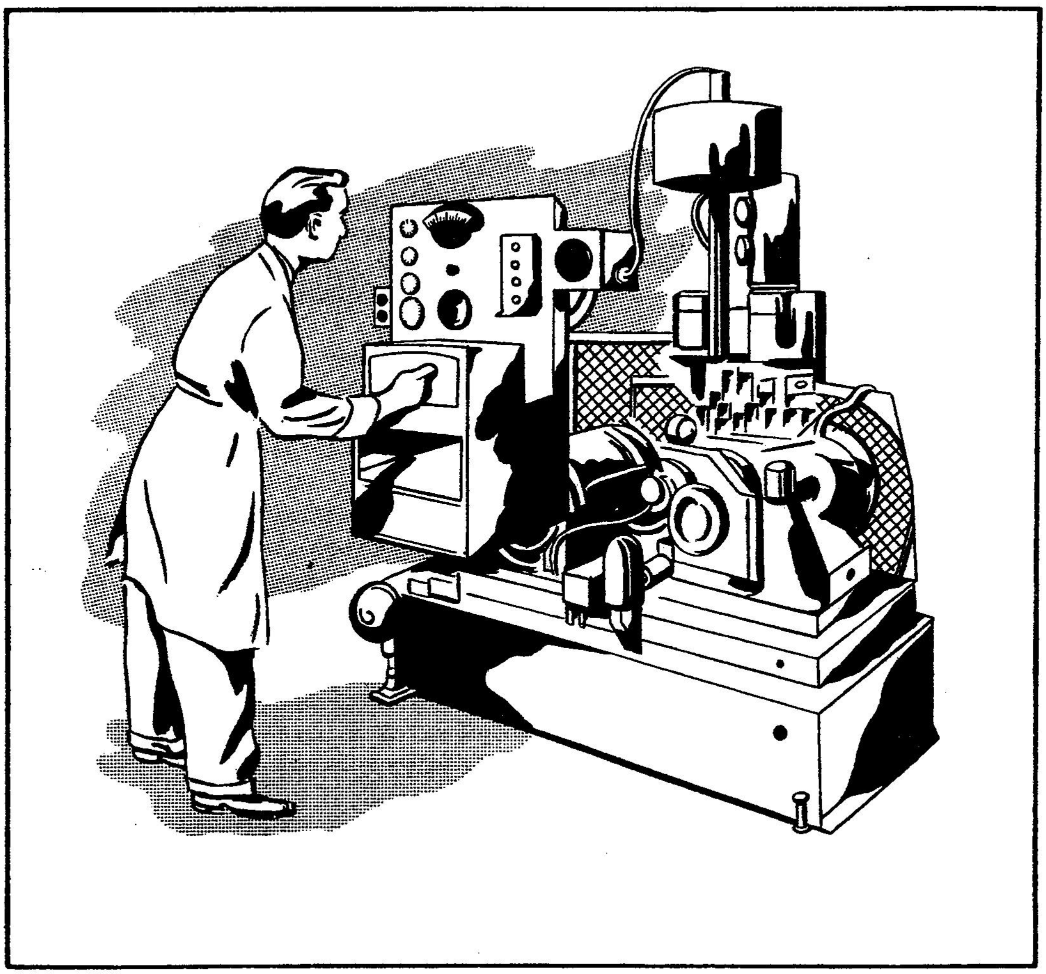


Figure 1-16 Knock Rating Test

engine and aircraft operation it is not obvious why fuels better than Grade 100/130 are not used in view of the large gains resulting from the use of Grade 100/130 in place of Grade 91/96. It is also not understood why the highest grade of fuel is not used for all flight purposes. Whether cost is or is not important in wartime, it is at least a good measure of the amount of man hours and materials used. To produce one gallon a day of Grade 100/130 during World War II, a plant cost of about $35.00 was involved, and this $35.00 represented about 120 pounds of metallic materials (mostly steel).

90 The amount of manufacturing plant and of manufacturing difficulty and expense increases very rapidly with increase of Performance Number of the fuel. To manufacture Grade 87 (an emergency grade in use during World War II but not now in use), simple distillation of widely available crude oil and addition of lead are the major operations involved. Most Grade 91/96 is made by a similar process, but the crude oil which will produce the required finished product is very much scarcer than that required for Grade 87.

91 The above should be sufficient to indicate why the RCAF has not adopted Grade 100/130 for all flight use both in training and in combat. While Grade 100/130 involves 120 pounds of metallic material for each gallon manufactured per day, increase of Performance Number above this value causes a very rapid increase in the amount of plant required. Grade 120/150 may easily involve a requirement of 300 to 500 pounds of steel per daily gallon produced. Increase of lean rating is the more difficult and more costly improvement since neither aromatics nor aromatic amines can be used for this purpose. Grade 120/140 was in commercial use for Trans Atlantic airline service prior to 1942 and higher Performance Number fuels were used by the Military Services for development purposes. The advantages of such fuels were thoroughly realized but the penalty in the form of manufacturing facilities was also known.

92 Triptane plus lead will give a lean Performance Number of about 200 and about 300 rich. Triptane, at present, can only be produced at the rate of a few hundred gallons per day by means of exceedingly costly plant facilities. Other fuels having rich Performance Numbers of 175 to 200 are also produced in limited quantities.

93 There is a present limited demand for fuels with a rich Performance Number of 200. Such fuels might have a limited combat use, but this would present difficulty with distribution in the field. Owing to manufacturing difficulties such fuels can only be procured on a very small scale.

KNOCK RATING DATA

94 The first serious studies of knock in aircraft engines were carried out some 30 years ago and indicated wide differences between gasolines made of crude oils coming from various parts of the world. Further engine studies indicated an apparent relation between chemical composition and tendency to knock. These studies led to the conclusion that aromatics were good, all paraffins bad and cyclic paraffins intermediate in knock properties. Aviation gasoline specifications until 1930 were therefore largely written around specification of chemical composition. The discovery of the excellent knock properties of iso-octane and their comparison with the poor properties of normal heptane in 1926 indicated that gasoline could not be considered as of increasingly inferior grade as the content of paraffins increased, and this was sufficient to indicate that the methods used then for specifying by chemical composition would not insure a satisfactory product.

95 Investigation of fuel supplied to one of the Military Services during 1929 and specified by chemical composition showed that this varied from 30 Performance Number as a low limit to a high limit of 50 Performance Number. Numerous attempts were made to define gasoline knock quality without the use of an engine, but these proved to be failures.

KNOCK RATING ENGINES

Requirement of Engines

96 After the use of an engine had been accepted as a necessity, it was observed that two gasolines which were equal in one engine were not equal in another. As a by-product of the early use of ethylene glycol as a cooling liquid for aircraft engines, tests were carried out using widely dissimilar fuels in a single cylinder liquid cooled engine at coolant temperatures varrying from 65°C to 176°C (150°F to 350°F). These tests showed that the relation between the various fuels continually changed

with cylinder temperature and this was sufficient to indicate that fuel ratings not only varied from engine to engine, but in any one engine as the engine conditions were changed. These tests also showed that if knock properties of aviation fuels were to be controlled the knock tests must be carried out with engine conditions which would give a reasonable prediction of behavior in full scale aircraft engines. This was the beginning of a program of testing a series of widely varied fuels in full scale engines to determine their relative behavior. This program is still continuing and new components of aircraft engine fuels are rarely accepted for service use without extensive testing in full scale multicylinder engines. The original test program of studying widely varying fuels in full scale engines not only provided information as to the effects of the fuels upon engine performance, but also gave relative ratings which could be used to set up engine conditions in single cylinder engines which would rate the knock properties of the fuels in the same relative order as the full scale multi-cylinder aircraft engines. If fuels are to be procured with definite minimum knock properties, a large number of knock determinations must be made as a matter of routine testing, and such tests must be made at each oil refinery manufacturing aviation gasoline.

SPECIAL TEST ENGINES

97 Such a requirement for testing fuels in an actual engine obviously rules out the full-scale multi-cylinder aircraft engine as a means of carrying out these control tests. To determine the knock properties of a fuel, it is obviously necessary that it must be made to knock; since knock is normally very destructive to full scale aircraft engines, a single full scale aircraft engine cylinder is obviously not a desirable test instrument if a more durable engine can be practicably utilized to obtain the same information. Fortunately it has been found possible to build small single-cylinder engines for use in laboratory testing of knock properties. By suitable adjustment of operating conditions, these engines will define the knock properties of fuels in the same order as the full scale engines. These laboratory engines can be and are built to withstand knock for extended periods without damage. Satisfactory laboratory engines have been available for a number of years. These are subjected to continuous modifications, for both mechanical reasons and to provide more accurate results as fuels are developed. This is hardly surprising since engines suitable for rating 70 Performance Number fuels can hardly be expected to be suitable for rating fuels in the order of 300 Performance Number.

REFERENCE FUELS-ESSENTIAL

98 In the early engine studies of knock, the relative resistance of a fuel to knock was expressed in terms of some engine variable such as spark advance, manifold pressure or cylinder compression ratio. In all these early studies, engines without superchargers were used and the engine was consequently subject to variations in atmospheric conditions which influenced the density, temperature and humidity of the fuel-air mixture taken into the cylinder. These variations alone were sufficient to prevent any one engine of given type from consistently giving the same rating to any given fuel over a period of days, months or years. Of the various methods of varying an engine function so that fuels could be made to knock, engines so built that the compression ratio could be varied while the engine was in operation proved to be by far the most satisfactory. While continuously variable compression ratio proved to be the most satisfactory engine variable for rating fuels, it was nevertheless not completely satisfactory. A fuel which would knock at 6 to 1 compression ratio (CR) in one engine might knock at 5 to 1 CR in an engine of different type. Two engines of identical type in different localities might differ by as much as one-half CR in the rating they assigned to a given fuel when both engines were run under supposedly identical conditions, except atmospheric variables. Any one engine would assign different compression ratio ratings to a given fuel as the mechanical condition of the engine deteriorated. It was found that variations in engine condition could be detected by always comparing the fuel being tested with a standard fuel for comparison. A single standard fuel proved to be insufficient, and it was found that two standard fuels were necessary. Of the two standards, one was much more prone to knock than any fuel to be tested, and the other much less prone to knock. Attempts to use two gasolines as standards proved unsatisfactory, and pure compounds having high and low Performance Numbers were investigated. Normal heptane and iso-octane see Figure 1-5, were finally adopted as an international standard and are still in use although

the use of gasoline of more than 100 octane number has necessitated the use of lead in octane, see Figure 1-9, to extend the upper range of the scale.

BRACKETING THE FUEL

99 In practice, any fuel being knock rated is compared with heptane-octane or octane-lead blends, one of which is slightly better and one of which is slightly worse in knocking tendency than the fuel being tested. This test method is known as bracketing the test fuel.

100 The use of standard reference fuel blends, one slightly worse than and one slightly better than the fuel being tested constitutes a system resembling the go and no go gauges used for checking dimensions machine shops. Furthermore, pure compounds are definite products which are capable of being reproduced exactly and which can be checked for purity although such purity checks are not simple.

101 The use of heptane and octane and octane plus lead as standard reference fuels for bracketing any test fuel in respect to knock properties was soon found to be desirable for rating fuels in full scale aircraft engines since while a full-scale engine may deliver constant power on any given fuel in the absence of knock with standard engine conditions in regard to rpm, fuel-air ratio, cylinder temperature, etc., the power at which knock will occur may vary significantly from day to day with atmospheric conditions and mechanical condition of the engine. Thus, all ratings of fuels in full scale engines are required to be bracketed between standard fuels, and iso-octane and normal heptane of slightly lower purity than required for the laboratory knock test engines are used.

CFR ENGINE LEAN RATING METHOD

102 As a result of a large amount of full scale multi-cylinder aircraft engine rating of fuels of widely varying composition and of extensive work in the laboratory rating the same fuels in small single cylinder engines, a rating method using the CFR 3 1/4" bore liquid-cooled knock test engine was standardized and is still in use. This engine is not supercharged, and the cylinder compression ratio is varied to produce "knock" with any fuel being rated. The fuel-air ratio producing a maximum degree of knock (about .070 F/A) is used, Actually fuels are not rated in terms of their tendencies to produce audible knock or ping, but rather in terms of their tendencies to cause increase of cylinder head temperature. This test method, like all other significant knock test methods, requires rigid standardization of engine test conditions.

103 This method is now known to provide satisfactory information in respect to lean mixture ratings and is known as the ASTM F3 Method (formerly 1-C Method). This method also appears to provide reasonable control of minimum quality in respect to preignition resistance.

104 In Canada up to 1941, only limited attention had been given to the rich mixture properties of fuels. This was largely due to the fact that fuels of a given grade from various sources were remarkably uniform in composition. Furthermore, Canadian objections to aromatics and the fact that the F3 Method penalized aromatics resulted in low aromatic content and consequently reduced the chance of major variation in rich mixture quality. In England and Germany aromatics were not considered objectionable, and in addition fuels were drawn from widely divergent sources and consequently varied more in behavior with the result that considerable attention had been given to rich mixture qualities. In general, unless special engine development fuels are available for each fuel grade, engine manufacturer tends to develop his engines up to the limit of the particular fuel available from his source of supply. The major engine manufacturers up to 1941 had, with the sanction of the Military Services, pursued this plan in the case of both Grade 91 and Grade 100. It was known that some sources of both grades were inferior to the sources used for engine development, but this had not appeared to be of serious moment. However, subsequent to 1941 the rapid expansion of aviation gasoline production soon produced evidence that the F3 Method rating did not produce satisfactory control of rich mixture quality, and that engines had really been developed on Grades 91/96 and 100/120, whereas fuels supplied to the Services might be as low as 91/91 and 100/100. This finding made essential the adoption of a laboratory method of rating rich mixture quality. This was rapidly forthcoming in the form of the ASTM F4 Method (formerly 3-C Method) which had been under development for approximately 5 years.

CFR ENGINE RICH RATING METHOD

105 The F4 Method involved a great increase of complication in comparison with the F3 Method, since it involves supercharging, measurement of power, intake air quantity and fuel quantity, all of which are not required in the F3 Method. The F4 Method uses the CFR engine as does the F3 Method, but in the F4 Method the variable compression ratio feature of the engine is not used and compression ratio is fixed at seven to one, the variables being manifold pressure and fuel-air ratio. The wide differences in rich-mixture knock properties of two fuels of equal lean mixture quality which appear in a supercharged engine are not apparent on richening the mixture in an unsupercharged engine with variable cylinder compression ratio. In general, however, the fuel with high rich mixture quality will become superior in the unsupercharged engine as spark advance, mixture temperature and cylinder temperature are reduced.

IMPORTANCE OF QUALITY CONTROL

106 With the F3 and F4 Methods plus standard reference fuels, control of both lean and rich mixture knock quality is obtained. It is the aim of the specifications and of these methods that quality shall never fall below a minimum specified value in respect to both lean and rich mixture full scale properties. This aim has been substantially attained, but unfortunately it has not yet been possible to completely insure that no fuel supplied to the specifications for any given grade shall be not inferior to the fuel on which the engine was developed. This situation is recognized by the engine manufacturer who allows a margin of safety for service fuel inferior to his development fuel. The fact that the specifications attempt to insure minimum full-scale knock qualities and that much of the fuel delivered to service theaters may be superior to the minimum can lead to serious service difficulties if Engineering Orders are disregarded in respect to maximum permissible engine operating conditions. Thus, a given theater of operations may for a considerable period receive fuel which is considerably above minimum rich mixture Performance Number. Experiment in this theater of operations may show that War Emergency Rating Power can be raised considerably above the maximum specified by the engine manufacturer and Engineering Orders. Satisfactory operation may be experienced at such increased power up to the point where the fuel supplied to the theater of operations suddenly diminishes to the minimum specified rich mixture Performance Number which will result in wrecked engines due to cracked cylinder heads, burnt valves, melted pistons, etc.

107 Determination of the maximum operating conditions permissible for any given engine or any given grade of fuel such as Grade 100/130 is a long and complicated process involving a large amount of testing over a wide range of operating conditions with a series of calibrated reference fuels and elaborate instrumentation. Most of these necessities for determining permissible engine ratings on various fuel grades are not available in service theaters. In certain cases, of course, theaters of operation find it necessary to take chances in respect to operating engines in excess of specified maxima; there can be no argument in such cases as long as the magnitude of the risks involved are realized by those responsible for the operation.

VARIABLES AFFECTING FUEL TESTS

108 The use of reference fuels with which any fuel under test can be compared has, to a large degree, taken the uncertainties out of fuel rating. The use of reference fuels slightly better than and slightly worse than the fuel under test largely removes difficulties due to engine condition or atmospheric variations. The difficulties due to engine and atmospheric variations are not entirely solved by the use of reference fuels, however, since the fuel under test and the reference fuels may be affected differently. Thus, sensitive fuels such as highly aromatic blends suffer a greater relative reduction in performance due to bad engine condition (such as leaking valves or other causes of overheating) than do the reference fuels. Likewise high atmospheric humidity will improve the relative performance of some fuels more than it will that of the reference fuels. Thus, despite the use of reference fuels it is necessary to give attention to engine and atmospheric conditions. This does not infer that fuels should always be tested in engines which are in first-class condition, although the tendency is to do so since this makes for precision. It may be desirable, in setting up operational factors of safety, to know the behavior of a particular type of fuel in a full scale multi-cylinder aircraft engine which is in bad condition due to: leaky valves, combustion chamber

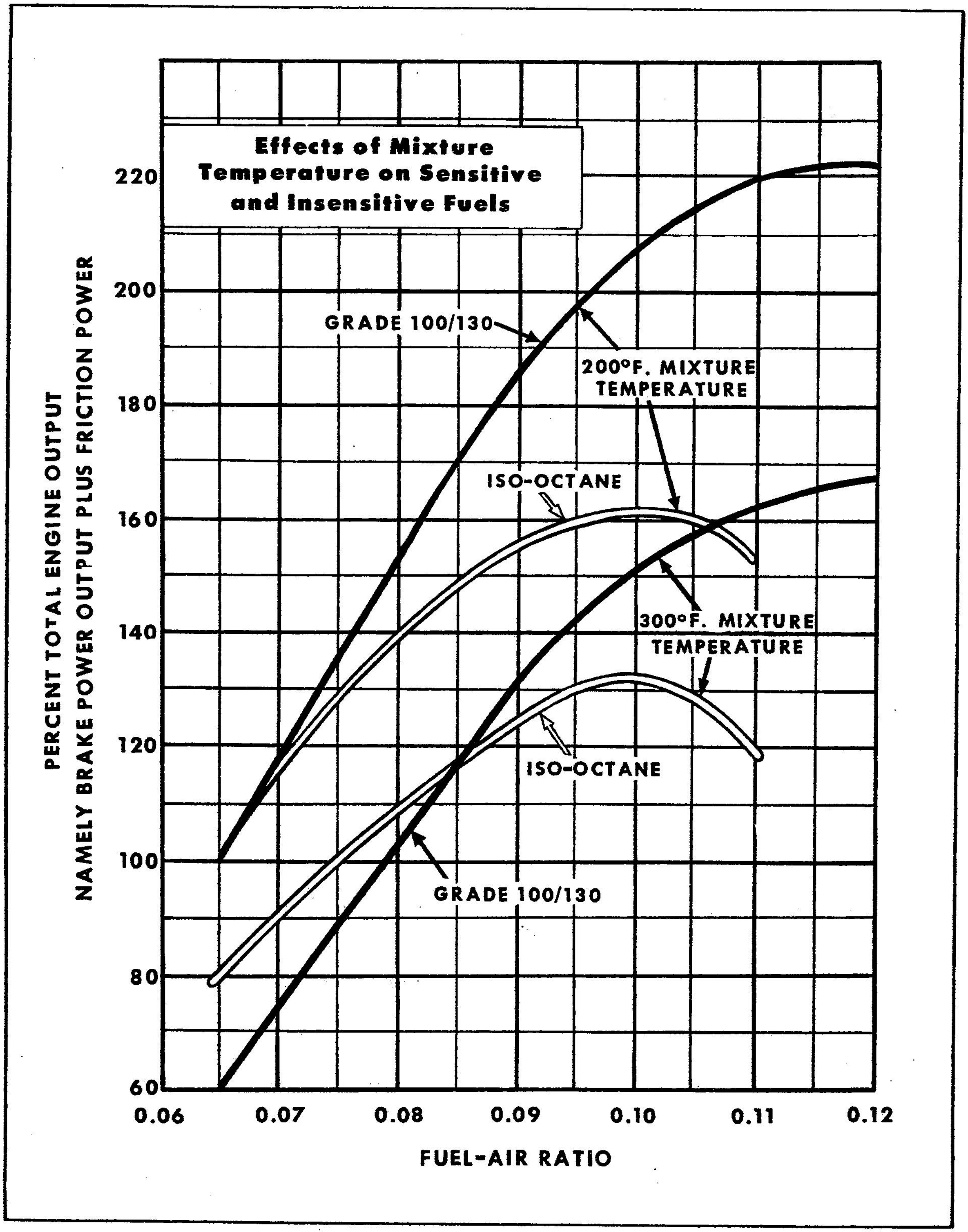

Effects of Mixture Temperature on Sensitive and Insensitive Fuels
PERCENT TOTAL ENGINE OUTPUT
NAMELY BRAKE POWER OUTPUT PLUS FRICTION POWER
220
200
180
160
140
120
100
80
60
0.06
0.07
0.08
0.09
0.10
0.11
0.12
FUEL-AIR RATIO
GRADE 100/130
200°F. MIXTURE TEMPERATURE
ISO-OCTANE
300°F. MIXTURE TEMPERATURE
ISO-OCTANE
GRADE 100/130

Figure 1-17

deposits, oil pumping, etc. Generally speaking, such tests need not be carried out since the results can be predicted by knowledge of fuel sensitivity obtained with standard laboratory test engines.

109 The use of the standard reference fuels, namely heptane-octane and octane-lead in both laboratory and full scale testing, has produced considerable progress in testing technique. The reference fuels are objected to in some quarters since they differ considerably from current service gasolines in respect to volatility and from most current gasolines in respect to sensitivity. The volatility differences do not appear to be important and the sensitivity effects can be argued both ways. Certainly some fuels have approximately the same sensitivity as the reference fuels, on the other hand Grade 100/130 does not, neither do the most probable improved fuels of the future. Furthermore, the present reference fuel system has an upper limit of 161 Performance Number and any known fuel which will be usable as a means of extending the reference fuel system to higher Performance Numbers is more sensitive than octane plus lead.

FUTURE REFERENCE FUELS

110 If fuels of more than 160 Performance Number are to be tested and used on more than a very limited scale, use of a reference fuel system will be almost essential. It is possible (and essential in certain studies involving fuel) to maintain constant engine performance on a given fuel from day to day and year to year; this involves a large amount of engine maintenance and elaborate control of engine cooling and intake air condition. While this is possible, it still requires a reference fuel and this reference fuel should preferably be of a Performance Number which will permit checking the engine at the maximum output at which the engine is used. While there is a need for a reference fuel of more than 161 Performance Number, no such fuel is presently available, and there is no general agreement as to what it should consist of. For the present, fuels of more than 161 Performance Number are tested against iso-octane + 6 ml. lead and the results reported in terms of power. Thus, if a fuel has a knock limited power 10% higher than iso-octane + 6 ml. lead it is reported as 161 x 1.1 or 177 Performance Number. Since a reference fuel system of more than 161 Performance Number is only required for rich conditions or lean conditions in a mild engine, sensitive components can be used and possible systems such as: (80% (heptane + iso-octane) + 20% toluene + 4 ml. lead or (97% (heptane + iso-octane) + 3% monomethyl aniline) + 4 ml. lead may be considered. In both systems illustrated above the amount of heptane in the iso-octane-heptane blend would be varied to match, or to bracket the test fuel under consideration.

PERFORMANCE NUMBER SCALE

111 While the Performance Number scale is now used for fuels of more than 100 octane number and is used in conjunction with octane numbers for fuels of less than 100 octane number nevertheless all testing of fuels is carried out by finding the blend of reference fuels which is equal under the particular conditions of test to the fuel being tested. When this matching reference fuel blend has been determined, the value is then converted to Performance Number by means of the standard tables of Performance Number versus octane number or octane plus lead. The Performance Number scale is merely a code for converting fuel knock values in terms of reference fuel into an index which is an approximate indication of relative engine performance.

112 The Performance Number scale is based on engine performance in terms of internal power plus external power, namely brake horsepower plus friction horsepower. Internal plus external power is used since this, rather than brake output, is the real index of the fuel performance. Furthermore, even on the basis of the sum of internal and external engine power the relative performance of fuels will not always be in proportion to Performance Numbers. Thus, the comparative performance of octane and octane plus 1 1/4 ml. lead (100 and 130 Performance Numbers, respectively) may be in the ratio of 100 to 120 or 100 to 140 depending on the engine type and engine conditions. Similar behavior below 100 Performance Number may be expected. The Performance Number scale is, however, set up on a basis of average behavior in a variety of engines. Performance Number is only an index of relative engine output in supercharged engines where the manifold pressure is varied to suit the knock value of the fuel. In the case of unsupercharged engines (naturally aspirated) or of supercharged engines run at constant manifold pressure, the Per-

formance Number of the fuel is not an index of relative permissible output, but rather of relative permissible compression ratio.

USE OF PERFORMANCE NUMBERS

113 Since fuel knock values are not measured in terms of Performance Numbers but rather in terms of reference fuels (except where fuels are above the limits of the present reference fuel scale), it may be questioned as to why fuels are not expressed in terms of the units in which they are measured. The answer is that neither of the present reference fuel systems bears a linear relation to engine performance. Thus in the case of octane numbers, each octane number represents an increasingly large increment of engine performance as the upper end of the scale is approached. Thus the difference between 70 and 72 octane numbers is 1 3/4 Performance Numbers, whereas between 98 and 100 octane number the difference is almost 6 3/4 Performance Numbers. In the case of octane plus lead, the effect found with octane numbers is reversed and each unit becomes of less importance toward the upper end of the scale. Thus, with octane plus lead, the difference between 100 and 100 plus 1 ml. lead is 26 Performance Numbers, whereas the difference between 100 plus 5 ml. lead and 100 plus 6 ml. lead is only 4 Performance Numbers. The adoption of the Performance Number scale results in a clearer understanding of fuel values and the fuel user has a better appreciation of his supplies. As long as octane numbers and particularly lead in octane were used to express values, the user had only a limited appreciation of the significance of fuel knock quality. Furthermore, a generalized discussion of the relationship of fuel knock quality to engine performance, such as is given in this EO, would not at present appear to be possible if knock quality is described in terms of values given in octane numbers and octane plus lead.

MANIFOLD PRESSURE RELATIONSHIP

114 It is not possible to express any reasonably accurate relationship between manifold pressure and Performance Number, since neither total power (brake power plus friction power) nor brake power are directly proportional to manifold pressure even at constant mixture temperature. However, a very approximate relationship between manifold pressure and fuel Performance Number does exist under conditions where manifold pressure is the only variable. For manifold pressures in excess of about 24 inches of mercury (hereafter hg) absolute, the manifold pressure minus seven inches is proportional to the fuel Performance Number required to just give knock-free operation at each manifold pressure level. As an example, the take off manifold pressure may be considered in the case of an engine set for operation on Grade 91/96 but which is to have its carburettor reset for operation on Grade 100/130.

115 Assume that the permissible manifold pressure which will just give knock-free operation on Grade 91/96 is 36" hg abs. The rich Performance Number of Grade 91/96 is 88 and for Grade 100/130 is 130. The manifold pressure permissible on Grade 100/130 assuming constant fuel-air ratio will be; $(36-7) \times \frac{130}{88} + 7$

$= (29 \times \frac{130}{88}) + 7 = 42.8 + 7 = 50$" hg abs. approximately. The relationship calculated above will only hold if it is possible to increase manifold pressure without significant increase of mixture temperature. This will hold in the case of an engine with a two-speed gear driven blower if the increase of manifold pressure can be obtained without changing from low blower gear to high gear. If a change to high blower gear is required, this will produce a considerable increase in mixture temperature and the figures calculated above will no longer be even very approximate.

116 Use of improved fuel knock quality by means of increased manifold pressure obtained by supercharging can have its limits unless cooling of the mixture after compression is resorted to. Since compression of mixture (or of air alone in a fuel injection engine or in a turbo supercharger) can produce a total temperature rise of as much as 176°C (350°F) in high blower gear, it is obvious that just raising manifold pressure will not give adequate power return, firstly due to low density of the ingoing fuel-air mixture and secondly, due to knock limitations resulting from high mixture temperatures.

117 In the case of an engine with a two-speed geared blower, the lower speed of which will permit full throttle operation at sea level takeoff on the available fuel, useful application of a higher Performance Number fuel will involve

change of engine or of takeoff procedure. If high blower gear is used for takeoff, it is possible that the higher mixture temperature may result in a lower takeoff power than is available with the lower Performance Number fuel and low blower gear. If the low blower gear ratio is increased so as to allow full throttle on the higher Performance Number fuel the increase in output will not be proportional to the percentage increase in fuel Performance Number owing to increased mixture temperature produced by increase of blower pressure ratio.

MANUFACTURE OF GRADES ABOVE 91/96

118 The case of Grade 91/96 versus Grade 100/130 discussed above is of interest since the Grade 100/130 will permit almost 50% more power than Grade 91/96 and since Grade 91/96 represents the highest grade which can be made from a gasoline which is found as such in the crude oil in the ground. The 50% increase in permissible power obtained with Grade 100/130 represents the improvement due to the elaborate chemical manufacturing which makes the Grade 100/130 possible.

119 The above discussion of Performance Numbers and Figure 1-6 show that the effectiveness of lead rapidly drops off as the concentration is increased. In November 1941 the lead concentration of Grade 100 was increased from 3.0 ml. to 4.0 ml; in the middle of 1943 the concentration was again increased to 4.6 ml. Since increase from 3.0 ml. to 4.0 ml. only increases Performance Number by 4 percent and from 4.0 ml. to 4.6 ml. by a further 2 percent, the gains hardly appear to be justified. When these changes were made, there were immediate demands for increased quantities of Grades 100 and 100/130, respectively, and the Military Services were not willing to reduce Performance Number to obtain increased fuel quantity. While the effects of changes from 3.0 ml. to 4.0 ml. and from 4.0 ml. to 4.6 ml. would have been slight in respect to Performance Number, they were very effective in increasing the total available production at fixed Performance Numbers. The change in 1941 increased output by 25% and the change in the middle of 1943 by 7%. These large changes in production are explained by the facts that they permitted increased use of gasoline distilled directly from crude oil (straight-run gasoline) and that straight-run gasoline becomes available at a rapidly increasing rate as its Performance Number is reduced. The question of the technical soundness of increasing lead content by 15 (i.e., 4.0 to 4.6 ml.) in order to obtain a Performance Number gain of 2% (or to avoid loss of 2%) has been vigorously debated by som of the engine manufacturers. Commercial specifications for gasolines for civil transport us do not permit more than 4.0 ml. lead in an grade except 115/145 whereas the militar Grades 91/96, 100/130 and 115/145 all perm the use of 4.6 ml.

FUEL SENSITIVITY

120 The question of sensitivity or the relatio between rich and lean ratings has been referre to a number of times in this booklet. Firstly it should be pointed out that sensitivity is purel relative. Engine output will be reduced on al fuels as engine conditions such as spark advance, cylinder compression ratio and mixtur temperature are made more severe. Sensitivit is an expression of change relative to the chang which would be experienced with the referenc fuels. Fortunately the two reference fuel systems, namely heptane-octane and octane plu lead, appear to be closely similar in sensitivity Sensitivity may be defined as the tendency t lose Performance Number as the engine conditions are made more severe. Conversely, o course, a sensitive fuel will gain in Performance Number as engine conditions are mad easier. As an illustration a 37°C (100°F) increase in mixture temperature may reduce th permissible output on iso-octane by 20%, where as a sensitive fuel equal to iso-octane at th lower temperature may lose 40% in permissibl output at the higher mixture temperature. Thus at the low mixture temperature the sensitiv fuel will be of 100 Performance Number, bu at higher mixture temperature its permissibl output is only six-eights of iso-octane. Thre quarters of the permissible output of octan indicates that the Performance Number is abou 75, but this assumption must be checked b bracketing the sensitive fuel with referenc fuels. If the sensitive fuel is found by bracketing to be equal to 91 octane number, its Performance Number is 75. Figure 1-17 illustrate the general pattern of behavior of iso-octan (namely 100/100 Performance Number) in comparison with a specially sensitive Grade 100/130.

121 In considering a specially sensitive Grade 100/130, it should be mentioned that fuels are

only required to meet minimum values for lean and rich Performance Number. Thus a gasoline of 110/130 and one of 100/150, both meet Grade 100/130 specifications although they represent fuels of widely differing sensitivity. Such variations in sensitivity can and do produce noticeable variations in full scale aircraft engine performance. Thus, a very mild engine may give significantly worse performance at takeoff on a 110/130 fuel than it does on one of exactly 100/130. Conversely, a very severe engine may, at the cruise condition, give better performance on a gasoline of 110/130 than it does on one of 100/150. This situation in regard to varying sensitivity represents a somewhat undesirable weakness of the fuel specifications. It rarely or never results in operational difficulty, however, unless the engine is operated beyond the ratings set up by the engine maker. In times when aromatic components are scarce, as at the present, gasolines of about 108/130 are quite usually supplied to meet Grade 100/130. To supply fuels which not only meet the minimum requirements of a particular grade but which are also of substantially uniform sensitivity represents an exceedingly difficult problem for which there is no present practical solution.

FUEL COMPONENTS VERSUS SENSITIVITY

122 The sensitivity of a finished fuel blend appears to be mostly controlled by the hydrocarbons in the blend. The addition of lead has practically no effect on sensitivity. (This is substantially true for typical aviation gasolines, but it appears that lead can increase sensitivity of motor gasolines which are already highly sensitive before the addition of lead.)

123 Aromatic amines on the other hand considerably increase sensitivity. Sensitivity is by no means thoroughly understood but present knowledge indicates that any engine effect which depresses the rating of a sensitive fuel results in producing an increased temperature to which the fuel-air mixture is exposed. The increased temperatures which relatively affect the sensitive fuel often cannot be directly measured.

124 The importance of sensitivity in aviation fuels is not at present capable of definite answer and the following points can be quoted as pros and cons of the question.

(a) Increase of sensitivity as a rule lowers the preignition resistance of the fuel.

(b) Engines with the maximum output per cubic inch of engine cylinder capacity as a rule tend to do best on the more sensitive fuels.

(c) Engines with very bad cylinder cooling as a rule do best on insensitive fuels. Reasons other than poor performance on sensitive fuels may suggest elimination of poor cylinder cooling.

DIFFERENCES BETWEEN AVIATION FUELS AND MOTOR GASOLINES

125 There are a number of differences in the properties of aviation fuels and of motor gasolines which make the latter unsafe for aircraft use unless both the engines and the aircraft are adapted to such use. Since the highest military grade of motor gasoline available is 80 octane number (58 Performance Number), use of motor gasoline in combat aircraft cannot be considered except for certain liaison types and other similar uses. Civil (personal) aircraft similar to light military liaison types usually operate on a fuel similar to Grade 80 but made to commercial specifications. Some of these aircraft operate on premium motor gasoline which has about the same Performance Number as Grade 80. This use often voids the guarantees of the makers of both the aircraft and the engine. Premium motor gasoline can mostly be used in an emergency if no other fuel is available but introduces a definite hazard from possible vapour lock. Vapour lock, which may result in loss of power during take-off, can have serious consequences. The major differences between aviation fuels and motor gasolines (both military and civilian) are as follows:

PERFORMANCE NUMBERS

126 Motor gasolines are specified by octane numbers, these octane numbers being determined by lean mixture methods somewhat similar to the "F3" lean mixture method used for aviation fuels. At present most civilian motor gasolines have their octane numbers determined by the ASTM F1 Method (Research Method) and are sold on the basis of such octane numbers. The F1 Method is much milder than the F3 Method and a civilian gasoline rated at 87 octane number by the F1 Method is of unknown quality as far as its use in an aircraft engine is concerned. Motor gasoline for military use is rated by both the ASTM F1 Method (Research

Method) and by the F2 Method (Motor Method). The Motor Method gives octane numbers very close to those determined by the F3 Method and thus usefully appraises gasoline for use in an aircraft engine. A motor gasoline of 80 octane number (58 Performance Number) will usually be equally as satisfactory in respect to knock properties in an aviation engine as Grade 80 aviation fuel. This will only be true, however, provided that the lower volatility and higher vapour pressure of the motor gasoline do not result in knock due to either bad distribution or lean mixture resulting from vapour locking.

VOLATILITY

127 The volatility of motor gasoline is usually lower than that of aviation gasoline in respect to the points at which 50% and 90% are boiled off in the standard distillation test. However, this is not always true and some civilian motor gasoline has very high volatility in winter (and high vapour pressure).

VAPOUR PRESSURE

128 The Reid vapour pressure of motor gasoline is usually higher than that of aviation fuel. Civilian winter grade motor gasoline may have a vapour pressure of 12 pounds per square inch. Current aircraft are not designed to handle fuels of more than 7 pounds Reid and use of such fuels therefore represents a hazard unless the aircraft are specified as being able to use such fuels.

CHEMICAL COMPOSITION

129 Motor gasolines are usually quite different from aviation fuels in chemical composition since the motor fuels usually contain considerable quantities of olefins. Motor gasolines may contain one part of sulphur in 400 parts of gasoline, whereas Military aviation fuels may not contain more than one part in 2,000 parts of gasoline, and this is often as low as one part in 10,000. The influence of the higher sulphur of motor gasoline on the operation of aircraft engines is not known.

130 The high olefin content of motor gasolines makes them less stable in storage than aviation gasolines unless the motor gasolines are specially treated for stability. Civilian motor gasoline does not have to stand extended storage and is usually much less stable (Tends to form more gum) than aviation fuel. Military motor gasoline (for example, Gasoline Automotive type 1) is required to have high storage stability and much larger inhibitor concentration is permitted than that allowed in aviation fuel.

131 Motor gasolines, by virtue of the facts that only a lean rating is specified and that the quantities of olefins and aromatics may vary over a wide range, are quite variable in rich mixture knock properties. For peace time use, the private motorist as a rule prefers gasolines of high olefin and aromatic content (although he does not know such gasolines by these terms, but rather by the behavior of his automobile). Combat grade automotive fuel has recently been improved in this respect since an F1 minimum rating of 86 ON is currently required.

ANTI-KNOCK COMPOSITION

132 Lead, if used in motor gasoline, has additions of both bromine and chlorine, whereas bromine only is used in aviation fuel. Lead concentration in motor fuel is not allowed to exceed 3 ml. per gallon.

SUMMARY

133 Regular and Premium civilian motor gasoline at present have F2 octane numbers of about 79 and 83 respectively and the Premium Grade can thus be said to correspond approximately to Military motor gasoline.

134 American Military or civilian aircraft have not been specifically designed and developed for the use of motor gasoline, but this practice has been followed to some extent in other countries. Use of motor gasoline in small civilian aircraft appears to be entirely feasible if it is desired to develop both engine and aircraft for the purpose.

135 Liaison type aircraft in combat theatres must depend on obtaining their fuel either from the Air Forces or from the Ground Forces. Since these aircraft are normally assigned to operate with the Ground Forces, it is most logical that operation be accomplished with the fuel available to the Ground Forces (and only Automotive Combat Gasoline is available), even though some increased maintenance may result.

136 Many of the engines used in liaison aircraft were originally designed to operate on unleaded fuel while all fuels (motor fuel and aviation gasoline) available in the combat theatres contain lead. In addition, increased main-

tenance may result from the fact that the higher "end point," the higher gum content and the increased inhibitor content of fuel used by Ground Forces all tend to increase combustion chamber, piston ring groove and valve stem deposits.

137 Use of any grade of aviation gasoline in ground equipment apart from representing the waste of relatively rare fuels, may cause operating trouble as a result of the higher lead content of Grades 91/96 and upwards.

PART 2

AVIATION TURBINE FUELS

GENERAL

1 Up to the present, petroleum has been the sole source of gas turbine fuels and this has been true for land and marine types as well as for aircraft types. A few turbines have been built to operate upon the natural gas produced with petroleum crude oil. The turbine of the turbo-supercharger used for both aircraft piston engines and Diesel engines is a gas turbine and petroleum is the source of the fuel used by the piston engines to which the supercharger is attached. In one form of catalytic cracking, gas turbines have been extensively used to supply the compressed air that is necessary to intermittently burn off the coke that forms on the catalyst during cracking. Combustion of the coke provides the heat energy to operate the turbine which in turn drives the compressor which forces the air through the catalyst on its way to the turbine. This use of gas turbines with catalytic cracking units is of interest since it is the only case where gas turbines burning solid fuel have been in successful service use. Gas turbines burning powdered coal are being developed but have not yet reached the state of service use.

2 In jet propulsion aircraft fuels, performance number has no present significance and range will be directly proportional to the heating value, specific gravity and Reid vapour pressure of the fuel which can be carried; provided, of course, that the fuel is completely burned, which would be unlikely in the case of a heavy tar-like fuel. A rather wide variety of fuels, varying from gasoline to kerosene, have been used successfully in jet engines. The more important factor appears to be that the design of the fuel injection nozzles and the combustion chamber should be such as to ensure thorough vapourization and proper burning of the fuel, see Figure 2-1.

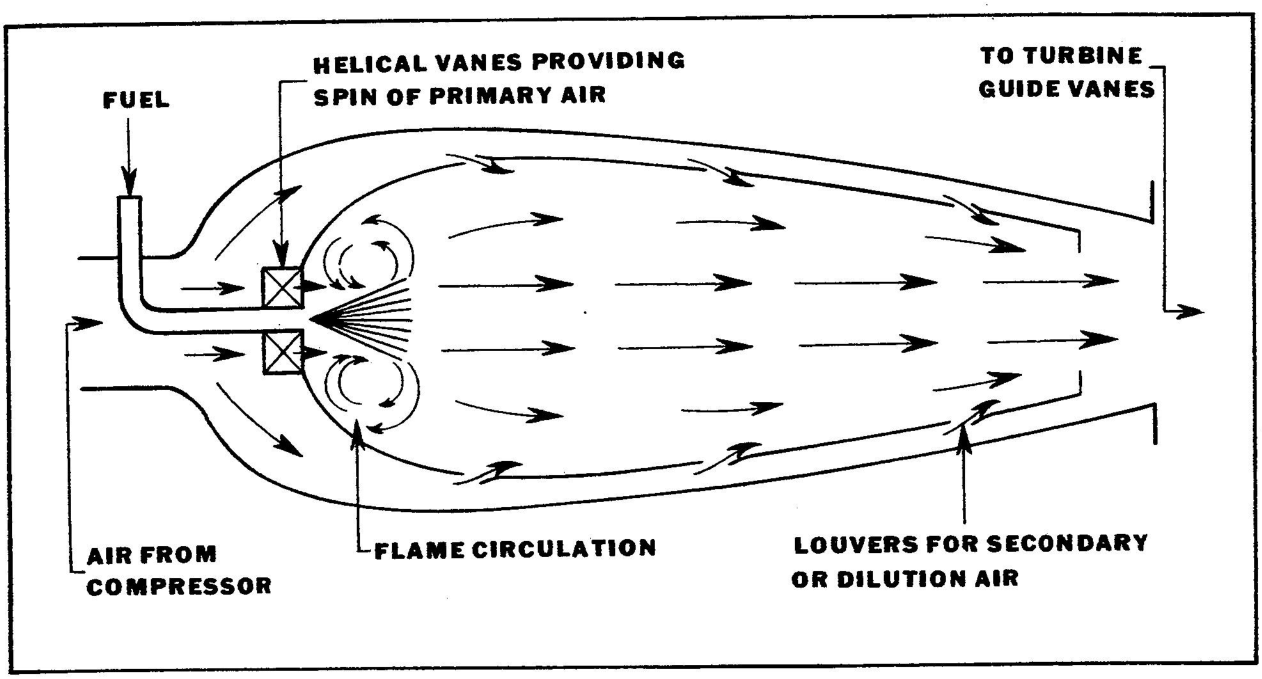


Figure 2-1 Turbine Fluid Flow

3 Turbine fuels in general and 3-GP-22 (now cancelled) in particular are similar to piston engine fuels in that they are required to consist exclusively of hydrocarbons but differ in that chemical composition is specifically limited by requiring that the aromatic content shall not exceed a specified maximum for combustion reasons. Due to the fact that 3-GP-22 permitted a 315°C (600°F) end point, the number of possible hydrocarbons which can be included in a blend becomes almost astronomical and in consequence this discussion will be almost entirely in terms of hydrocarbon type rather than in terms of specific hydrocarbons, e.g., normal heptane, toluene, diisobutylene, etc. By modifying 3-GP-22 to produce a blend with 1 to 2 lb Reid vapour pressure by removing hydrocarbons with four, five and six carbon atoms in the molecule, this reduces the number of possible hydrocarbons in the blend by about 100. If the end point of modified 3-GP-22 was cut to 204°C (400°F) the number of possible hydrocarbons which volatility restrictions would permit being included in a blend would still be nearly 6,000. 3-GP-22 modified to 204°C (400°F) end point and 1-2 lb Reid vapour pressure would, of course, be motor gasoline stripped of its light ends.

4 In the case of piston engine fuels, chemical composition includes various non-hydrocarbon additives such as: lead, aromatic amines, gum inhibitors and dyes. In the case of turbine fuels the only additives presently permitted are gum inhibitors.

AVIATION TURBINE FUELS

Qualities

5 Aviation turbine fuels should have the following qualities:

(a) Be "pumpable" and flow easily under all operating conditions.

(b) Be non-corrosive to the fuel system (sulphur content of 0.2% - 0.5%).

(c) Permit quick starting of the engine (flash point over 37.8°C (100°F)).

(d) Give good and complete combustion under all conditions.

(e) Good freezing point properties.

(f) Have as high a volumetric calorific value as possible or a high specific gravity.

(g) Lubricate efficiently certain moving parts in the fuel systems of some engines.

(h) Fuel combustion should not create any harmful by-products.

(j) Fire hazards should be reduced to a minimum.

6 Aviation turbine fuels, it appears, will only be limited, to type, by their availability. However the quality of the fuel, as in the case of aviation gasoline, must meet certain specifications.

VISCOSITY

Fuels Versus Water

7 Water, in small quantities is dissolved by fuel, and very often the accumulation of water may be sufficient to form a saturated solution. When the aircraft encounters freezing temperatures, liquid droplets or ice crystals form making adequate filtration necessary in the fuel system. The affinity of jet fuels for water makes it impossible to prevent fuel contamination by water. Therefore it is necessary to exercise extreme care in the handling, dispensing, and storage of this fuel.

8 Wax and other substances solidify when the fuel reaches its cloud point. Critical low temperature is that at which deposition of solids takes place. To specify this temperature ensures that the fuel will not become "non-pumpable" due to increase in viscosity.

9 It has been found that with heavier fuels the pour point temperature is generally too high for operation of aircraft at low temperatures. Therefore if distillates heavier than the kerosines are used as a turbine fuel, whenever very low temperatures are encountered, it would be necessary to heat the fuel in the aircraft tank in order to reduce its viscosity to a practical level, and to avoid deposition of solids. Such heating would be an unreasonable complication of the fuel system.

ADDITIVES

10 In the piston engines of the spark ignition type, additives such as lead and aromatic amines have, as seen above, marked effects

TABLE 1

AN PERFORMANCE NUMBERS ABOVE 100

Performance Number	*Knock Value	Performance Number	*Knock Value
100	0.00	131	1.36
101	0.02	132	1.43
102	0.05	133	1.51
103	0.07	134	1.59
104	0.10	135	1.68
105	0.13	136	1.77
106	0.16	137	1.86
107	0.19	138	1.96
108	0.22	139	2.06
109	0.25	140	2.17
110	0.28	141	2.28
111	0.32	142	2.40
112	0.35	143	2.52
113	0.39	144	2.65
114	0.43	145	2.78
115	0.47	146	2.92
116	0.51	147	3.06
117	0.55	148	3.22
118	0.59	149	3.37
119	0.64	150	3.54
120	0.69	151	3.72
121	0.74	152	3.90
122	0.79	153	4.09
123	0.84	154	4.29
124	0.90	155	4.50
125	0.96	156	4.72
126	1.02	157	4.95
127	1.08	158	5.19
128	1.14	159	5.45
129	1.21	160	5.71
130	1.28	161	5.99

*Knock Value	Performance Number	*Knock Value	Performance Number
0.0	100.00		
0.1	103.96	3.1	147.24
0.2	107.43	3.2	147.90
0.3	110.52	3.3	148.53
0.4	113.30	3.4	149.15
0.5	115.81	3.5	149.76
0.6	118.12	3.6	150.34
0.7	120.24	3.7	150.91
0.8	122.20	3.8	151.47
0.9	124.03	3.9	152.01
1.0	125.73	4.0	152.54
1.1	127.33	4.1	153.06
1.2	128.83	4.2	153.56
1.3	130.25	4.3	154.05
1.4	131.59	4.4	154.53
1.5	132.86	4.5	155.00
1.6	134.07	4.6	155.46
1.7	135.22	4.7	155.91
1.8	136.32	4.8	156.35
1.9	137.37	4.9	156.78
2.0	138.37	5.0	157.21
2.1	139.33	5.1	157.62
2.2	140.26	5.2	158.03
2.3	141.15	5.3	158.42
2.4	142.01	5.4	158.81
2.5	142.83	5.5	159.20
2.6	143.63	5.6	159.58
2.7	144.40	5.7	159.95
2.8	145.14	5.8	160.31
2.9	145.87	5.9	160.66
3.0	146.56	6.0	161.01

AN PERFORMANCE NUMBERS BELOW 100

ON(1)	PN(2)	ON	PN
100	100.00	79	57.14
99	96.55	78	56.00
98	93.33	77	54.90
97	90.32	76	53.85
96	87.50	75	52.83
95	84.85	74	51.85
94	82.35	73	50.91
93	80.00	72	50.00
92	77.78	71	49.12
91	75.68	70	48.28
90	73.68	**PN**	**ON**
89	71.80	99	99.72
88	70.00	98	99.43
87	68.29	97	99.13
86	66.67	96	98.83
85	65.12	95	98.53
84	63.64	94	98.21
83	62.22	93	97.89
82	60.87	92	97.57
81	59.57	91	97.23
80	58.33	90	96.89

PN	ON	PN	ON
89	96.54	68	86.82
88	96.18	67	86.21
87	95.82	66	85.58
86	95.44	65	84.92
85	95.06	64	84.25
84	94.67	63	83.56
83	94.27	62	82.84
82	93.85	61	82.10
81	93.43	60	81.33
80	93.00	59	80.54
79	92.56	58	79.72
78	92.10	57	78.88
77	91.64	56	78.00
76	91.16	55	77.09
75	90.67	54	76.15
74	90.16	53	75.17
73	89.64	52	74.15
72	89.11	51	73.10
71	88.56	50	72.00
70	88.00	49	70.86
69	87.42	48	69.67

(1) ON = Octane Number. (2) PN = Performance Number

*Knock Value = ml.TEL/US Gal. in Iso-octane

1 Imp.Gal.= 1.2 US Gal.

$$PN = \frac{2800}{128 - ON} \qquad ON = 128 - \frac{2800}{PN}$$

TABLE 2

VISCOSITY OF FUELS AND WATER						
LIQUID	VISCOSITY(1) AT TEMPERATURE					
	100° F			MINUS 40° F		
	MAX.	MIN.	TYPICAL	MAX.	MIN.	TYPICAL
3-GP-23A	1.25	0.9	1.0	8.5	3.5	4.0
3-GP-22A (3LB. REID VAPOUR PRESS)	1.0			3.5		
GRADE 100/130	—	—	0.52	—	—	1.25
MOTOR GASOLINE 400° F END POINT AND 8 LB. REID VAPOUR PRESS	—	—	0.55	—	—	1.50
WATER	.69			1.54 AT PLUS 40° F		
(1) IN CENTISTOKES						

in controlling combustion. In Diesel engines, additives such as amyl nitrate have marked effects on combustion control but are presently used only to a limited extent in practice.

11 Combustion control additives for gas turbines are not used for the simple reason that to date no effective material has been found which can be blended into liquid fuels. Many liquids have been tested which make combustion worse but none that make it better. Acetylene added in the combustor would improve combustion of petroleum fuels but carrying this gas in an aircraft is obviously impracticable for reasons of weight and safety, apart from cost and limited availability.

GUM INHIBITORS

12 At present, inhibitors used in US military turbine fuels are identical in type and permissible quantity with those used for military aviation gasolines. That these inhibitors are the best for preventing development of gum in turbine fuels is not yet known and changes may be made in the future. The presently used inhibitors appear to provide reasonably good control of stability.

13 The importance of gum in turbine fuels is not completely known. Gum in aviation gasoline is almost completely soluble in the gasoline and only becomes apparent when the gasoline is evaporated. In very unstable motor gasoline or "cracked kerosene" and blends of the two, gum may exist in soluble form and may also occur in an insoluble form which is precipitated out as a tar somewhat resembling rubber cement. Either type of gum and particularly the insoluble form can be expected to have serious effects on the fuel system of turbine engines. Insoluble gum is likely to have serious effects on the fuel metering pumps and on the fuel valves and is likely to choke fuel filters. The soluble type can be expected to cause difficulty in the fuel system at points where microscopic leakage occurs and exposes thin films of fuel to air and thus to evaporation. Fuel valves represent points usually having microscopic fuel leakage.

14 The importance of gum on combustion properties is not known but since both soluble and insoluble gums are materials of very high boiling points they are likely to have an unfavourable effect. However, the effects on combustion are likely to be minor since it takes

only a small amount of gum to produce fuel system difficulties and these difficulties will become apparent before combustion effects have shown up.

15 To some extent the unfavourable effects of gum on turbine fuel systems can be estimated from experience with gummy domestic fuel oil in household heating appliances.

COMPOUNDS PRODUCING SOLIDS

16 Fuels which contain compounds which burn to solids (except carbon which has been discussed above) are undesirable since the solids may deposit in the combustors, on the nozzle guide vanes and on the turbine buckets. The deposits, even if inert, may break loose and cause damage or may reduce engine output by change of profile of the guide vanes or the turbine buckets. The solids may be corrosive and, if so, all parts exposed to combustion products, i.e. combustors, nozzle guide vanes, turbine buckets, jet pipe, etc., may be attacked.

17 The materials which are soluble in fuel and which form solids on combustion are nearly all compounds based on a metal. Amongst the metals which may be involved are lead, vanadium, calcium and sodium. Lead (tetraethyl) is the most important of these metals and results from the use of aviation gasoline. Many Canadian aircraft turbines are designed for use of combat aviation gasoline but this fuel significantly reduces engine life. Vanadium compounds are extremely corrosive but so far have not proved a problem with aircraft turbine fuels. Vanadium compounds are a problem with land marine turbines using heavy residual fuels (residual meaning that the fuels are not distilled and cannot be distilled without decomposition). Calcium can and has been present in aircraft turbine fuels but is not important. Calcium compounds burn to inert solids and can result from careless refining or contamination with calcium (lime) base greases. The solids produced by sodium compounds can be and are likely to be very corrosive, sodium is most likely to occur in aircraft turbine fuels as a result of careless refining or by contamination with sodium (soda) base greases.

18 While atmospheric dust is not a fuel problem it may be mentioned as a solid which can cause turbine difficulties. It may deposit in the hot parts of the engine (combustors, etc.) and particularly so if the dust has a low fusion temperature. It can also cause difficulties by forming deposits on the blades of axial compressors and this trouble may be serious if oil is present on the blades.

CORROSION

19 Sulphur is a component of all petroleum products to a greater or lesser degree and since it can form sulphuric acid on combustion, it is immediately under suspicion as being a source of corrosion. Aviation gasolines are not permitted to contain more than 0.05% sulphur by weight. Present aircraft turbine fuels are permitted to contain 0.4% sulphur, and heavy bunker (boiler) oils may contain as much as 4%. Heavy bunker oils containing 4% sulphur are successfully burned in some marine Diesel engines without causing more corrosion than fuels with less than 1% sulphur.

20 Pure nickel and alloys containing high percentages of nickel have, in the past, been found to be rapidly attacked by hot gases resulting from the combustion of high sulphur fuels. As a result of this experience, high sulphur fuels have been under particular suspicion for aircraft turbine use since the hottest parts (combustor liners, turbine guide vanes and turbine buckets) in some engines are made of alloys containing as much as 75% nickel.

21 Sulphur in a fuel can, when the fuel is burnt, form a variety of compounds. When the over-all fuel-air ratio is lean (lower than "chemically correct", the combustion gases thus contain free oxygen and are said to be oxidizing), it will burn to oxides of sulphur. Sulphur dioxide and trioxide can combine with the water present in the combustion gases to form sulphurous and sulphuric acids respectively but this requires that the gases be cooled nearly to atmospheric temperature. If the fuel-air ratio is rich (if there is insufficient oxygen available to completely burn all the fuel this results in combustion gases which are said to be reducing) then the combustion gases may contain hydrogen sulphide or sulphur vapour.

22 In recent years it has been shown that the effects of sulphur upon nickel alloys depend, to a marked degree, upon the existence of oxidizing or reducing conditions. If the gases are strongly reducing and the temperature is high enough, a fluid slag of nickel sulphide is formed and drips off the surface of the exposed parts. Reducing gases may also very significantly reduce the strength of highly stressed parts by a process known as "stress corrosion"

and this can occur without visible surface corrosion. When the hot combustion gases are strongly oxidizing, the effects of sulphur upon the corrosion or "stress corrosion" of nickel and its alloys may be so slight as to be unimportant.

23 The over-all fuel-air ratio of an aircraft gas turbine rarely exceeds 0.018 and the combustion gases thus contain in combined form about three-quarters of the oxygen in the air drawn into the compressor. Corrosion due to sulphur in the fuel has not proved to be an important problem in aircraft gas turbines and this is probably due to the fact that the combustion gases are so strongly oxidizing. While the over-all fuel-air ratio rarely exceeds 0.018, the fuel-air ratio in the primary combustion zone (that is, in the immediate zone of the fuel spray - see figure 2-1) may be richer than 0.066 and hydrogen sulphide may be present in this zone. Under some conditions of combustion, such as those in some types of domestic heating apparatus, sulphur is known to cause increased deposition of coke. Up to the present, any difficulties due to high sulphur in aircraft turbine fuels would seem to be the result of increased coke deposition.

VOLATILITY

Effect Of Chemical Type

24 The effect of chemical type and of structure of a given chemical type upon boiling point (volatility) is roughly as follows:

Paraffins

25 For a given number of carbon atoms in the fuel molecule, the paraffins have the lowest boiling points. For a given number of carbon atoms, the straight-chain types have the highest boiling points and the highly branched types the lowest. For example, two heptanes may be considered with normal heptane being the least branched and triptane the most highly branched types possible with 7 atoms. Normal heptane has a boiling point of 98°C (209°F) and triptane of 81°C (178°F).

Olefins

26 Olefins usually but not always have slightly higher boiling points than a paraffin of the same number of carbon atoms and the same branching of the structure, see Table 6, Compounds 8, 25 and 26.

Cyclic Paraffins (Naphthenes)

27 Naphthenes usually have higher boiling points than a paraffin with the same number of carbon atoms.

Aromatics

28 Aromatics have higher boiling points than paraffins and olefins of the same number of carbon atoms. There is no regular relationship between the boiling points of cyclic paraffins and aromatics having the same number of carbon atoms and identical structure, e.g. Compounds 14 and 15, 53 and 55, 52 and 57 of Table 6.

BOILING POINT VERSUS CARBON ATOMS

29 It is possible to generalize on the number of carbon atoms in the lightest and heaviest compounds which can be included in turbine fuels as a result of boiling point, Reid vapour pressure or flash point restrictions in the specifications. Thus, a 316°C (600°F) end point will permit the inclusion of compounds of all chemical types having a maximum of about 17 carbon atoms. A 204°C (400°F) end point permits the inclusion of compounds having a maximum of about 12 carbon atoms (normal paraffins and aromatics being about equal in this respect). 3-GP-23A having a flash point of 43°C (110°F) minimum will be restricted to compounds with a minimum of about 10 carbon atoms and with a maximum of about 16. 3-GP-22 having a permissible maximum Reid vapour pressure of 7 psi, can contain compounds with as few as four carbon atoms.

30 If the Reid vapour pressure of 3-GP-22 is reduced to 1-2 psi, compounds with six carbon atoms as a practical minimum can be present. A fuel with a 204°C (400°F) end point and 1-2 lb maximum Reid vapour pressure would contain compounds with six minimum and 12 maximum carbon atoms.

31 The Reid vapour pressure test and the flash point test are different methods of measuring what is essentially the same property — that is vapour pressure. To measure the flash point of a fuel with a Reid vapour pressure of 7 psi would require an inconveniently low fuel temperature (roughly of the order of minus 100°F). The Reid vapour pressure test conducted at the standard temperature of 38°C (100°F) is not an accurate test determination for fuels such as kerosene. To obtain accurate

and reproducible values of the vapour pressure of kerosene by the Reid method would require that the test temperature be increased to a level that would make the test very inconvenient to operate.

32 The quickness and ease of starting a jet turbine depends on the volatility of the fuel at starting temperatures and on the viscosity of the fuel. It is essential that the turbine should start readily under all temperature conditions. Therefore the atomized spray of fuel must be readily ignitable down to low temperatures. It is obvious that ease of starting will depend on fuel volatility, but in practice it is found that the fuel viscosity is the more critical requirement. The critical viscosity in this respect is usually at a temperature approximately equal to the cloud point of the fuel. It is sufficient to specify a maximum cloud point temperature of the fuel, and it should be possible, by suitably high fuel pressure, to ensure ready starting.

COMBUSTION PROPERTIES

Composition Versus Combustion

33 In discussing the relation of composition to combustion it should be borne in mind that even with a given chemical type of hydrocarbon (for example, the paraffins), variation of composition nearly always involves changes in physical properties such as boiling point and viscosity. Changes in physical properties can have considerable effects upon combustion properties.

34 Therefore, in considering the relation of the combustion properties of various chemical types of hydrocarbons they should be compared on a basis of approximately similar boiling points. In general, where turbine fuels of liquid type are involved, the combustion problem becomes less difficult as:

(a) The amount of hydrogen in the fuel molecule is increased. For the rest of this discussion the per cent by weight of hydrogen in the molecule divided by the weight per cent carbon and known as hydrogen-carbon ratio or H/C ratio will be used.

(b) The boiling point of the hydrocarbon compound is reduced.

(c) The range of combustibility increase: The range of combustibility is the ratio of th richest mixture which will burn divided by th leanest mixture which will just burn. Thus in a piston engine, paraffins will usually giv steady ignition from 0.13 fuel-air ratio on th rich side to 0.045 fuel-air ratio on the lea side (the latter only in a particularly good engine), thus the range of combustibility is 2. to 1.

(d) The flame speed increases. The flam speed can be defined as the speed at which flam spreads in a non-turbulent mixture of fuel vapour and air. Flame speed can obviously onl be determined for a liquid fuel which can b vapourized without decomposition. Very heav fuels (for example, Grade 1120 lubricating oil cannot be vapourized in air without decomposition of the heavy hydrocarbon molecules.

NOTE

On the above basis, when considerin chemical compounds of equal boilin point, paraffins will be the best, cycli paraffins (naphthenes) and olefins nex best and aromatics poorest. For the present, diolefins and acetylenes will be neglected since they can only be presen in very minor proportions and furthermore, their combustion properties are known only in the case of a few compounds. Of the compounds which can be present, high boiling aromatics will have the least favourable combustion characteristics. There is some evidence that aromatics boiling higher than 204°C (400°F) are particularly unfavourable.

35 While it is generally true that H/C ratio is an excellent measure of the combustibility of liquid fuels, it has marked exceptions when gases are concerned. Acetylene with the low H/C ratio of 0.084 has outstandingly good combustion properties. Gases are not used as fuels for aircraft gas turbines and will not be further discussed.

H/C RATIO VERSUS CARBON ATOMS

36 In considering the H/C ratios of various groups of chemical compounds, the behaviour with increasing number of carbon atoms in the fuel molecule is significant.

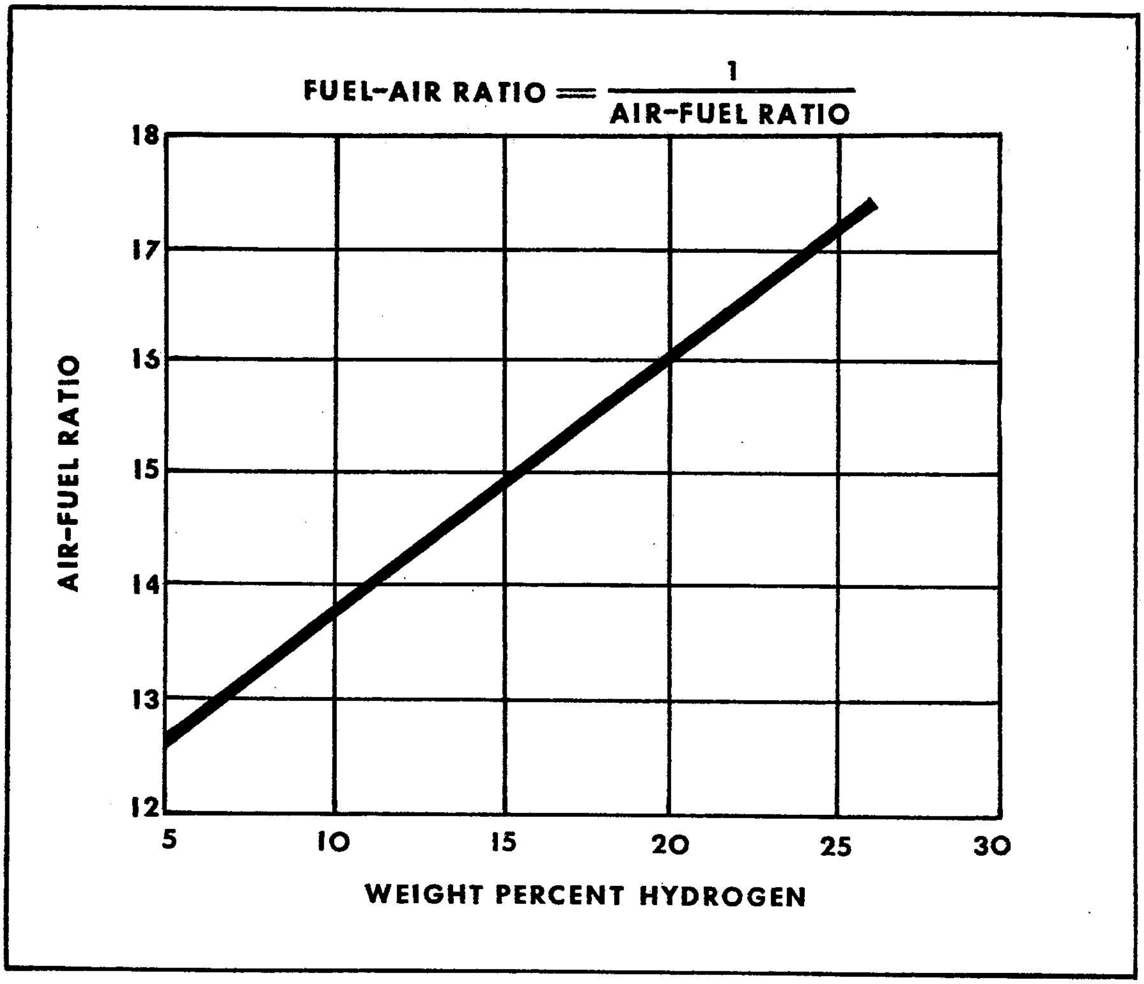


Figure 2-2 Hydrogen Versus Air-fuel for Complete Combustion

Paraffins

37 The ratio drops with increasing number of carbon atoms. It is 0.336 for one atom (methane) and 0.178 for sixteen atoms but does not change very significantly after eight atoms.

Olefins

38 The H/C ratio is independent of number of carbon atoms and is 0.168 for all chain compounds, e.g. Compounds 23-26 inclusive and 59 to 66, Table 6. There are cyclic olefins which have different H/C ratios but these are not included here.

Aromatics

39 The ratio can be as low as 0.067, which is the value for naphthalene (moth balls - Compound 55, Table 6) but it is generally higher than 0.084 (benzene) for the hydrocarbons of interest in turbine fuels.

Dilefins And Acetylenes

40 The ratio is the same for a diolefin and an acetylene if both have the same number of carbon atoms. Acetylene has a ratio of 0.084 and this is the same as that of benzene. Butadiene (a diolefin) and butyne (an acetylene) have a ratio of 0.126.

EFFECT OF HYDROCARBONS AND FUEL-AIR RATIO ON COMBUSTION

41 The hydrogen content of hydrocarbons has a marked effect on the fuel-air ratio for complete ("chemically correct") combustion.

For instance, naphthalene (moth balls) requires about 33 wt % more fuel per lb of air than does methane (due to the fact that methane has a higher H/C ratio). One pound of hydrogen requires 34.2 lb of air (the air containing 23.2 wt % of oxygen) for complete combustion to steam and releases 52,000 Btu in the process. One lb of carbon requires 11.5 lb of air for complete combustion to carbon dioxide and releases 14,100 Btu, see Table 6, in the process.

42 It should not be assumed that a fuel containing 20% hydrogen-80% carbon will release heat in proportion to its overall composition. Thus, a fuel containing 20% hydrogen (almost exactly that of ethane) will not release (52,000 x 0.2) + (14,100 x 0.8) or 21,680 Btu but slightly less, see Table 6. The heat release for some types of hydrocarbons may, however, be more than would be computed from the hy drogen and carbon content. This discrepan is explained by what is known as the "heat formation". Thus, if hydrogen and carbon combining to form a given compound, relea part of their heats of combustion, the con pound, as in the case of ethane, will have heat of combustion less than calculated fro its hydrogen and carbon contents. If heat en ergy has to be added to make the carbon ar hydrogen combine, as in the case of acetylen then the heat of combustion of the compour will be higher than calculated from the hydro gen and carbon contents.

43 One pound of air burning with hydroge releases 1520 Btu and burning with carbon re leases 1225 Btu. The air-fuel ratio (the in verse of fuel-air ratio) of hydrogen is 34.

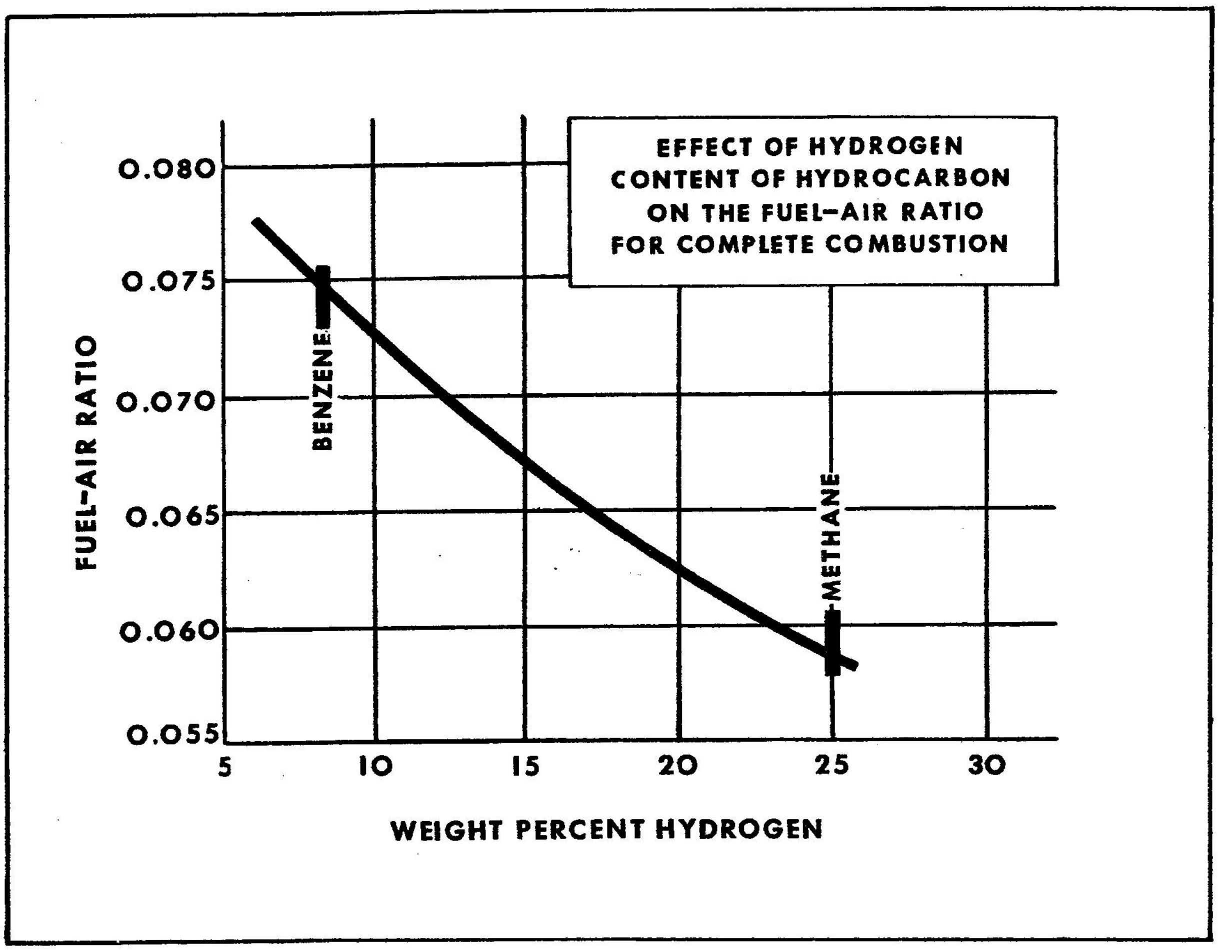


Figure 2-3 Hydrogen Versus Fuel-air for Complete Combustion

and is 11.5 for carbon. It can be shown that the relation of air-fuel ratio to hydrogen content is a straight line between zero per cent hydrogen (pure carbon) and 100% hydrogen, and the air-fuel ratio for complete combustion of any pure hydrocarbon is readily computed if the hydrogen content is known. Figure 2-2 shows this relationship between 5% and 25% hydrogen which covers almost the entire range of possible hydrocarbons.

44 Thus, if a hydrocarbon contains 20% hydrogen, one lb of fuel will require:

34.2 x 0.2 = 6.84 lb air for combustion of hydrogen content
11.5 x 0.8 = 9.20 lb air for combustion of carbon content

or a total of 16.04 lb air per lb of fuel.
Fuel-air ratio =

$$\frac{1}{\text{air-fuel ratio}} \quad \text{therefore} \quad \frac{1}{16.04} = 0.0623$$

which is the fuel-air ratio for complete combustion of a hydrocarbon containing 20% hydrogen 80% carbon. Figure 2-3 shows the fuel-air ratio for complete combustion versus wt % hydrogen. Since H/C ratio has been freely used in the discussion of turbine fuel properties, Figure 2-4 has been included to show the relation of fuel-air ratio to H/C ratio.

45 In the case of commercial fuels of which the hydrogen content is known, Figure 2-3 will give fuel-air ratio values which are slightly in error if the fuel contains significant quantities of impurities such as sulphur or nitrogen.

FREEZING POINT PROPERTIES

Effect Of Chemical Type

46 In discussion of the effects of chemical type upon freezing point it must be considered that a compound that has a high freezing point may be blended with a compound or compounds of much lower freezing point and that the blend will have a freezing point much lower than that of the high freezing point compound. Thus, about 5% of benezene with a freezing point of 5°C (42°F) may be blended with 95% of a normal aviation gasoline and the blend will have a freezing point of about -60°C (-76°F). Likewise, two paraffins, each having a freezing point of-60°C (-76°F) will, when blended 50-50, have a freezing point which may be significantly lower than -60°C (-76°F). These blending effects should be considered in connection with the following discussion.

Paraffins

47 The straight chain paraffins up to 7 carbon atoms (heptane) have a freezing point below-60°C (-76°F) but beyond 7 carbon atoms (normal heptane) it rises above this value. Branching the chain in general reduces the freezing point but if carried to the maximum possible degree of branching causes a very considerable increase, for example, normal heptane and triptane, see Table 6. Straight chain paraffins of 9 carbon atoms and more may cause difficulty with freezing point and may have to be removed but are preferably retained since they have excellent combustion properties. They are, however, very desirable constituents of high grade Diesel fuel and thus may not be available for turbine fuel. The straight chain paraffins of more than 7 carbon atoms occur abundantly in crude oil and consequently kerosenes consisting very largely of paraffins usually have freezing points considerably above-40°C (-40°F). Such kerosenes constitute the highest grade required for household lamps using wicks and required to burn without smoke or charring the wick.

Cyclic Paraffins (Naphthenes)

48 Naphthenes in general have lower freezing points than straight chain paraffins of 8 carbon atoms and more. Naphthenes with a boiling point lower than 315°C (600°F) occur naturally in crude oil and sometimes in high percentages. Naphthenic kerosenes of low freezing point are very rare, however. Naphthenes of more than 150°C (300°F) boiling point will cause less interference with freezing point of turbine fuel than will naturally occurring paraffins of similar boiling point.

Olefins

49 Olefins of more than 150°C (300°F) boiling point will usually have lower freezing points than the naturally occurring paraffins of similar boiling point. Thus, a crude oil fraction containing a large amount of paraffins boiling above 150°C (300°F) may not be usable in turbine fuel because it produces too high a freezing point. This portion may be given a mild cracking treatment, which converts the paraffins to ole-

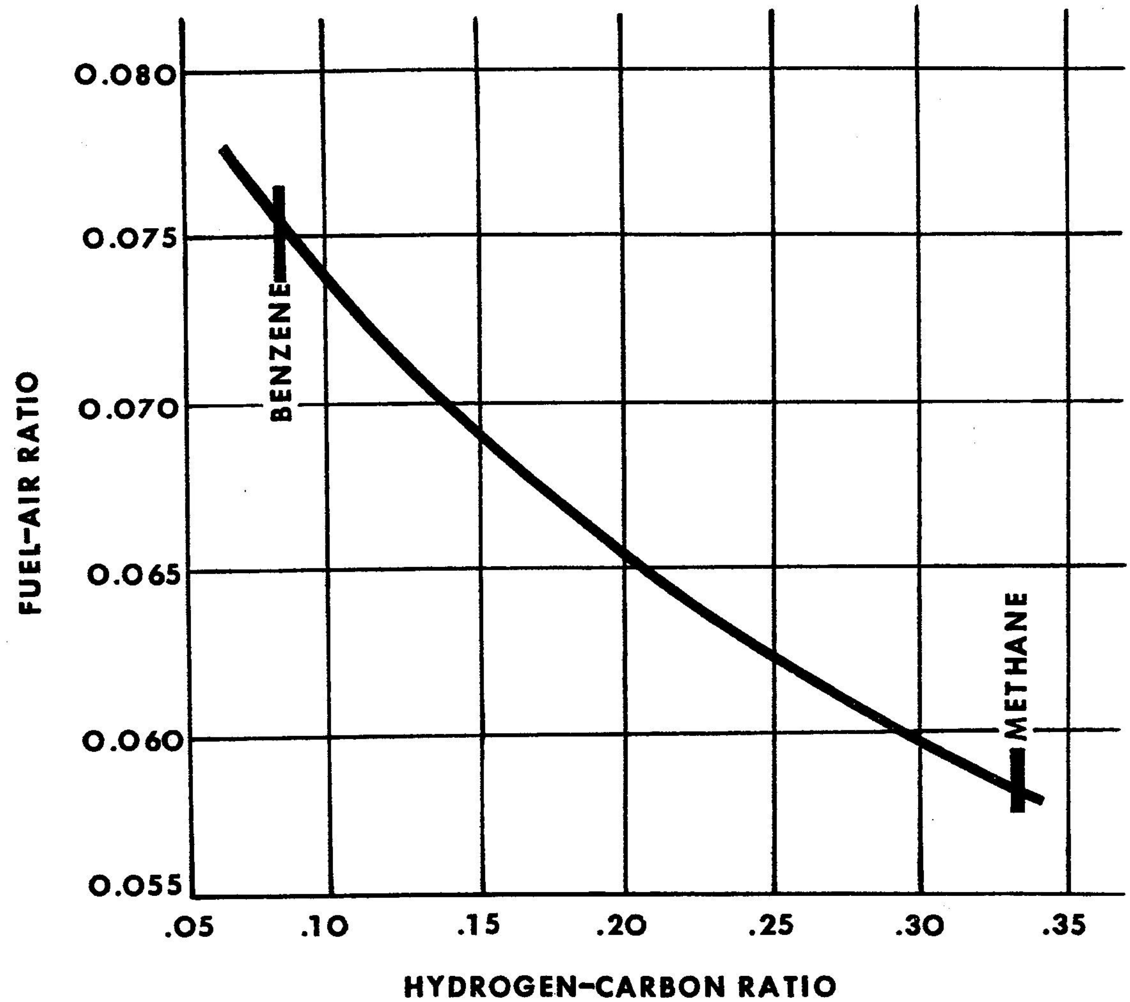


Figure 2-4 H/C Versus Fuel-air for Complete Combustion

fins of lower boiling point, and will then meet freezing point requirements.

Aromatics

50 Some of the simpler aromatics with up to 8 carbon atoms have very high freezing points, for example, benzene, ortho-xylene and paraxylene, see Table 6, and thus are undesirable components of turbine fuel. These materials, however, have great value for other uses and are excluded if they can be economically removed or recovered. The aromatics of 9 carbon atoms and more are usually much lower in freezing point than paraffins and naphthenes of corresponding boiling point. Many straight-run kerosenes of very low freezing point owe their freezing points to the presence of a considerable amount of aromatics. Most "cracked kerosenes" of low freezing point have a very considerable aromatic content. It may be said that the higher the end point of turbine fuel, the more useful aromatics become in regard to meeting a freezing point requirement of

-60°C (-76°F).

CALORIFIC VALUE

Heat Of Combustion

51 The heat of combustion is a deciding factor in the use of petroleum products for jet fuel. The amount of heat (energy) produced from a given quantity of fuel should be as high as possible, as this gives greater energy (hence aircraft range) from a given volume of fuel. However, the "heavier" grades of petroleum have higher calorific values than the "lighter" grades, but the "heavier" grades cannot be used as aircraft turbine fuel due to their high pour points. In view of the above it is imperative that only one grade of jet fuel should be tolerated, for in wartime storage and distribution of various grades is difficult and does not constitute sound logistics.

52 Certain additives have been mixed with jet fuel to combat the formation of carbon in the burners. Tests have shown that a fractional percentage of special additives keep the burners and atomizer nozzles free from any heavy deposits of carbon. Further investigation is being conducted to obtain a stable fuel with all the necessary desirable qualities and elimination of corrosive and deleterious contents.

FIRE HAZARD

Causes

53 There are three main fire hazards caused from the use of jet fuel.

(a) The spilling of the fuel onto a surface, with subsequent ignition from a spark or other hot point in the vicinity.

(b) The spilling of the fuel onto a surface sufficiently hot to cause self ignition of the fuel.

(c) The existence of inflammable or explosive mixtures in the aircraft fuel tank.

54 These hazards depend on the volatility, spontaneous ignition temperature of the fuel and on the temperature and pressure in the

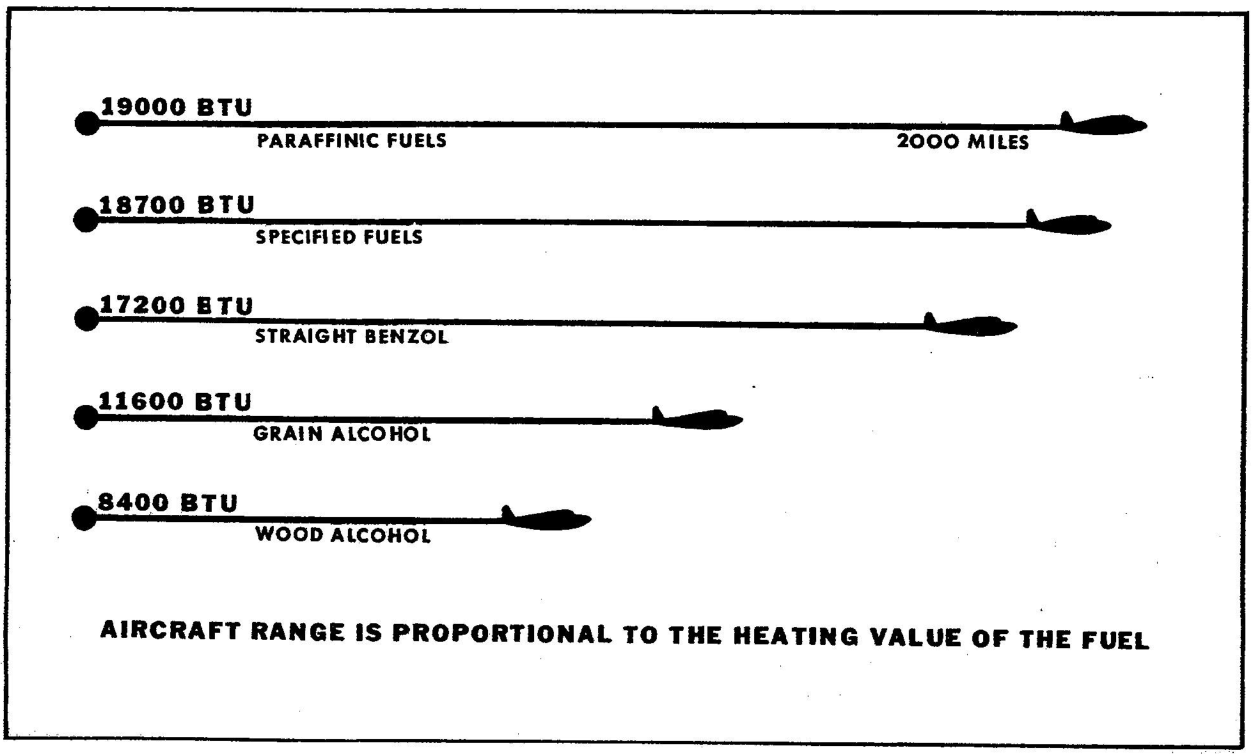


Figure 2-5

aircraft fuel tank. The fire risk is slightly higher with jet turbine fuels than with gasoline, but should a fire occur the rate of spread with jet fuels will be much lower, owing to its lower volatility.

EXPLOSIVE LIMITS

55 Gasoline is considered to be a high vapour pressure fuel which means that it vapourizes readily. This fact adds somewhat to its safety in storage and handling, since in a tank it forms so much vapour that the air is driven out and the resulting mixture in the vapour space in a tank is usually too "rich" to burn. The term "usually" is used because the vapour pressure changes with fuel temperature. In the case of 3-GP-25B aviation gasoline temperature of the fuel in a tank drops to -7°C (20°F), the vapour mixture in the tank is explosive, see Figure 2-6. Below -40°C (-40°F), the vapour pressure is so low that the vapours formed in the tank are too "lean" to burn. Therefore, for aviation gasoline, 3-GP-25B -40°C (-40°F) and -7°C (20°F) are considered the lower and upper explosive temperature limits respectively for fuel vapours in a tank.

56 One can see then that for the most part aviation gasoline is stored and handled at temperatures at which the vapours in closed tanks are above the upper or "rich" explosive limit. Kerosene, 3-GP-23A, on the other hand, has a very low vapour pressure and a lower or "lean" explosive limit of about 37°C (100°F). Here again storage and handling is normally conducted at temperatures outside the explosive range.

57 The new 3-GP-22A turbine fuel has an intermediate or medium vapour pressure (2-3 psi). Although this vapour pressure is dictated by fuel availability and engine and aircraft performance, it does create an additional storage problem. In this case, the temperature range in which explosive vapours are formed are from -23°C (-10°F) to 27°C (80°F). This will include most of the temperatures at which this fuel will be stored or handled, hence the need for additional caution in all storage, handling, transfer and refuelling operations with 3-GP-22A fuel.

58 This fuel is no different from any other petroleum fuel in one respect. It and its vapours still require a source of ignition to inflame or explode. Therefore, if all safety regulations are followed and ignition sources are excluded from the vicinity, this fuel will be no

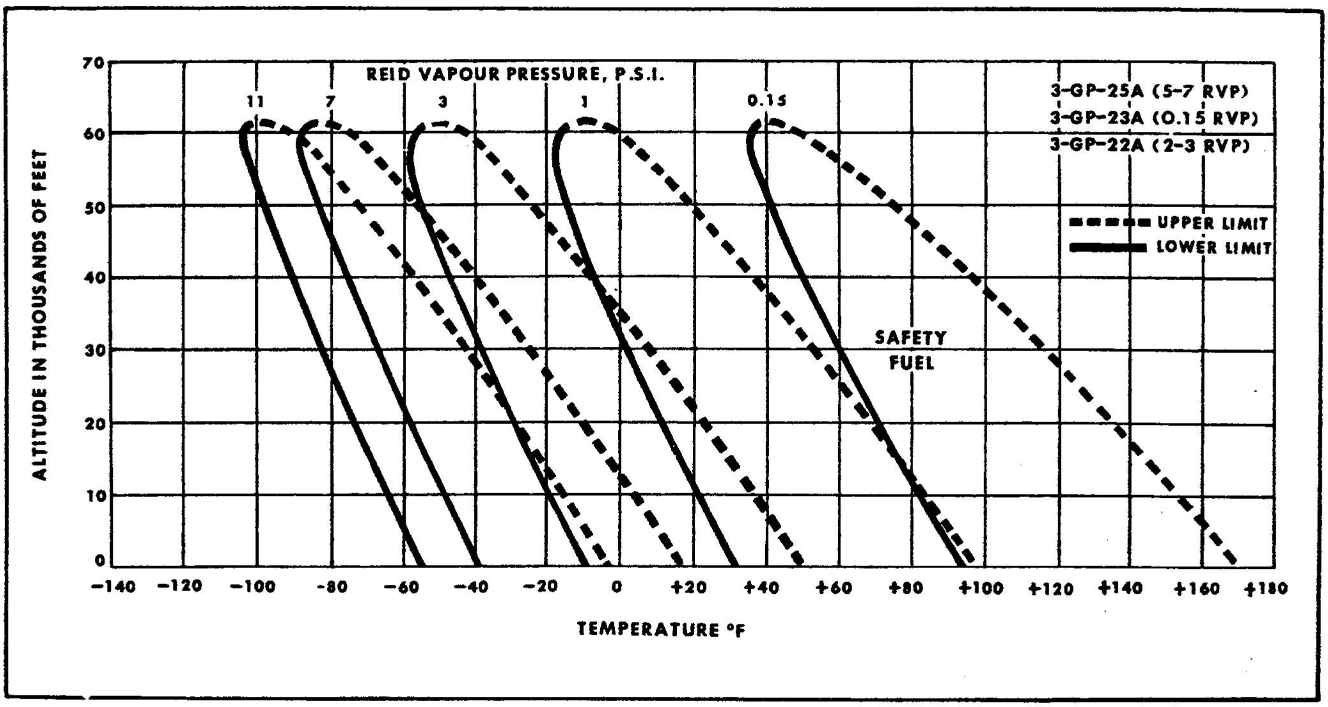


Figure 2-6 Explosive Limits of Aviation Fuels

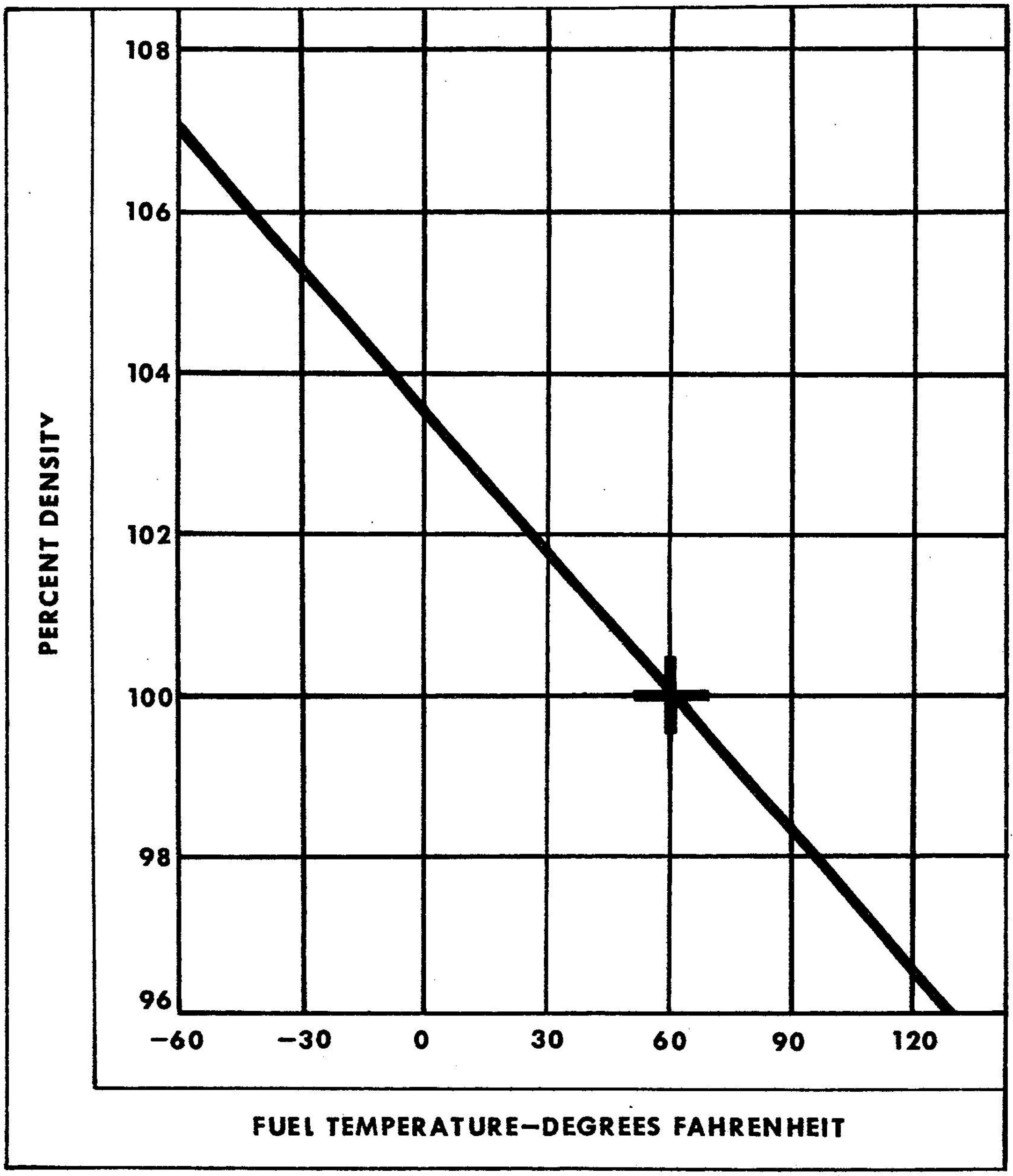


Figure 2-7 Per Cent Fuel Density Versus Temperature

more dangerous than fuels previously handled. The purpose of this article is to caution against ANY LAXITY in handling 3-GP-22A fuel, since accidental ignition of its vapours is more likely to cause an explosion than with other aviation fuels, therefore, special attention is called to bonding.

59 When operations permit, it is desirable that aircraft fuel tanks be filled prior to being placed inside the hangar. This procedure will be carried out at the discretion of the Chief Technical Officer or upon direction by AMCHQ.

FUEL WEIGHT VARIATION

Weight Versus Temperature

60 The aircraft designer has, of recent years, been disturbed over the possible vari-

ation of the weight of fuel carried by an aircraft with full tanks. The aircraft designer as a rule blames this variation on the changes of composition that are possible within the limits of past and present fuel specifications. To some extent the aircraft designer is correct in his assignment of the blame for the variation. It is possible in peacetime to supply aviation gasolines of relatively constant volatility and composition so that density (pounds per gallon) at constant temperature varies only slightly. Similarly, kerosene for turbine use can be held to very slight variations in density at constant temperature. High grade kerosene suitable for long time burning in lamps equipped with wicks is a relatively very constant product and subject to only slight variations in density (at constant temperature) the world over. Such restrictions on density increase cost in peace time but in periods of emergency they interfere very seriously with availability. More recently, as a result of the introduction of turbo-jet aircraft, the aircraft designer has raised increasing objections to variation of fuel density. In turbo-jet aircraft in general, the fuel load is a very high proportion of the all-up weight, and variation of fuel load therefore may have a pronounced effect on performance (particularly at take-off). Also their fuel carrying capacity is, as a rule, volume-limited, thus fuel tank space to take care of variation of volume of a given fuel weight is not available.

61 The aircraft designer has been inclined to neglect the fact that the density of all fuels varies quite considerably with temperature. Figure 2-7 shows the average variation in percentage fuel density over a temperature range from -51°C (-60°F) to 48°C (120°F) with 15.6°C (60°F) being used as the 100% point. In this section fuel density has been discussed in terms of 15.6°C (60°F) as the standard temperature. (This is at variance with the treatment in Table 6 where 20.0°C (68°F) is the standard temperature. In chemical practice, dealing with pure compounds, 20.0°C (68°F) is the standard temperature whereas 15.6°C (60°F) is the standard temperature for measuring and reporting petroleum fuels). Figure 2-7 is based on the average variation for all grades of aviation gasoline and for all types of turbine fuel. This figure is only for general information and cannot be considered as applying to any particular batch of any particular grade. Such a range of fuel temperature may seem ridiculous but unfortunately both combat and civil aircraft have been and still are refuelled with fuel hav ing a temperature as high as 48°C (120°F Refuelling with fuel at a temperature of -51° (-60°F) is unlikely but possible in the Arctic refuelling with fuel at a temperature belo zero Fahrenheit is by no means unlikely durin winter in the high Northern and Southern lati tudes. An aircraft having tanks full of a give fuel at a temperature of -51°C (-60°F) wi carry 11% greater fuel weight than when th tanks are full of the same fuel at 48°C (120°F

62 Table 3 shows that the most dense gas oline is 6.1% heavier than the lightest gasoline The most dense turbine fuel (3-GP-23A) i 5.9% heavier than the lightest (3-GP-22).

63 The maximum possible divergence du to fuel type may also be considered by com paring the heaviest turbine fuel (3-GP-23A with the lightest gasoline, and in this cas maximum density 3-GP-23A is 15.4% heavie than the lightest gasoline. This last case is on that can happen in combat military service When the total variations in fuel load due t fuel type and fuel temperature are considere they add up to a total but unlikely variation o 28% in fuel weight for a turbine engine aircra with full tanks.

64 The increase of fuel density with reduc tion of temperature has, on occasion, been use as a means of increasing fuel load in a volum limited aircraft by means of fuelling the air craft with previously refrigerated fuel. Fue refrigeration has also been applied as a mean of reducing or eliminating vapour lock wit aviation gasoline.

CURRENT AVIATION TURBINE FUELS

Kerosene Type

65 Up to the present the greater part of th operation of aircraft gas turbines (which hav been almost entirely turbo-jets) has been wit what has been loosely described as kerosene In Canada, kerosene by definition, is a pro duct suitable for burning in lamps equippe with wicks. It is legally required to have a minimum flash point of 49°C (120°F) and to have an end point in the ASTM distillation test see Figure 1-11, of not more than 300°C (572°F) In Canada, the oil industry uses this term to designate a straight-run (that is, it exists as such in the crude oil and is extracted from it by simple distillation) product with an initial

TABLE 3

DENSITY AND SPECIFIC GRAVITY OF AVIATION FUELS AT 60° F

GASOLINES

FUEL GRADE	MAXIMUM PERMISSIBLE AROMATIC CONTENT				AROMATIC CONTENT ESSENTIALLY ZERO			
	MINIMUM		MAXIMUM		MINIMUM		MAXIMUM	
	DENSITY *	SP. GR.	DENSITY	SP. GR.	DENSITY	SP. GR.	DENSITY	SP. GR.
91/96...........	5.97	0.717	6.05	0.727	5.79	0.696	5.87	0.705
100/130........	5.98	0.718	6.10	0.733	5.74	0.690	5.89	0.708
115/145........	6.00	0.721	6.09	0.732	5.77	0.693	5.85	0.703

TURBINE FUELS

FUEL GRADE	MINIMUM		MAXIMUM	
	DENSITY	SP. GR.	DENSITY	SP. GR.
3-GP-23A.......	6.58	0.791	6.63	0.796
3-GP-22........	6.26	0.752	6.53	0.785

* DENSITY IN LB. U.S. GALLON. MULTIPLY BY 1.2 TO GIVE DENSITY IN LB. IMPERIAL GALLON

boiling point of about 163°C (325°F) min., a final boiling point of about 274°C (525°F), a flash point of about 60°C (140°F) min., a low aromatic content, a relatively pleasant odor and suitable for burning for long periods without attention in lamps having wicks. In Europe and other parts of the world, such a product is generally known as "lamp oil".

66 The flash point of a fuel is the fuel temperature which results in sufficient vapour being formed at the liquid surface so that the vapour will ignite in air when a flame is applied, see Figure 2-8. The flash point of a hydrocarbon or mixture of hydrocarbons, has a very approximate relationship to the initial boiling point in the ASTM distillation test. The flash point is about 93°C (200°F) lower than the initial boiling point.

67 Kerosene, as produced in Canada, does not contain cracked material and aromatics have to be removed when it is produced from some crude oils. For purposes of this discussion, material having a minimum flash point of 41°C (105°F) and an end point of 316°C (600°F) will be described as kerosene. (In Canada, a petroleum product with a flash point of less than 41°C (105°F) is legally considered to have the fire hazards of gasoline). Material of this boiling range containing cracked products will be described as "cracked kerosene". As pointed out above, both these descriptions are in conflict with accepted designations of the American

oil industry. They are, however, adopted for simplicity of discussion.

GASOLINE

68 Next to kerosene, aviation gasoline has been the most widely used fuel for military (turbo-jet) purposes. This fuel has been used as a matter of availability under circumstances where it was not possible to have different fuels for piston and turbine engines.

GASOLINE - KEROSENE BLENDS

69 3-GP-22, which is the currently specified standard military turbine fuel, can, for practical purposes, be described as a blend of motor gasoline (containing no lead) with kerosene and "cracked kerosene".

AVAILABILITY OF TURBINE FUELS

70 There are decided differences of opinion regarding the most suitable fuel type for air-

craft gas turbines. The first service type ai
craft turbines operated on kerosene, this to
considerable extent being the result of a long
standing opinion that fuels of high flash poi
had a considerable advantage for aircraft us
While other fuels, gasoline, for example, hav
some operating advantages over kerosene
kerosene would probably continue to be th
standard aircraft turbine fuel except for th
question of availability. The term availabili
is here used in the sense of the total amou
of fuel which can be manufactured from a give
supply of crude petroleum and not in the sens
of what fuel may be available at some partic
ular area of operations. Thus, an aircra
carrier operating a large number of pisto
engined aircraft may have supplies of Grad
115/145 aviation gasoline and no 3-GP-22 bu
this is not a question of the general availabilit
of Grade 115/145 and 3-GP-22.

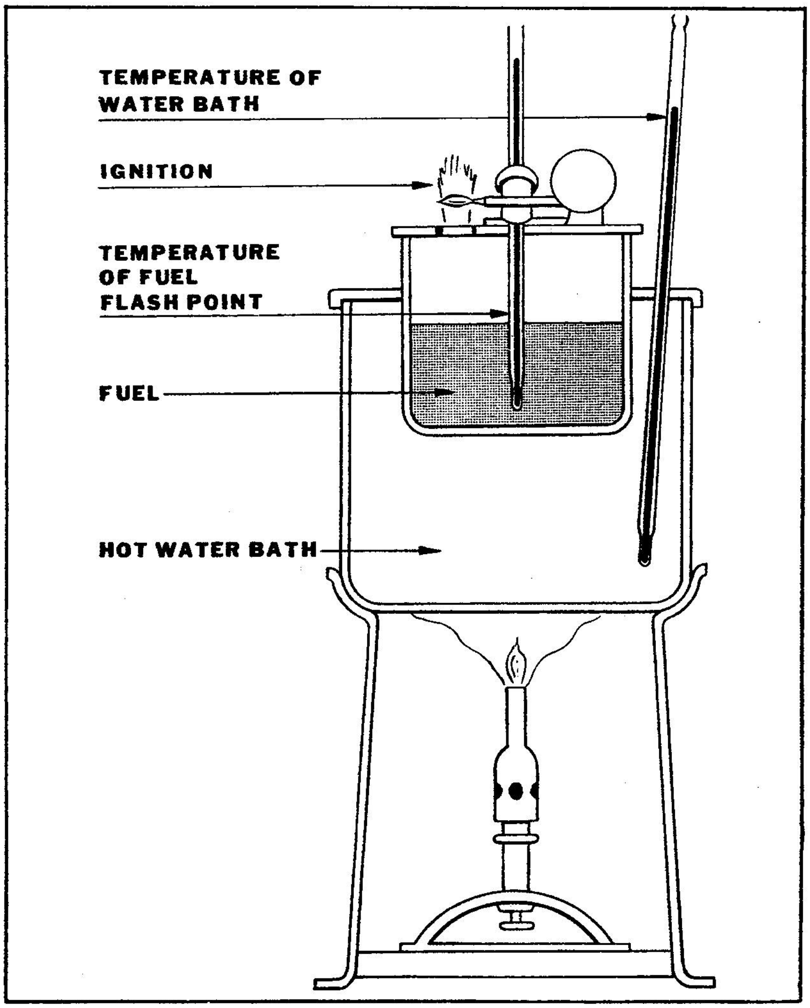


Figure 2-8 ASTM Tag Closed Tester

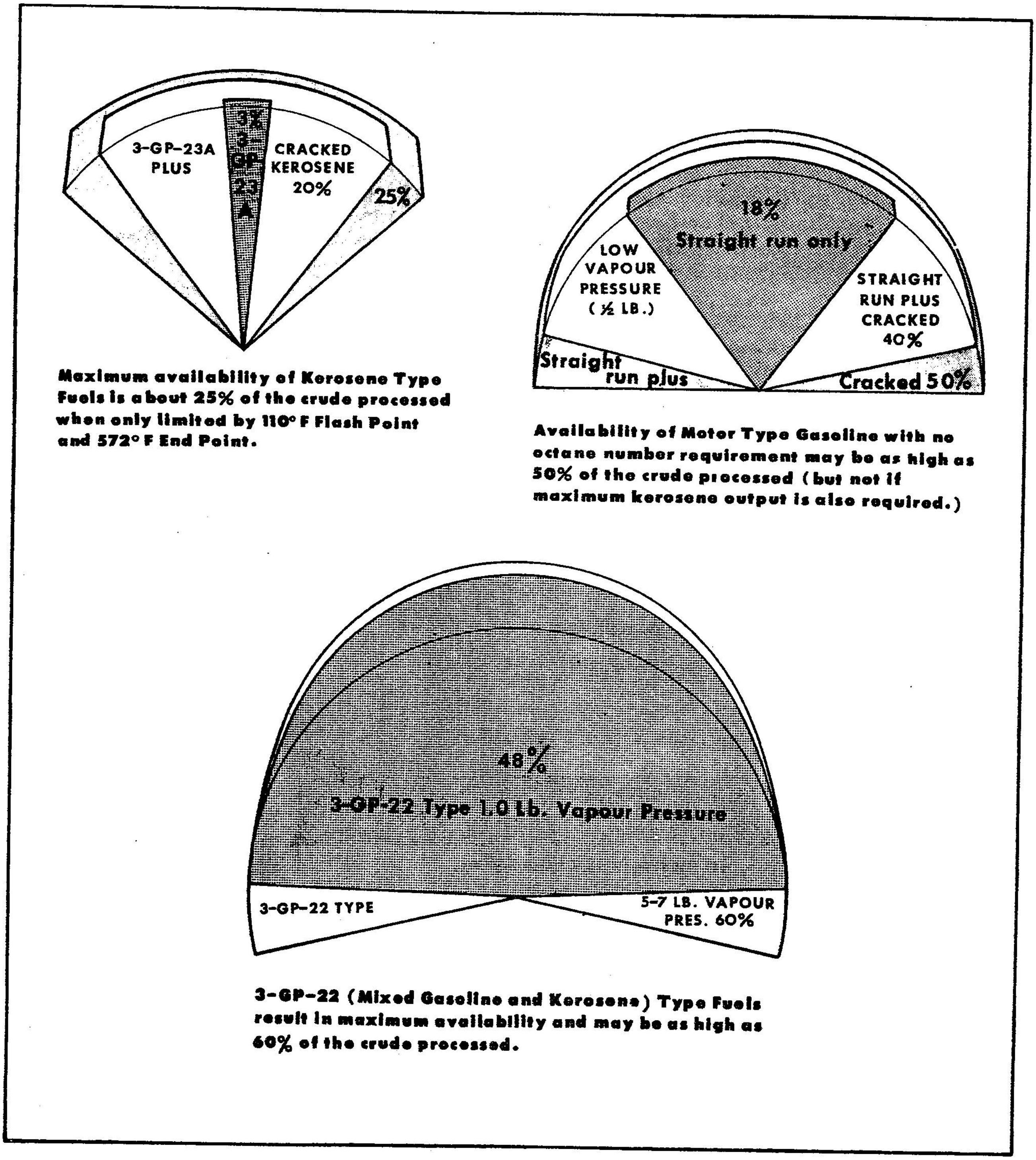


Figure 2-9 Potential Availability of Turbine Fuels

KEROSENE

71 Kerosene for aircraft turbine use has, in the RCAF, been procured to 3-GP-23A specifications, Table 5. This specification excludes cracked material,* requires a freezing point of -60°C (-76°F). a maximum aromatic content of 20 volume % with a flash point of 43°C (110°F); the end point is permitted to be 300°C (572°F) maximum. If only the flash point and end point limits are considered, about 25% of straight-run kerosene can be refined from average crude oil. Of this 25%, however, a very large amount will fail to meet the freezing point requirement. A portion of this 25% will also fail to meet specifications on account of the aromatic content being above 20 volume %. The material failing to meet the maximum aromatic requirement, while important to an individual refinery, would be unimportant in over-all Canadian production since it could be blended with material of much lower than 20 volume % aromatics. The total amount of kerosene which can be produced and which will meet all requirements of the 3-GP-23A specification is less than 3% of the crude refined when average crude oil is considered.

72 If "cracked kerosene" is permitted to be used (that is, if bromine number is increased to 30 as in the 3-GP-22 specification) and if the permissible aromatic content is increased to 25%, about 20% of the crude oil can be processed into material having -60°C (-76°F) freezing point. The major difficulty in producing kerosene meeting 3-GP-23A specification is that of freezing point. Even in the case of "cracked kerosene" the freezing point requirement has an important effect in restricting the amount which can be produced.

73 It has been suggested that the shortage of kerosene of low freezing point be obviated by use of the more widely available material of high freezing point in conjunction with provision for heating the fuel in the aircraft and in storage. Even if such heating was technically practical, kerosene supplies would be inadequate since it is required for some domestic and agricultural uses (lamps, for example) and even in times of national emergency such supplies cannot be completely cut off. Kerosene is an important component of high grade Diesel fuel used by the railroads and the Navy, and these uses are also important in times (national emergency.

GASOLINE

74 A considerable amount of gasoline ha been used in military turbo-jet aircraft. Thi fuel, of course, all contained lead since it wa standard combat fuel and the lead is decidedl undesirable for turbine use.

75 In Canada, average crude petroleum con tains about 20% of straight-run motor gasolin having a 204°C (400°F) end point. This 20% in cludes the gasoline recovered from the ga that is associated with the production of crud petroleum from the ground. A considerabl proportion of this straight-run material is c low octane number and makes an inferior moto gasoline unless it is cracked or otherwise pro cessed. The low octane number is no disad vantage for turbine fuel and is, in fact, some what of an advantage since it is the result of preponderance of paraffin compounds.

76 After removal of straight-run gasolin from the crude oil, the remaining material ca be cracked and otherwise processed so that th total gasoline (motor and aviation gasolines produced represents about 50 volume % of th crude oil refined. 50% gasoline cannot, how ever, be produced while simultaneously refin ing 25 volume % of the crude oil into kerosene In cracking to produce motor gasoline for tur bine use, a greater yield can be obtained tha if the gasoline produced is to be used in auto mobile engines. The greater yield is due to th fact that for turbine use, cracking is only re quired to produce the necessary volatility with out reference to octane number.

GASOLINE - KEROSENE BLENDS

77 Subsequent to World War II, the RCAF with the assistance of the oil industry, ha studied the question of aircraft turbine fue supplies. The problem was studied from th viewpoint of setting up specifications whicl would permit the greatest possible amount o the crude oil available to Canada to be pro cessed into a turbine fuel which would give sat isfactory engine and aircraft performance. Th result of the study indicated the best answe would be obtained by blending all the availabl motor gasoline with all the available "cracke kerosene".

* Cracked material is not found as such in the crude oil but is produced from higher boilin material by combinations of heat and pressure or heat and catalysts. Cracked materia is essentially excluded in the 3-GP-23A specification by the low bromine number of 3.

78 A fuel specification covering turbine fuel, which is essentially produced by blending as described above, was prepared and such fuel is known as 3-GP-22, see Table 5 In emergency 60% of the available crude oil can be processed into 3-GP-22. It was not (and is not now) thought that in an emergency any such large percentage of the available crude oil supply would be necessary as turbine fuel or could be diverted to this use even if it was required. However, by specifying a material which is potentially available on such a large scale, the supply of smaller quantities creates the minimum of interference with production of other essential petroleum products such as aviation gasoline, Diesel fuel and motor gasoline, all of which would of necessity be required in a national emergency.

79 In view of vapour locking difficulties with high performance turbo-jet aircraft, it was found necessary to reduce Reid vapour pressure of 3-GP-22 which is required to be 5 psi minimum and 7 psi maximum. 3-GP-22, on the average, would consist of 65-70% gasoline and 35-30% "cracked kerosene". If the gasoline portion is so distilled as to remove hydrocarbons containing 4, 5 and 6 carbon atoms per molecule, see Table 6, or, in other words, to remove butanes, pentanes and hexanes, the volume would be decreased by about 15% and the Reid vapour pressure would be lowered from 7 psi to about 1 psi. In removing the 15%, the freezing point would probably be increased to above -60°C (-76°F). To lower the freezing point, removal of about 5% of material with the highest boiling point might be necessary. Assuming that the original blend contained 70% gasoline and 30% kerosene, the revised blend will now contain 69% gasoline and 31% kerosene, will have a Reid vapour pressure of about 1 psi and a freezing point of -60°C (-76°F). The components of the revised blend will be available to the extent of about 80% of the availability of 3-GP-22. Thus, if 60% of the crude can be refined to 3-GP-22, then, low vapour pressure 3-GP-22A can theoretically be produced to the extent of 48% of the crude. Practically the availability is less than 48% of crude since plant capacity to strip butanes, pentanes and hexanes from the gasoline fraction is not sufficiently available. In consequence of the insufficiency of distillation plant capacity, it was necessary to permit the Reid vapour pressure to be as high as 2-3 psi.

80 After lowering the vapour pressure of 3-GP-22 the final fuel blend obtained is substantially the same as regards vapour pressure and volatility as JP-2, see Table 5, which was specified in 1944 by the USAF as a means of relieving the potential shortage of 3-GP-23A. JP-2 (no equivalent RCAF specification) had a Reid vapour pressure of 2 lb maximum and greatly reduced the difficulty of meeting the -60° C (-76°F) freezing point specified for 3-GP-23A. JP-2 was used only for experimental testing and experimental service use.

81 The above survey was completed in December 1950. As this EO goes to the printer, a specification for 3-GP-22A which is substantially low vapour pressure 3-GP-22, has been issued. 3-GP-22A was approved and issued as a result of the recent survey of availability. For a summary of specification requirements of 3-GP-22A, see Table 5.

LOW VAPOUR PRESSURE ME GASOLINE

82 As a result of combustion difficulties thought to be the result of aromatics in the "cracked kerosene" fraction of 3-GP-22, consideration has been given to the use of low vapour pressure motor gasoline as a turbine fuel. Motor gasoline stripped of butanes, pentanes and hexanes and having a Reid vapour pressure of 1-2 psi, will be available to the extent of about 40% of the crude oil refined.

83 Since the demand is likely to be less than 40% of the crude or the demand for other petroleum products will prevent the production of 40% crude as turbine fuel, the components that have more value for other uses can be removed and those which are just as good or better for turbine fuel can be retained in the final blend. Butanes, pentanes and hexanes are all usable directly in motor gasoline and either directly in aviation gasoline or for manufacture of aviation gasoline components. Most of the straight-run components heavier than hexane are poor products for motor gasoline and unusable in aviation gasoline so they are left in the blend. Some of the cracked gasoline components which are heavier than hexanes would be the first to be removed from the blend leaving the straight-run products which are somewhat better as turbine fuel components.

ADVANTAGES OF VARIOUS TURBINE FUELS

84 Engine and particularly aircraft operation are quite significantly affected by the volatility of turbine fuels. There has been and still is a very vigorous controversy on this

subject. The relative advantages and disadvantages of each type are discussed below.

KEROSENE - ADVANTAGES

85 It practically eliminates loss of range due to evaporation and related causes discussed under disadvantages of gasoline, and largely eliminates vapour lock.

86 It is a better lubricant due to higher viscosity, see Table 2, and this is important in regard to fuel metering pumps.

87 Kerosene has about 10% higher heat energy per unit volume than gasoline, the heat energy is about 6% higher per unit volume than 3-GP-22.

88 While the potential supply of kerosene is limited in comparison with gasoline type fuels, the supply is entirely sufficient for use in civil turbine-type aircraft where kerosene appears to be the most desirable fuel. Kerosene appears to be most desirable for civil use on the grounds of safety and particularly so in regard to refuelling the aircraft on the ground with passengers aboard. Kerosene would also appear to reduce fire hazards when an aircraft crashes. The safety features of kerosene for civil use are almost entirely the result of its higher flash point.

KEROSENE - DISADVANTAGES

89 It has slightly lower (about 3%) heat per unit weight than gasoline.

90 Has some combustion disadvantages in comparison with gasoline. Combustion efficiency is slightly lower, starting on the ground at very low temperatures is decidedly inferior. Relighting in flight at very high altitude is also decidedly worse than with gasoline. Blowout at altitude is more likely than with gasoline. Carries more solid matter (dirt) in suspension. The ability of a fuel to carry solid matter in suspension is directly related to its viscosity, see Table 2, and the higher viscosity of kerosene results in filtering it out. The higher viscosity of kerosene results in a significant and undesirable increase of the time required to refuel an aircraft. Fuel tank explosions in combat are more likely than with gasoline as discussed below.

GASOLINE - ADVANTAGES

91 The advantages of gasoline are largely summarized by the disadvantages of kerosene which are discussed above. The combustio advantages of gasoline appear to be importan but in general these advantages will only b obtained in an engine designed for gasoline To some extent these advantages are obtaine in engines which were designed for kerosene Many turbo-jet engines are specifically designed for operation on combat grade aviatio gasoline.

92 Gasoline has an important military advantage in respect to explosions in fuel tank when penetrated by bullets. Gasoline, see Figure 2-5, maintains a non-combustible fuel-ai mixture in the vapour space of the fuel tank over a much wider range of fuel temperatur and altitude than does kerosene.

GASOLINE - DISADVANTAGES

93 The advantages of kerosene discusse above in general summarize the disadvantage of gasoline.

94 The outstanding disadvantages of gasoline are vapour lock and loss of fuel in fligh due to evaporation of light ends. Loss of fue due to the evaporation is manifested both b straight loss of vapour and also by evolutio of vapour which carries (or entrains) considerable quantities of liquid with it while escapin to atmosphere. This loss of liquid carried b the escaping vapour is known as slugging. Gasoline makes the problem of the fuel meterin pumps more difficult since it is a much poore lubricant than kerosene. Gasoline is a particularly bad lubricant when it is accompanied b slugs of water. The fuel pump problem is obviously capable of solution since the pumps used for cylinder injection of gasoline in pisto engines have successfully solved an even mor difficult problem.

3-GP-22 MERITS

95 3-GP-22 has all the operating disadvantages of gasoline plus some that do not exis with gasoline. Due to the fact that it has a muc higher end point than either aviation or moto gasoline it can and does contain high boilin materials with undesirable combustion characteristics. Its only major operating advantag over gasoline is a higher energy content pe unit volume.

96 In comparison with 3-GP-23A kerosene 3-GP-22 has combustion advantages in regar to cold starting, relighting at altitude and altitude and altitude blowout. The last two o

these advantages will be increased when compared with "cracked kerosene".

3-GP-22A MERITS

97 The advantages of low vapour pressure 3-GP-22A over gasoline or 3-GP-22 are almost entirely those related to operation of the aircraft in respect to reduction or elimination of vapour lock, slugging, etc.

98 The light ends (butanes, pentanes and hexanes) that exist in 3-GP-25B, gasoline or 3-GP-22 are of importance in respect to: cold starting on the ground, relighting in flight and altitude blowout. Thus, the combustion performance of 3-GP-22A can be expected to be inferior to either gasoline or 3-GP-22. Combustion properties are likely to be superior to 3-GP-23A and definitely superior to "cracked kerosene".

LOW VAPOUR PRESSURE ME GASOLINE

99 Low vapour pressure motor gasoline will retain most of the combustion advantages of gasoline but will be poorer in respect to starting at low temperatures on the ground. It will have significant combustion advantages over kerosene, "cracked kerosene" and 3-GP-22 fuel.

100 As regards aircraft operation as distinct from engine operation, low vapour pressure motor gasoline will greatly reduce problems of vapour locking, slugging, etc. A Reid vapour pressure of 1-2 psi does not completely eliminate such problems, however, but does very greatly reduce them.

FUEL TANK EXPLOSIONS

101 The problem of fuel tank explosions when penetrated by bullets is discussed at some length, see paras. 55 - 59, of this Part, and the advantages of gasoline in helping to prevent such explosions is pointed out. It may be mentioned that lightning may provide a hazard of the same type as bullets when the fuel tanks contain a combustible mixture which can be ignited at the tank vent.

102 Depending upon the vapour given off by a fuel with high vapour pressure as a means of preventing tank explosions may be an illusion. If, due to high fuel temperature at take-off and a long flight at high altitude, considerable fuel evaporation occurs, the fuel lost will be very largely the fractions having high vapour pressure, and the remaining fuel will not then have the necessary vapour pressure to prevent tank explosions. Thus, when high vapour pressure is relied upon, it is important to take available precautions to prevent loss of vapour pressure. Thus, fuel should be as cold as possible when pumped into the aircraft tanks and the aircraft should not stand for long periods in the hot sun after fueling. Likewise, fuel in reserve tanks (even with piston engined aircraft using gasoline) should be used up (or drained), and the practice of topping-off reserve tanks after each flight should be avoided.

103 The fuel tank explosion hazard with fuels less volatile than gasoline (that is, less than 5 psi Reid vapour pressure) can be eliminated if the vapour space in the tank is filled (to the extent that the space is not occupied with fuel vapour) with an inert gas which will not support combustion when mixed with fuel vapour. This method is commonly known as blanketing or "inerting". Suitable inert gases are: carbon dioxide, nitrogen, helium, argon, and cooled exhaust gases which must be almost entirely free of both uncombined oxygen and water. Of these gases, the first four must be carried in the aircraft under high pressure in suitable containers. Carbon dioxide is the most readily carried since it can be liquefied at moderate pressure but tends to produce vapour lock due to the fact that it is extremely soluble in the fuel. Nitrogen can be ruled out because of the weight of the containers required to carry a sufficient supply, helium and argon can be rejected for the same reason but more importantly because of their rarity (admittedly the atmosphere contains almost 1% argon by volume but separating it requires an elaborate and bulky plant). Cooled and dried exhaust gas appears to be the best practical answer to the blanketing problem but the exhaust gas of a turbo-jet or turbo-prop is not suitable since it will contain about 15-18% oxygen by volume and this must be largely removed in order to make it suitably inert. The exhaust gas can be burnt with more fuel (in effect, the use of a small after-burner), then cooled and the water extracted. Alternatively, blanketing gas can be produced by the use of a small combustion heater similar to that used for space heating of aircraft cabins. Combustion gas which is substantially free of oxygen and water will contain about 15% (by volume) of carbon dioxide and in view of the high solubility of this gas in gasoline or turbine fuel it might appear that it should be removed (which would leave substantially pure nitrogen as the final gas). How-

ever, while the presence of carbon dioxide in the cooled and dehydrated combustion gas is not desirable, it is present in sufficiently diluted form so that its solubility in the fuel is not high enough to a serious cause of vapour lock. Removal of carbon dioxide from the combustion gas would necessitate heavy and bulky apparatus requiring frequent servicing. If carbon dioxide must be removed from combustion gas used for blanketing, it would seem that combustion gas cannot be considered and must be replaced with compressed nitrogen carried in cylinders.

104 In the long run it appears that fuel as volatile as gasoline (that is, having as high a Reid vapour pressure) will prove less desirable for military purposes than a fuel intermediate between gasoline and kerosene. It seems that in the ultimate, engine development and development of tank blanketing systems will eliminate most of the relative advantages of gasoline. With the advantages of gasoline eliminated, its disadvantages of fuel loss in flight due to evaporation and slugging become of outstanding importance.

SUMMARY OF FUEL OPERATING PROBLEMS

105 Constructors of aircraft prefer kerosene since it virtually eliminates vapour lock and loss of range resulting from evaporation and slugging. Vapour lock and related problems with 3-GP-22 and gasoline become of startling magnitude in some turbo-jet aircraft designed for both exceedingly high rates of climb and exceedingly high operational altitudes. Some turbo-jet aircraft presently in service are, however, designed and developed for use with either gasoline or 3-GP-22. The aircraft constructors are generally in favour of kerosene since its volumetric heat energy is higher than gasoline or 3-GP-22.

106 Most engine builders are in favour of unleaded gasoline but only after their metering pumps have been made to work with gasoline since it generally improves engine performance (at least in terms of the fuel which actually reaches the engine).

SUMMARY OF PRINCIPAL CENTRAL FUEL REQUIREMENTS

107 In general, it may be concluded that fuel can have important effects upon the operation of aircraft gas turbines as discussed below.

LOW TEMPERATURE OPERATION

108 The fuel should be suitable for operati at very low temperatures including: lack freezing, starting on the ground and restarti engines in flight at very high altitude.

HANDLING CHARACTERISTICS

109 The ability to be satisfactorily handl in the fuel system of the aircraft and the engi means that the fuel must be non-corrosiv should not clog fuel filters even at very lc temperatures and should not produce vapo lock in the fuel tanks or in the various fu pumps nor slugging out of the fuel tank vent As far as is possible, while being compatib with other requirements, the fuel should ha enough of the properties of a lubricant to avo significant wear of the fuel metering pump These requirements do not mean that fuel pr perties can be expected to do more than l helpful to the designer of the fuel system. Fu properties cannot eliminate the very difficu problems that the fuel system designer wi encounter with any liquid, no matter how rar which can be used as a fuel.

LOSS OF FUEL BY EVAPORATION

110 Loss of aircraft range due to evaporatio and especially at high altitude, puts a ve heavy burden on the aircraft designer. Gasc line is worst from the standpoint of such losse and kerosene practically eliminates loss. Whil kerosene is not sufficiently available for mili tary use, a fuel between kerosene and gasolir can be expected to overcome most of the evap orative loss.

COMBUSTION EFFICIENCY

111 The fuel should produce maximum com bustion efficiency and particularly so under th most difficult conditions produced by the lo atmospheric density and the low temperatur at extremely high altitude. While the require ments of low temperature operation and han dling set partial limits on fuel combustion pro perties, they still permit the inclusion of fuel with characteristics which are decidedly unde sirable in the present state of combustion sys tem design and development. It appears, in th light of present knowledge, that aromatics ten to produce combustion difficulties and that th higher the boiling point of the aromatics, th more undesirable they are. While it is imprac tical to produce any substantial quantity of lo freezing point turbine fuel which is almost fre of aromatics, reduction of end point is practica and will eliminate the worst of the possibl

aromatic components of present turbine fuels. While the undesirable components are discussed as aromatics, it is the low H/C ratio of the components which is the undesirable feature. In practice it is the aromatic components which have the lowest H/C ratio. The H/C ratio of aromatics of similar boiling point can vary widely, however, e.g. 2-phenyl-octane and alpha-methyl-naphthalene with H/C ratios of 0.131 and 0.076 respectively with boiling points of the same general order, Compounds 56 and 57, Table 6. While combustion system development is likely to improve combustion of aromatic components in the future, it is likely that for military purposes at least, these improvements will be largely offset by flight at increased altitude and at increased aircraft speed. At sea level static conditions, combustion properties of any hydrocarbon liquid meeting requirements for low temperature operation and handling have initially only a very small effect upon the output and fuel consumption of an aircraft gas turbine. Continued operation at sea level static conditions with liquids meeting the requirements for low temperature operation and handling but having poor combustion characteristics may very seriously shorten the life of present turbo-jet engines. While the life of present engines may be seriously shortened at sea level conditions, it appears that relatively minor changes in combustion systems will obviate such reduction of life. Although fuel combustion characteristics have minor effects on sea level output, it appears that possible variations in combustion properties of current fuels can have marked effects upon the limiting operational altitude of military aircraft. Thus, the difference between a good and a bad fuel may reduce maximum operational altitude by 10,000 ft.

AIRCRAFT RANGE

112 The requirements listed above define the qualities that are desirable or necessary in a fuel as regards operation of the turbine itself. Operation of the turbine itself is only part of the whole problem of operating the complete aircraft and this brings in the requirement that the fuel shall have maximum heat energy both on a weight and on a volume basis. On a weight basis a gasoline completely composed of paraffins will have the highest energy. On a volume basis the high boiling aromatics are best since they may contain 20% more heat energy per unit volume than a paraffinic gasoline but contain about 10% less energy per unit weight. While the high boiling aromatics may have an advantage of 20% in energy upon a volume basis, part of this advantage may not be obtained due to reduced combustion efficiency.

THE TURBINE ENGINE AND ITS FUELS

113 The gas turbine has a major similarity to the piston engine in that both of them produce useful power by means of the expansion of heated air. The turbo-jet and the turbo-prop differ only in the means by which they apply the power they produce to obtain propulsion of the aircraft. In the turbo-jet the thrust is produced entirely by the jet and in the turbo-prop thrust is obtained mostly from the propellor but also from the jet effect of the exhaust. The turbo-compressor used for supercharging piston engines is excluded from this discussion since, while it produces work by expanding heated air, it does not directly propel the aircraft; and its fuel, which it does not burn directly, is necessarily that used by the piston engine to which it is attached.

114 All gas turbines consist basically of an air compressor (or compressors), a combustion section and a turbine (or turbines). The gas turbine functions by taking in atmospheric air and compressing it, fuel is then burnt in the compressed air, which then expands through a turbine which drives the compressor. In the turbo-jet the heated air is expanded in the turbine so that only sufficient energy is extracted from the gases to drive the compressor, the remaining pressure energy being retained to eject the gases in jet form and thus produce thrust. In the turbo-prop the gases are almost completely expanded in the turbine (that is, they are expanded almost down to the pressure of the surrounding atmosphere), leaving only a relatively small amount of pressure energy to produce thrust when ejected from the exhaust tail pipe (jet).

COMPRESSION THEORY

115 All aircraft gas turbines have at least two stages of compression and in this they differ from land and marine gas turbines which may be built (but very rarely are) with only a single stage of compression. The first stage of compression in the aircraft gas turbine is the ramming air intake which cannot be embodied in land or marine gas turbines. Thus, the first stage of compression in the form of the ramming air intake precedes the second and maybe subsequent stages of compression (hereafter mechanical stages). Where only a single mechanical stage is involved, this is

invariably a centrifugal compressor. In both turbo-jets and turbo-props the first stage (ramming intake) may be followed by ten or more stages of mechanical compression if an axial compressor is used. Some turbo-prop engines have two stages of centrifugal compression and others have several axial stages; the axial stages may be followed by one centrifugal stage. The compressor (including all stages except the first or ramming intake stage) increases the pressure from that existing at the entrance to the first mechanical stage by a ratio of four or more and this is known as the pressure ratio. Thus, if the absolute pressure at the entrance to the first mechanical stage is 15 psi and the pressure at the compressor discharge is 60 psi absolute or about 45 lb gauge, the pressure ratio is then 4 to 1.

116 The term compression ratio is applied to the compressors of gas turbines is sometimes used erroneously where pressure ratio is the measured function referred to. If the pressure ratio is 4 to 1 the compression ratio is a good deal less than 4 to 1. The compression ratio of a centrifugal compressor or an axial compressor is somewhat difficult to determine whereas the pressure ratio can be determined easily with a pressure gauge and a barometer. The pressure ratio of a gas turbine is normally determined at sea level and without any ram at the ramming air intake. The compression ratio of the compressor of a gas turbine may be defined as the ratio:

$$\frac{\text{Density of air at compressor discharge}}{\text{Density of air at compressor intake}}$$

Density may be expressed in any convenient units such as lb per cubic foot. The pressure of a gas (of known composition) is not a measure of its density but rather a measure of its combined density and temperature. The compression ratio of a piston engine, see Figure 2-10, is essentially the same as that given above but is not exact due to the delayed closing of the intake valve. A piston engine with 7 to 1 cylinder compression ratio has a pressure ratio of a great deal more than 7 to 1. The pressure ratio of a piston engine can be determined with elaborate instrumentation but varies with every condition of engine operation.)

117 The air discharged by the compressor is delivered to the combustion chambers where fuel is mixed with part of the air and ignited. The burning mixture of fuel and air is then diluted with additional air and this diluted (a cooled) gas steam is delivered to the turbi nozzle box where guide vanes deflect it by suitable angle for impingement on the turbi wheel. The nozzle guide vanes have other in portant functions besides deflecting the gas but discussion of these duties is not suitab for this EO.

118 In many turbo-jets only a single sta turbine is used but more than one stage m be used and if so, guide vanes are interpos between each pair of turbine wheels. The ga after leaving the turbine wheel (or the la wheel if more than one stage is used), ente the jet pipe which discharges to atmospher

MECHANICAL DETAILS OF GAS TURBINE

119 This elementary discussion of the ai craft gas turbine will not attempt to show ar actual mechanical details of turbines but wi rather confine itself to such diagrammatic lay outs as may be necessary to illustrate th problem of turbine fuels and their combustio Figure 2-10 shows a diagrammatic layout a turbo-jet engine having a single stage centri fugal compressor and a single stage turbin The upper half of the illustration shows a nor mal jet pipe and the lower half shows a je pipe equipped for afterburning.

120 Figure 2-11 shows a diagrammatic lay out of a turbo-prop engine having an axial com pressor and a two-stage turbine. In this cas both stages of the turbine are connected to th compressor. A wide variety of arrangement have been proposed or built. In one arrange ment the first stage of the turbine drives th compressor and the second stage is not con nected to the compressor and drives the pro pellor through a reduction gear. Except fo the fact that an afterburner is not used (at pre sent) with a turbo-prop, its fuel and combus tion problems are essentially identical wit those of the turbo-jet and will be thus treate in the following discussion.

121 Before passing to details of fuels an turbine engine performance it may be well t emphasize the relatively enormous air con sumptions of turbo-jet and turbo-prop engine when compared with piston engines. For thi purpose air used per unit weight of fuel and ai used per propellor horsepower (in the case o the turbo-prop) may be considered. In comparison with the piston engine, both turbo-je and turbo-prop engines use about four times

as much air per pound of fuel burnt (except when afterburning is used) and the turbo-prop uses a minimum of seven times as much air per propellor shaft horsepower. Turbine performance in terms of the combustion air used is given in more detail in the text which follows.

THE JET PROPULSION PROCESS

122 The thrust of a jet engine is directly proportional to the weight of gas discharged from the jet pipe nozzle multiplied by the velocity of discharge. The effective velocity of discharge as regards producing thrust, is the velocity relative to the surrounding atmosphere and not that relative to the jet pipe nozzle. At sea level static conditions, the effective velocity is, however, that relative to the jet pipe nozzle. The effect of pressure in the jet pipe is one of producing velocity at the jet nozzle and not of pushing against the surrounding atmosphere. As the pressure in the jet pipe (pressure here being used in the sense of the difference in pressure between that in the jet pipe and that of the surrounding atmosphere) increases, the velocity of the jet of gases issuing from the jet pipe nozzle increases until the velocity of sound is reached. When the velocity of sound is attained by the gases, further increase of pressure in the jet pipe does not produce increase of velocity. When a gas is moving at the velocity of sound (or an object, such as an aircraft, is moving relative to the gas at the velocity of sound), it is said to have a Mach number of 1. If the gas is moving at velocities of a quarter or a half of the speed of sound, it is said to have Mach numbers of 0.25 and 0.5 respectively. The velocity of sound in air (for the present purpose it is sufficiently close to consider the gas in the jet pipe as air) is about 1100 ft/sec at 15.5°C (60°F), about 1800 ft/sec at 537.7°C (1000°F) and about 2600 ft/sec at 1371°C (2500°F) and does not vary with pressure. Since, if the jet is to propel an aircraft, its velocity must be greater than that of the aircraft, it is of interest to note that the velocities in miles per hr for a Mach number of 1 are, in round figures, 750, 1250 and 1750 for temperatures 15.5 °C (60 °F), 537.7 °C (1000 °F) and 1371°C (2500 °F) respectively. When the pressure in the jet pipe exceeds that required to produce the velocity of sound at the jet pipe exit or a Mach number of 1, the engine or the jet pipe is said to be "choked". The ratio of the absolute pressures in the jet pipe and the surrounding atmosphere which produces a Mach number of 1 at the jet pipe nozzle is called the "critical pressure ratio" of the jet.

123 Both the pressure and the temperature of the gas in the jet pipe have effects in producing thrust. Thus, a typical jet engine with a fixed area jet pipe nozzle may be considered at static sea level conditions. As the "throttle" is opened the weight of air delivered by the compressor increases, and this in turn increases the pressure. The fuel-air ratio also increases which raises the temperature of the gases in the jet pipe. The temperature of the gases in the jet pipe has two important relationships to the propulsive effect. Firstly, it affects the velocity which can be obtained with a given pressure, the velocity which can be obtained with a given pressure is related to the density of the gases. If the density is reduced by 50%, then the velocity for a given pressure is increased by roughly 40% (the increase of temperature from 540°C (1000°F) to 1371°C (2500°F) will approximately reduce gas density by about 50% at constant pressure). This increased velocity which can be produced by a given pressure can, however, only be obtained provided the increased velocity is below the speed of sound in the gases at the temperature prevailing at the nozzle. Secondly, it increases the velocity of sound so that increased jet velocities may be used, For example, increasing the temperature of gases at the jet pipe nozzle from 537.7°C (1000°F) to 1371°C (2500°F) increases the "choking" velocity from about 1800 ft/sec to 2600 ft/sec. Thus, by this increase of temperature the "choking" velocity and the possible thrust have both been increased by about 40%. This is sufficient to show that the heat energy of the gases leaving the jet pipe nozzle produces work in the propulsion process and is not merely waste heat energy as it may seem to be on first consideration.

COMPUTATION OF PERFORMANCE

124 Computing the performance of aircraft turbine engines requires a few simple computations involving velocity energy, heat energy, thrust, etc and the following quantities are used:

w = weight of gas per second in lb (as regards the compressor w equals the weight of air, while in the case of the turbine w equals the weight of air plus fuel or fuel plus water-alcohol).

Mass = m = $\frac{w}{g}$ where g = acceleration due to gravity = 32.2 ft/sec/sec

v = velocity in ft/sec

(1) Velocity (or kinetic) energy = $\frac{mv^2}{2}$

(2) Thrust = momentum = mv

Thrust in a jet engine is equal to momentum or rather the change of momentum since v becomes the difference in the velocity of the gases at the jet pipe nozzle and the speed of the aircraft (fps).

At sea level static conditions v is, of course, the velocity of the gases at the nozzle.

Btu = British thermal units

1 hp = 33,000 foot pounds per minute = 550 foot pounds per second

1 hp = 2545 Btu per hour = 42.42 Btu per minute = 0.707 Btu per sec

125 The above is sufficient to show why performance of turbines is discussed usually in terms of pounds of air per second in contrast to piston engines where pounds per hour is the usual measure.

THE COMBUSTION PROBLEM

126 The combustion problem in the gas turbine appears to be very simple but this apparent simplicity is very deceptive. It would seem that the problem of merely mixing fuel in air and burning it is vastly simpler than the combustion problem of the piston engine which involves knock, distribution, ignition timing and other difficulties.

LOW FUEL-AIR RATIO

127 The essential difficulty with combustion in the gas turbine is due to the fact that the fuel-air ratio is so low that if the fuel and air were uniformly mixed, the mixture would not ignite. The low fuel-air ratio is required in order to keep the temperature of the gases delivered to the turbine down to a value which the turbine wheel can tolerate. The highly stressed blades or buckets of the turbine wheel cannot (with present materials of construction), stand a temperature of more than about 815.5°C (1500°F), and this means that the gases at tl entrance to the turbine guide vanes cannot e› ceed about 898.8°C (1650°F) for more thз exceedingly brief periods. In a piston engir fitted with a carburettor, complete combustic of both fuel and air is obtained with a so-calle "chemically correct" fuel-air ratio of 0.06 (for iso-octane) and it is very unusual to t able to obtain steady firing with a fuel-air rat of less than 0.045.

128 While it is stated that complete combus tion of both fuel and air is obtained with isc octane at a fuel-air ratio of 0.066, this valı is the theoretical one which would produce com plete combustion given sufficient time to reac equilibrium. In practice, complete combustic of either fuel or air requires an excess of or or the other. Thus, if all the air is to be burn fuel must be in excess and a fuel-air ratio ‹ about 0.080 is required. When maximum out put is required with a piston engine, the fuel air ratio without water-alcohol injection i about 0.10. This enables the engine to bur more air as a result of the increase of per missible manifold pressure, but the rich mix ture reduces the power obtained per pound ‹ air. With water-alcohol injection, the water alcohol-fuel-air ratio is about 0.11, the fuel air ratio being about 0.08. While water-alcohc injection permits much greater power than i available with fuel alone and a 0.08 fuel-ai ratio, it does so because of increased manifol pressure, and this much more than offsets th reduction in power per pound of air. If all fue is to be burnt (when maximum fuel econom at cruise is required), then air must be avail able in excess and maximum economy fuel con sumption is usually obtained at a fuel-air rati leaner than 0.066.

129 While it is stated that a pisto.. engin equipped with a carburettor will rarely ru without misfiring at a fuel-air ratio leane than 0.045, this is not true of one type of spar ignition piston engine which injects the fuel int the combustion chamber when the compressio stroke is almost complete. It differs from ; Diesel engine, since a spark ignites the mix ture rather than the heat of compression whicl produces ignition in the Diesel engine. It als differs from the current piston aircraft en gines equipped with fuel injection and whicl have completed the injection period prior tc the beginning of the compression stroke. Thi engine will run without misfiring at a fuel-ai ratio of about 0.010 and this is the result o

air swirl in the cylinder and suitable disposition of injection nozzle and spark plug. The combination results in a local fuel-air ratio of about 0.06 to 0.10, which is ignited and then diluted with the available excess air. This engine, when running at a fuel-air ratio of about 0.015, has essentially the same combustion problem as a gas turbine. In this engine and in the Diesel engine, power output is controlled by variation of fuel-air ratio. This is in contrast with the present types of piston engines used in aircraft and automobiles where output is controlled by variation of air supply.

130 In the gas turbine, control of power output is very largely by means of fuel-air ratio. In the turbo-jet, at any given altitude, power output (thrust) is entirely controlled by fuel-air ratio. While power output is entirely controlled by fuel-air ratio, change of fuel-air ratio varies the air quantity by changing the rpm of the engine. Thus, increasing fuel-air ratio increases the quantity of air and the temperature at which it is discharged at the jet pipe exit. In the turbo-prop, power output is usually controlled by both fuel-air ratio and air quantity but fuel-air ratio is the dominant factor.

131 This discussion of control of engine output is an attempt to indicate the primary variable and has no relation to mechanical methods of accomplishing control. Thus, in an automobile, air supply is the primary variable and fuel supply is the secondary variable. An automobile running at a steady speed of 15 mph in high gear on a level road may be chosen as an example. When the throttle is opened wide, the engine at once starts to consume more air per revolution, the fuel supply per revolution also increases roughly in proportion to the increase in air supply. Since full power causes the car to accelerate, the engine not only takes in more air per revolution but also increases its rpm as the car accelerates. The power developed is roughly proportional to the weight of air consumed and this in turn is equal to weight per revolution multiplied by rpm.

132 In a truck with a Diesel engine operated under similar conditions, fuel supply is the primary variable since the engine takes in roughly a constant quantity of air per revolution. When running at a steady speed of 15 mph on a level road, the fuel-air ratio may be 0.015. When full power is required, the fuel-air ratio is increased to about 0.045 and the engine accelerates thereby consuming more air. Thus, air supply does vary with power but only as a distinctly secondary variable, since power is not proportional to air consumed but roughly to fuel consumed.

LIMITATIONS ON TEMPERATURE

133 Due to the limitations of permissible gas temperature at entrance to the turbine wheel, the fuel-air ratio usually cannot exceed 0.018 at maximum output and is progressively reduced as output is reduced. At cruise thrust (sea level static), a modern turbo-jet will operate at a fuel-air ratio of about 0.01. It is, as mentioned above, the lean over-all fuel-air ratio which makes the combustion problem so difficult. Since. in some engines the gas velocity through combustor at full engine speed is about 100 fps and since the combustion chamber is about 2 ft. long, the process has to be completed in about 1/50 second. In this 1/50 second fuel has to be sprayed into air at a local fuel-air ratio of about 0.06-0.10, combustion completed, combustion products diluted with air, and the combustion products and dilution air thoroughly mixed so that the stream of gas discharged from the combustor has a uniform temperature. It is quite easy to have a hot core of gases surrounded by an annulus of cold air at the combustor discharge, and this produces local hot spots on the turbine guide vanes and the turbine buckets. The combustion must be almost completed prior to the beginning of the addition of the dilution air. If combustion is not largely complete, the addition of dilution air quenches the flame leaving partly burnt fuel products. Under these conditions the fuel is not completely oxidized to carbon dioxide and steam and cannot give up all its available heat energy prior to discharge of the gases from the jet pipe to atmosphere. The combustion problem would be greatly simplified if weight and space were not so important in an aircraft gas turbine. For instance, in the absence of such limitations, the air supply from the compressor could be divided and a portion of it, appropriate to the desired power output, burnt at approximately "chemically correct" fuel-air ratio in a long low-velocity combustion chamber. Subsequent to completion of combustion the products could be diluted with the other portion of the air delivered by the compressor. The proportion of the air delivered by compressor which would be burnt at "chemically correct" fuel-air ratio would, of course, have to be varied with load reaching the upper limit of about 25% at maximum out-

put. It is not unlikely, however, that the friction losses of such an arrangement would offset the gain in combustion efficiency. Thus, the over-all fuel efficiency (pounds of fuel per pound of thrust in the case of a turbo-jet or pounds of fuel per propellor shaft horsepower in the case of a turbo-prop) might well be no higher than with the best of present combustor types.

COKE FORMATION

134 Figure 2-10 shows an approximate diagrammatic view of the "can" type combustor which is at present the most widely used type. It seems to be clearly established that the flame circulates in the combustor as shown in Figure 2-10. For simplicity and ease of illustration this discussion is written around the "can" type combustor and neglects the annular type. Figure 2-10 shows the fuel to be directly sprayed into the primary air where it is ignited. When fuel is injected as in Figure 2-10, the injection pressure at full load is usually high and may be as high as 2000 psi.

135 Another method of fuel injection is known as the vapourizing burner. In this method, a small tube passing a limited amount of air into the primary combustion zone is heated by th flame in that zone. The fuel is injected into th tube at relatively low pressure, travels wit the air stream and is vapourized by the tim it reaches the primary combustion zone. Th vapourizing burner is used with both annula and "can" type combustors. Concentration c discussion on one type of combustor in no wa indicates the merit of any particular type. De scriptions of turbine engines are only carrie as far as seems necessary for discussion o combustion and fuel problems of such engines

136 The circulation of the flame into th spray in the "can" type combustor serves t secure early evaporation of the fuel (fuel doe not burn until it is either vapourized or cracke so that it becomes a vapour), to produce mor complete mixing of fuel and air and very im portantly, to lengthen the time available fo completing combustion. Fuel which is onl partly oxidized of course diminishes combustion efficiency (i. e. reduces the amount o energy delivered per unit weight of fuel) but i addition it may produce free carbon which ca firstly and most importantly result in coke deposits on the combustor liner (flame tube) o produce a smoky exhaust. The carbon produce

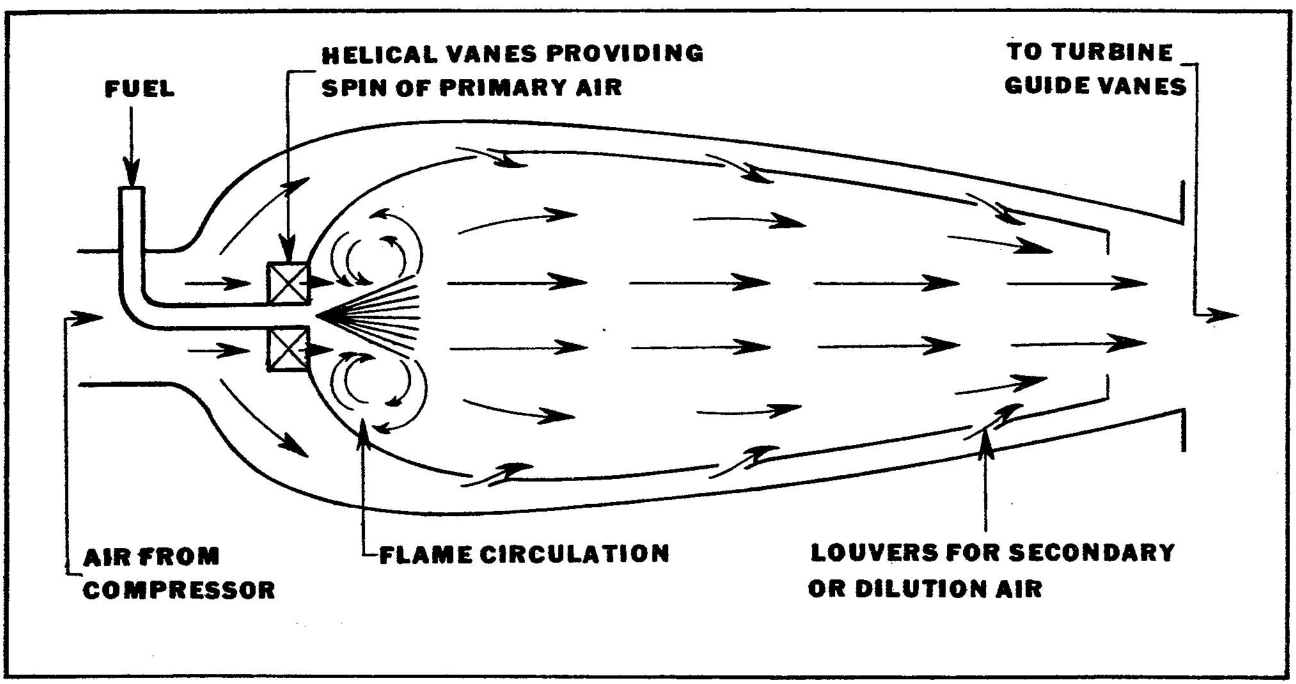


Figure 2-10 Diagrammatic View of "Can" Type Combustor

may really be almost pure carbon or may resemble the so-called carbon (hereafter coke) often obtained in piston engines when running on fuel not containing lead. This coke, while it contains a very high percentage of carbon, chemically resembles an asphalt and contains some hydrogen and some oxygen. The smoky exhaust is particularly undesirable in the case of military aircraft since it facilitates detection. A smoky exhaust may be obtained without measurable loss of combustion efficiency at sea level with completely aromatic fuels but these are not presently used for either military or civil service.

137 Coke formation on the combustor liner is very undesirable since it tends to produce warping and burning of the liner, and pieces of coke may break loose and damage the turbine buckets. Coke formation can readily result if liquid fuel strikes the surface of the combustor liner and this means that the fuel spray discharged by the fuel nozzle should maintain a fairly constant relation to the axis of the combustor and that the nozzle should not dribble. Coke formation on the tip of the spray nozzle is a major cause of impingement of liquid fuel on the combustor liner. Maintaining a constant spray position and avoiding dribbling is obviously difficult (at least with present nozzle and fuel system designs) if for no other reason than the wide variation in rate of fuel supply. Rate of fuel supply has a large influence since the pressure required for discharge varies as the square of the quantity delivered (that is, twice the weight of fuel discharged requires four times the fuel pressure). Fuel quantity delivered to the engine will, of course, vary widely with engine output ("throttle" setting) at any given altitude. It will also vary widely at "full throttle" with altitude, thus at sea level a jet engine may be consuming 5500 lb of fuel per hr and only 2000 lb/hr at 35,000 ft altitude. The fuel pressure at 5500 lb/hr will be about 7 1/2 times (with single rather than duplex nozzles) as great as it will be at 2000 lb/hr, and this variation obviously makes the problem of maintenance of suitable spray shape a difficult one. Fuel viscosity also has a marked effect on the character of the spray and viscosity varies both with fuel type and with fuel temperature. A spray nozzle may have to handle both kerosene and gasoline and over a fuel temperature range of -40°C (-40°F) to 37.7°C (100°F). It can be seen from Table 6, that the viscosity of kerosene at -40°F may be 16 times that of gasoline at 37.7°C (100°F). While the range of viscosity can be 16 to 1, it is more likely to be 8 to 1. With any one fuel, the change in viscosity due to temperature may be 7 to 1 but is more likely to be a maximum of 4 to 1. The above variations in viscosity are sufficient to show the difficulties of fuel spray nozzle design.

138 The combustion problem is also related to the pressure in the combustor. The higher the pressure the easier the problem, thus a combustor which gives good combustion at a pressure of 60 psi absolute may give poor combustion when the pressure in the combustor falls to 8 psi absolute at very high altitude. Combustion efficiency in a good combustor design with the most favourable conditions in regard to fuel type may be as high as 98% at sea level but may fall to as low as 40% at extremely high altitude with a badly designed combustor and unsuitable fuel. As combustion efficiency is reduced, a point is reached when the turbine does not develop enough power to drive the compressor and thus the engine speed is reduced.

139 Combustion efficiency also tends to drop off in piston engines as pressure in the cylinder is reduced below a given level but this is rarely important in aircraft engines. It is, however, very important in automobile engines. In automobile engines, as the intake manifold pressure is reduced below 15" Hg absolute, combustion efficiency becomes steadily lower until a pressure is reached at which the engine will not fire. This behaviour is in part due to the reduction of cylinder pressure (reduction in density) but is also due to an increasing contamination with exhaust gas left from the preceding explosion. In a piston engine there is, of course, a direct relation between pressure in the cylinder and intake manifold pressure.

RICH AND LEAN BLOW-OUT

140 Under the conditions of poor combustion described for the turbine engine, increasing the fuel supply in order to maintain or increase engine speed may fail to do so and fuel supply may be increased until the flame is extinguished - this is known as "Rich Blow Out". In contrast to "Rich Blow Out" is the opposite condition known as "Lean Blow Out" which occurs when the mixture becomes too lean to burn. The mixture may not be too lean to burn under conditions of efficient combustion, but when combustion efficiency is very low the mixture may be ignited from an external source (such

as a spark plug) and will then either be extinguished when the spark ceases or may burn so slowly that the flame is carried out of the combustor and through the turbine. "Lean Blow Out" can occur when the fuel supply is reduced in order to reduce engine speed. When fuel supply is reduced in order to lower engine speed, the mixture is suddenly leaned off (since the fuel is immediately reduced), whereas the air supplied is reduced relatively slowly due to the fact that the flywheel energy of the compressor and turbine is available to drive the compressor and is used up relatively slowly. The flywheel energy in the main rotating parts of the engine is exceedingly important in respect to the problem of accelerating the engine whether the combustion efficiency is good or poor. In a turbo-jet engine, at any given rpm, the power developed by the turbine is substantially equal to the power absorbed by the compressor. If rpm is to be increased this can only be done by making the turbine develop more power. This increased power (excess power) is used: firstly, to increase the flywheel energy of the rotating parts and secondly, to provide the extra power required by the compressor as rpm increases. The rate of change of rpm increases very slowly as the point is approached where the turbine is just putting out enough power to drive the compressor. Even with very good combustion efficiency, engine acceleration becomes increasingly difficult as altitude increases. The change in flywheel energy resulting from a given increase of rpm is independent of altitude whereas the power developed by the turbine and that absorbed by the compressor decreases roughly in proportion to atmospheric density. Thus, when the atmospheric density decreases to 25% of the sea level value, the turbine power is roughly only 25% of the sea level value. The power absorbed by the compressor is likewise only roughly 25% of that at sea level. But the excess turbine power available to increase the flywheel energy of the rotating parts is likewise only about 25% of that available at sea level. The problem of engine acceleration thus becomes increasingly severe with increase of altitude. The problem of reduction of combustion efficiency is likewise one of increasing severity with increase of altitude. A turbo-jet may be operating at high altitude and at below maximum rpm with such low combustion efficiency that increase of rate of fuel supply (increase of fuel-air ratio) merely causes a further reduction of combustion efficiency rather than an increase of temperature of the gas at the combustor exit. Under such conditions, celeration of the engine by normal meth may become impossible and attempts to p duce acceleration are likely to result in "F Blow Out".

141 In general the power of a turbo-jet c not be increased without increase of rate revolution. It is possible, in a turbo-prop, increase the power available at the prope without increase of propellor or compres rpm.

142 This is particularly likely to be so w a two-stage turbine is used with the first st coupled to the compressor, with the sec stage driving the propellor and having no me anical connection with the compressor. I also true in some cases where compress turbines and propellor are rigidly coupled cannot rotate independently. In this latter c increase of power is the result of increa available energy in the gas supplied to the t bine as a result of increased temperature p duced by burning more fuel in the same amo of air. Such an increase of power without crease of propellor rpm necessitates an crease of propellor pitch. In general, wit turbo-prop, the best fuel consumption per p pellor shaft horsepower at any given propel horsepower will be obtained with the condit that gives the maximum jet pipe temperatu Thus, a given propellor shaft horsepower m be obtained with the propellor in flat pitch gi ing high compressor rpm which will suppl large amount of combustion air (and use a of horsepower to compress it) and using a ve lean fuel-air ratio with a low jet pipe tempe ature. The converse condition involves t propellor in high pitch, the compressor d livering less air (and using less power to co press it) and using a higher fuel-air ratio w a higher jet pipe temperature. While the hi pitch propellor setting may improve fuel co sumption per propellor shaft horsepower may not improve fuel mileage of the aircr if the high propellor pitch causes a serio drop in propellor efficiency.

COMPRESSOR EFFICIENCY

143 In any gas turbine, efficiency of con pression of the combustion air is exceeding important, in fact it may be said that the g turbine would not be possible without the eff ciency of the modern compressor (it would al not be possible without modern materials whic will stand up at the gas temperatures which a

necessary to obtain any useful power). In fact, the power available for propulsion in an aircraft gas turbine engine is always less than the power absorbed by the compressor. This is possibly best illustrated by a turbo-prop delivering 3000 bhp at the propellor shaft. In this case, at sea level the turbine will develop about 7500 bhp and the compressor will absorb about 4500 hp. In the case of a typical turbojet engine developing 5000 lb static sea level thrust, the energy absorbed by the compressor is over 10,000 hp while the mechanical (velocity) energy in the jet is only about 8000 hp. In view of the relative magnitude of the power absorbed by the compressor it is obviously necessary to avoid either increasing it or wasting it by loss of pressure between the compressor discharge and the entrance of the gas into the turbine nozzle guide vanes. This means that the pressure of the gas leaving the combustor should be as close as possible to that of the air as it enters the combustor. This requirement of low pressure drop through the combustor adds to the difficulty of the combustion problem since turbulence facilitates combustion.

TURBULENCE

144 Turbulence may here be defined as a disordered motion of the gases relative to the axis of the combustor. The most orderly flow through the combustor would involve each particle of gas flowing parallel (or very nearly so) to the axis of the combustor. Turbulence in a combustor is found in several forms. In Figure 2-10 the recirculation of the gases around the fuel spray is one form, the swirl of the primary air produced by the helical vanes shown in Figure 2-10 is another and yet another is produced by the secondary air flowing through the louvers in the combustor liner to join and dilute the burning gases.

145 The importance of turbulence in piston engine combustion was shown some forty years ago in a large slow speed gas engine burning city gas. In this engine, the speed was slow enough so that a record of the pressure could be obtained during the compression and explosion strokes. In this engine, as in modern engines, the pressure in the cylinder increased suddenly almost immediately after the spark occurred. Pressure diagrams were obtained with normal operation and also under conditions where the valves and ignition were made inoperative after a fresh charge of mixture had been sucked into the cylinder. As a result of suppression of valve and ignition operation, the charge was compressed and expanded about five times. Valve and ignition operation was then revived and the charge fired. The repeated compression and expansion had allowed the turbulence which occurs as a result of the charge rushing into the cylinder through the open intake valve, to almost die out. As a result of lack of turbulence, the pressure diagram showed that the charge gave a very weak explosion producing far less energy than the normal explosion.

146 The production of turbulence unfortunately requires energy and in the case of the turbine engine the energy can only be produced by a partial loss of pressure available at the entrance to the combustor. In a good modern engine, having a pressure ratio of 4 to 1, the pressure drop through the combustor at sea level is about 3 psi. Thus, the pressure at the compressor discharge is about 45 lb gauge (at sea level) and about 42 lb gauge at the combustor discharge.

147 Combustor design involves a practical compromise between loss of pressure due to turbulence and loss of combustion efficiency due to insufficient turbulence. A combustor with a very low pressure drop and insufficient turbulence may increase thrust in a turbo-jet at sea level but at the expense of increased fuel consumption resulting from discharge of unburnt fuel at the jet pipe nozzle. At altitude this combustor may give such low combustion efficiency that engine speed and thrust are lower than would be obtained with a more turbulent combustor having higher pressure drop and higher combustion efficiency. Turbulence is only one phase of combustor design but it has to date proved to be important. It is, at present, difficult to see how the necessary oxygen for complete combustion can be supplied to each fuel particle in the primary zone without turbulence. It is likewise difficult to see how fairly complete and uniform mixing of the primary combustion gases with the secondary (dilution) air can be accomplished without some turbulence.

INCREASED THRUST BY AFTERBURNING AND BY SUPPLEMENTAL INJECTION

The Problem Of Increasing Thrust

148 To return to the typical jet engine it may be assumed that the "throttle" is full

open at static sea level conditions and that full "throttle" produces the maximum combustion gas temperature that the turbine wheel will permit. It may also be assumed that it is required that thrust be increased. To produce a thrust increase, several avenues are open as follows:

149 A bigger engine burning more air at the same fuel-air (and the same turbine wheel temperature) may be used.

150 More fuel may be burnt in the gases after they have passed through the turbine wheel. As shown later, this adds to the available thrust producing energy in the gases. Since the gases have already passed the turbine wheel, increased temperature does not affect the wheel. This process is known as "afterburning" and is discussed further below.

151 The weight of the products discharged by the jet pipe may be increased without increasing engine size and without increasing the temperature of the gases either at the turbine or the jet pipe nozzle. This process is currently practiced by the supplementary injection of water or water-alcohol into the combustion gases prior to their passage through the turbine. The process, in effect, is one of carrying in the aircraft a liquid which can be gasified as a substitute for atmospheric air. It is known as "water-alcohol injection" and is discussed below.

152 Burning more air in the engine by increasing its rpm is not presently practical since it can only be done by increasing the temperature of the combustion gases by raising the fuel-air ratio. In present turbines, at the "Dry Rating" the combustion gases are close to the maximum permitted by the turbine wheel, etc. Apart from temperature effects, increase of rpm will increase turbine wheel stresses which are close to the permissible maximum at "Dry Rating" rpm. Increase of temperature of the gases passing through the turbine wheel may become practical in the future as a result of improved turbine blade materials or internal cooling of the blades.

AFTERBURNING

153 In a turbo-jet engine, the jet pipe may be extended and a burner added close to the turbine wheel Figure 2-10. Fuel is injected into this burner and on combustion in the exhaust gases (which have previously burned only about one-quarter of the available oxygen dur ing combustion in the combustors), raises th temperature of the gases by as much as 871.1°((1600°F) depending on the amount of fuel burnt thus adding to their energy available to produc thrust. This process is known as afterburnin or reheat and is relatively inefficient as re gards use of fuel. Afterburning is usually onl used during climb or when emergency militar power is required. Afterburning may increas static sea level thrust by 30%. At high aircraf speed and high altitude, the increase of thrus due to afterburning may be greatly in excess o 30%. In the case of a typical turbo-jet usin about 1.1 lb fuel per hour per lb thrust at nor mal "Dry Rating" when the afterburner come into use and increases thrust by 30%, the con sumption increases to about 2.2 lb fuel pe hour per lb thrust. The total hourly consump tion has increased by about 160% and the engin now uses about 2 1/2 times as much fuel pe hour. Afterburning usually requires the use o a variable area nozzle at the exit of the jet pipe

154 The variable area nozzle is necessar because the engine may "choke" due to high je pipe nozzle velocity and this "choking" will result in the compressor delivering less air. The variable area nozzle is also of value for accelerating the engine at high altitude. If the variable area nozzle is opened the pressure in the jet pipe is decreased. As a result of reduced jet pipe pressure the compressor takes less power to drive it and the turbine develops more power. Thus, the turbine is developing more power than necessary to drive the compressor and as a result the engine rpm is increased.

WATER-ALCOHOL INJECTION

155 Afterburning has only recently come into use as a means of augmenting the thrust of turbo-jets for brief periods. Prior to the development of afterburning, which requires: redesign of jet pipe, a considerable increase of jet pipe bulk and produces a small drop in efficiency during normal operation, there was need for temporary augmentation of thrust and this was met by water-alcohol injection.

156 The reasons for the increased thrust obtained with water-alcohol injection may be briefly and incompletely discussed. It may be shown that water-alcohol injection increases thrust by increasing the weight and the velocity of the gases discharged from the jet pipe. If the thrust is to increase by 15% and the jet pipe

temperature is to be held constant, then the weight of gases discharged must increase by about 7%. In an engine with a centrifugal compressor where the water-alcohol mixture is added at the compressor inlet, the effect is approximately as follows. The engine is assumed to be consuming 88 lb of air/sec (without water-alcohol injection), 1.56 lb of fuel/sec (fuel-air ratio 0.0177), the fuel rate being independent of whether water-alcohol is or is not in use, and having a water-alcohol injection rate of 5 lb/sec. When the water-alcohol is injected, it immediately starts to evaporate and its latent heat of evaporation, roughly 800 Btu/lb for the usually used mixture of water-methanol, see Table 6, reduces the air temperature slightly before compression starts and considerably during compression. As a result of the refrigerating effect before and during compression, the weight of air delivered by the compressor increases by about 2% (it may be more than this in some cases), the pressure of the air delivered is increased, the compressor efficiency is increased (less power absorbed/lb of air compressed) and the temperature of the air delivered is decreased. The engine is now using 89.8 lb air, 1.56 lb fuel, 1.75 lb methanol and 3.25 lb water/sec. The total weight of products discharged from the jet pipe nozzle has increased by 7.8%. These figures apply to a typical turbo-jet engine at sea level static conditions. At maximum output without water-alcohol injection (known as the "Dry Rating") the engine uses 1.1 lb fuel/hr/lb thrust. When the thrust is increased by 15% by water-alcohol injection (known as the "Wet Rating"), the total liquid consumption increases to about 4.1 lb/hr/lb of thrust, the total liquid consumption having increased by about 325%. In other words, at the "Wet Rating" output the engine uses about 4 1/4 times as much liquid as it does at the "Dry Rating".

157 Water alone can be used as a means of increasing thrust but its use requires that the fuel flow to the engine be increased with the start of water injection. Such revision of the fuel supply system leads to undesirable complication which is avoided with water-alcohol injection where combustion of the alcohol supplies approximately enough heat to offset the cooling effect of the water.

158 Water-alcohol was first used as a means of temporary thrust augmentation under conditions of high atmospheric temperature. A gas turbine engine loses power several times as fast as does a piston engine for each degree increase of atmospheric air temperature. This loss of power was particularly serious in respect to take-off with early turbo-jet aircraft, and water-alcohol was an answer that required little revision of the engine or of its operating procedure. While water-alcohol was and is of value in respect to take-off, the increase of thrust is also of value in respect to Emergency Military Power. Water-alcohol injection has an obvious application to turbo-props which suffer from high atmospheric temperatures in a similar manner to turbo-jets.

159 The question may be raised as to why use water-alcohol injection rather than making a bigger engine and to this there are two answers. Firstly, no engine is ever big enough since no sooner is a military aircraft built around it than either the aircraft designer or the operator of the aircraft wants more power. Secondly, since turbine engines usually have poor part load fuel economy (at least in comparison with a piston engine), use of a bigger engine means that the cruising fuel consumption of the aircraft is adversely affected by the larger engine, since cruising will be accomplished at a lower percentage of maximum output. By use of water-alcohol injection with the smaller engine, the part load economy is not affected, and the maximum thrust can be increased by about 15% over that available with the same engine without injection. The additional thrust is, as shown above, obtained at the expense of an enormous increase in liquid (fuel + water-alcohol) consumption. In spite of this fuel consumption the range of the aircraft is better than it would be with the bigger engine since the additional liquid consumption is only used for very brief periods.

160 As mentioned above, water-alcohol is used so that weight of combustion products is increased while keeping temperature of the gases at the turbine substantially constant. The best present compromise in the way of a water-alcohol mixture for this purpose is 60% water + 40% methanol by volume (approximately 35% methanol by weight). Injection and combustion of this mixture usually results in a slight increase of jet pipe temperature which can be tolerated since the periods of use are exceedingly brief.

161 Water-methanol is injected into the compressor inlet in the case of centrifugal com-

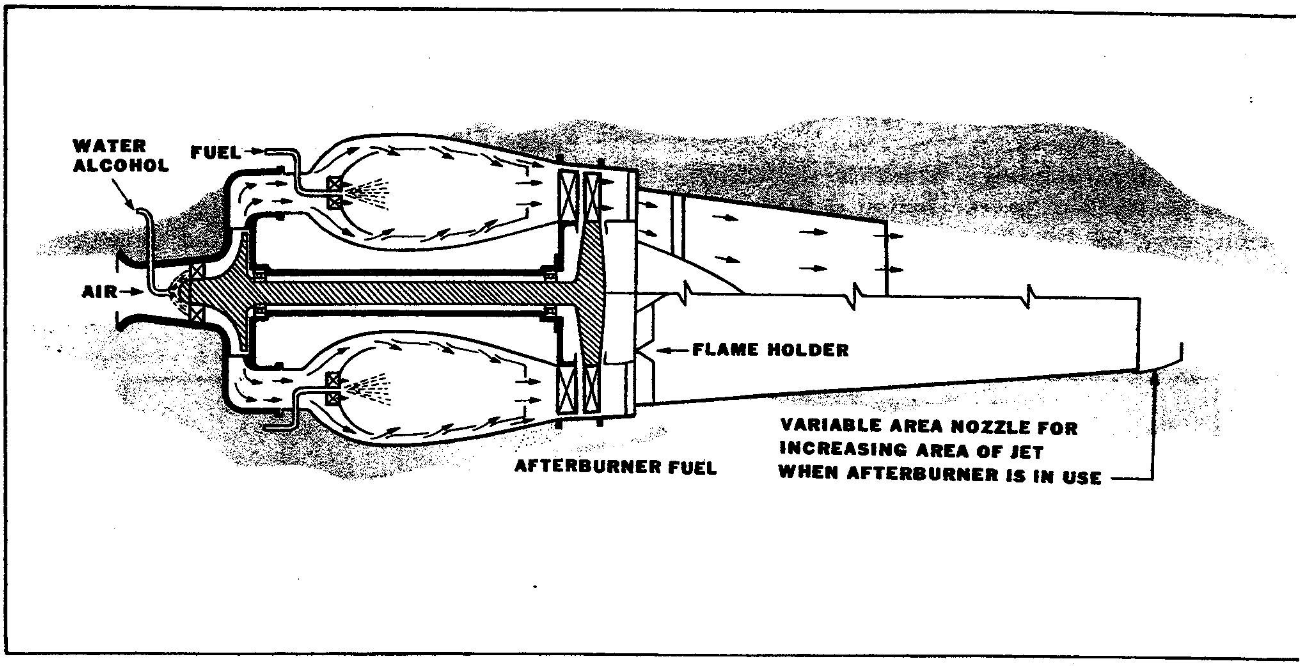


Figure 2-11 Diagrammatic Layout of Turbo-jet Engine

pressors. To date, injection of water-methanol into the inlet of axial compressors has not proved to be feasible and if used, it is usually injected into the combustor or combustors. Where supplementary liquid is injected into the compressor inlet, water-methanol is superior to water since its greater volatility ensures more complete evaporation and more uniform distribution of vapour or residual liquid to the combustors.

162 In a water-alcohol injection fluid, the alcohol has the second function of acting as an anti-freeze as well as providing heat for evaporation of the water and some heat for the combustion air. With turbine engine aircraft operating at altitudes of 50,000 ft, water not protected against freezing is an obvious hazard.

WATER-ALCOHOL VERSUS AFTERBURNING

163 Some of the relative advantages and disadvantages of afterburning and water-alcohol injection may be considered. Afterburning has the advantage that the over-all specific liquid consumption is only about 50% of that obtained with water-alcohol. Afterburning also has the advantage that it operates with only a single liquid as against two if water-alcohol is shipped as a blend or three if the alcohol has to be blended with water in the field. The disadvai tages of afterburning are rather considerabl Gas temperatures of 1370°C (2500°F) in tl jet pipe produce significant problems with mi terials, cooling and mechanical operation the variable area jet pipe nozzle. When use on the ground, the high temperature of gase issuing from the jet pipe presents a probler

164 Water-alcohol injection may be used : conjunction with afterburning but present some difficulties with afterburner operatio

TURBO-JET THRUST DATA

General Technical Data

165 The average turbo-jet engine with a pres sure ratio of 4 to 1 produces 55 to 60 lb c static sea level thrust per pound of air pe second. (These figures correspond to 65.5 t 60 lb of air per hour per pound of static se level thrust. Therefore, the take-off stati sea level thrust is roughly equal to the air con sumption in pounds per minute.)

166 The performance of a typical turbo-je engine equipped with a centrifugal compresso having a pressure ratio of about 4 to 1 is dis

cussed here as an example of turbo-jet performance at static sea level conditions. Performance in flight either at sea level or altitude is considered to be too complex for this Engineering Order which is essentially only concerned with the relation of fuel to engine performance.

167 - This typical turbo-jet has a "Dry Rating" of 5000 lb static sea level thrust and at this condition uses 88 lb of air per second. The air consumption corresponds to 56.7 lb thrust per lb of air per second (and to 63.4 lb air per hour per lb of thrust). The total air consumption per hour is 317,000 lb or 160 tons per hour in round figures. At 5000 lb thrust, the fuel consumption is 5600 lb hr corresponding to a fuel-air ratio of 0.0177. The "Wet Rating" of this engine is 5750 lb using 5600 lb of fuel per hour and 18,000 lb of water-methanol per hour. At the "Wet Rating" the total liquid consumption is 4.1 lb per hour per pound of thrust. For every additional pound of thrust produced by water-methanol, the water-methanol consumption is 24 lb per hour.

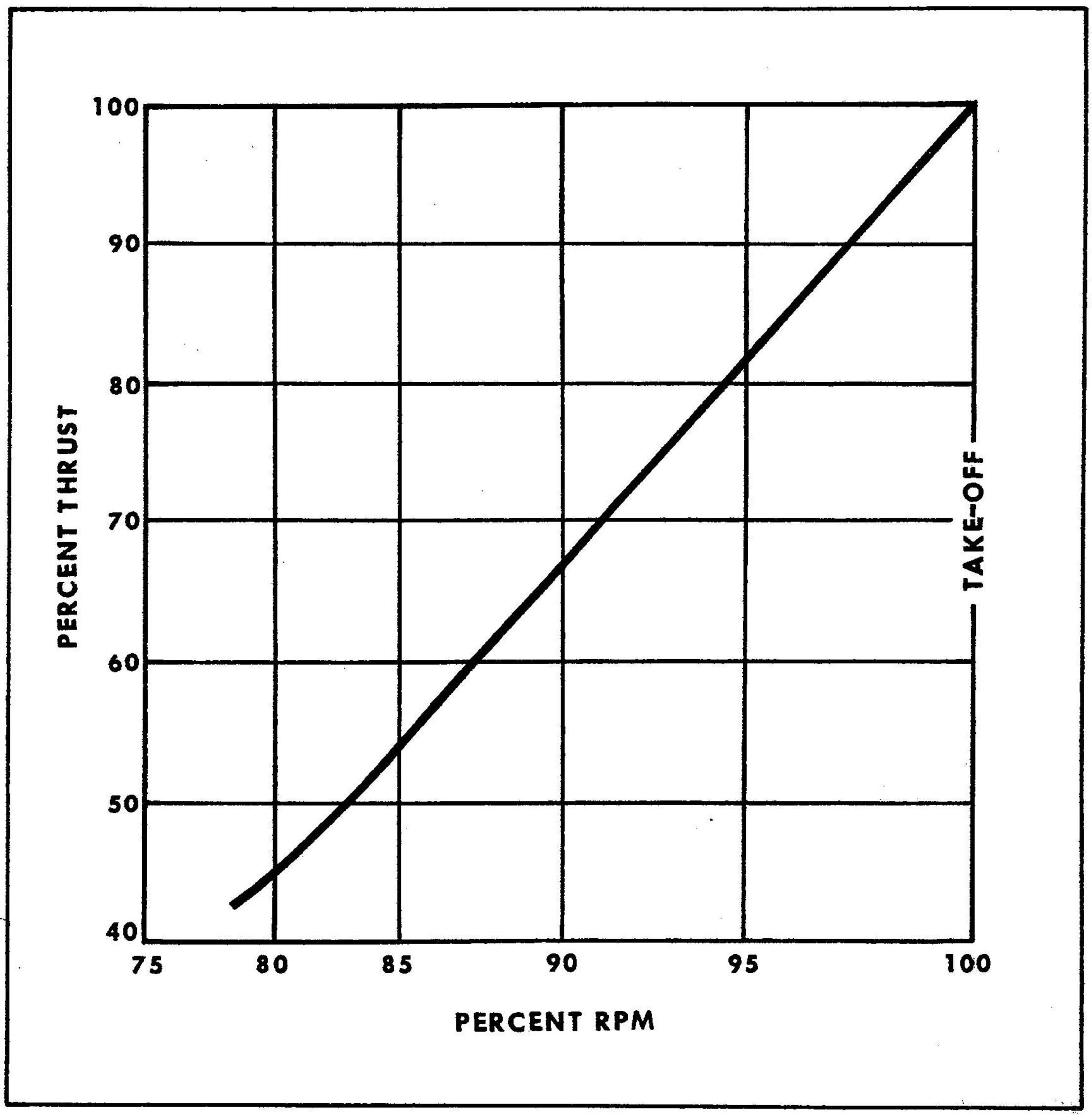


Figure 2-12 Static Sea-level Thrust Versus RPM. In a Centrifugal Turbo-jet Engine

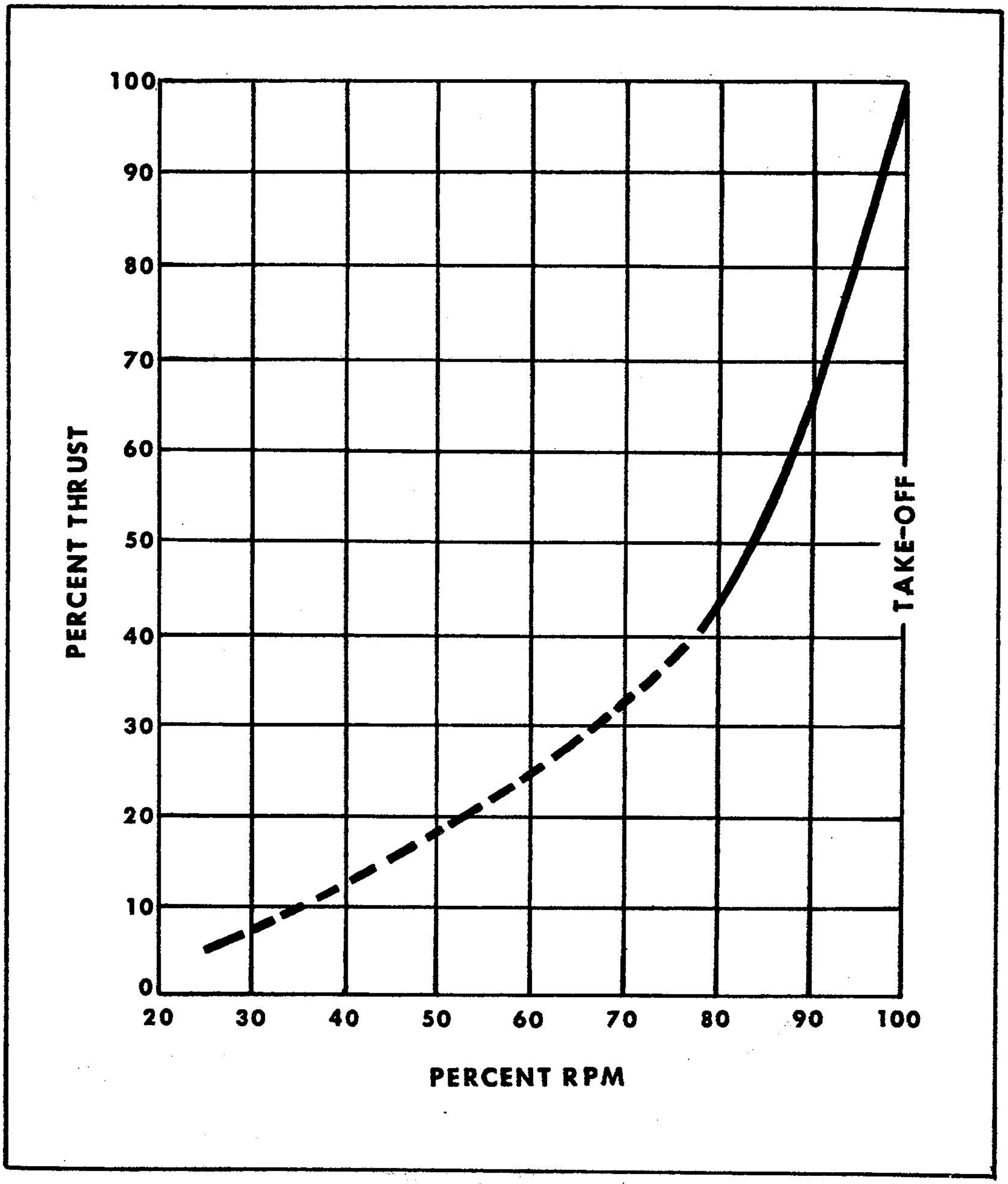


Figure 2-13 Static Sea-level Thrust Versus RPM

168 In this engine, the thrust, from rated take-off to 40% (low cruise) thrust varies almost directly as the fourth power of the rpm (i. e. 90% rpm will produce two-thirds of the thrust). Figure 2-11 shows per cent thrust plotted against the fourth power of the rpm and it will be noted that it is almost a straight line relationship. In this figure, the per cent rpm divisions are non-linear, being labelled as the first power of per cent rpm but plotted in pr(portion to the fourth power, thus the line f(90% is plotted in proportion to $(0.90)^4$ or 0.65 Figure 2-12 shows per cent thrust from take off to idle plotted against the first power of tl rpm. Figure 2-13 shows specific fuel consum tion and approximate specific air consumptic plotted against per cent static sea level thrus Figure 2-14 shows approximate fuel-air rat

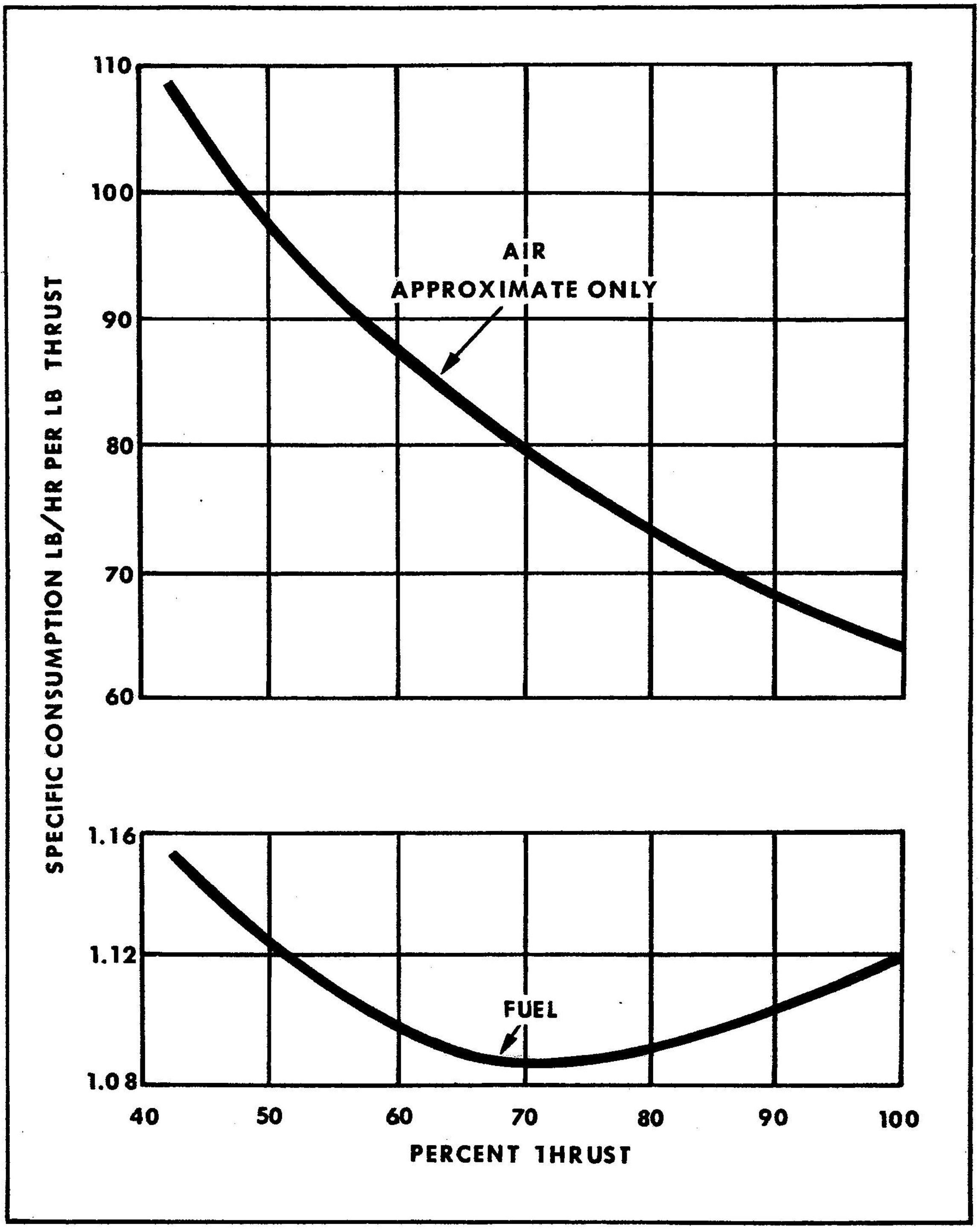


Figure 2-14 Specific Fuel and Air Consumption Versus Per Cent Static Sea-level Thrust in a Turbo-jet Engine

plotted against per cent static sea-level thrust for the same engine, this figure being derived from Figure 2-13. This engine idles at about 25% rpm which gives 4% thrust. At the idle condition the engine uses about 800 lb of fuel per hour (14.3% of that at "Dry Rated" power) and the fuel-air ratio is about 0.010.

169 In the case of the turbo-jet engine the specific consumption of combustion air is relatively enormous compared to a piston engine. Throughout the discussion of turbine engines and their fuels, the term combustion air h[a] been applied to the air that passes through t[h] compressor and the turbine. This term m[a] possibly be considered misleading since maximum of only about one quarter of the a is actually burnt and the remainder is real dilution air. As a maximum, only the air ne[c]essary to give the "chemically correct" fue air ratio can be said to actually take part combustion and the remainder is dilution ai If the combustion efficiency is low, less a than that required for the "chemically correc

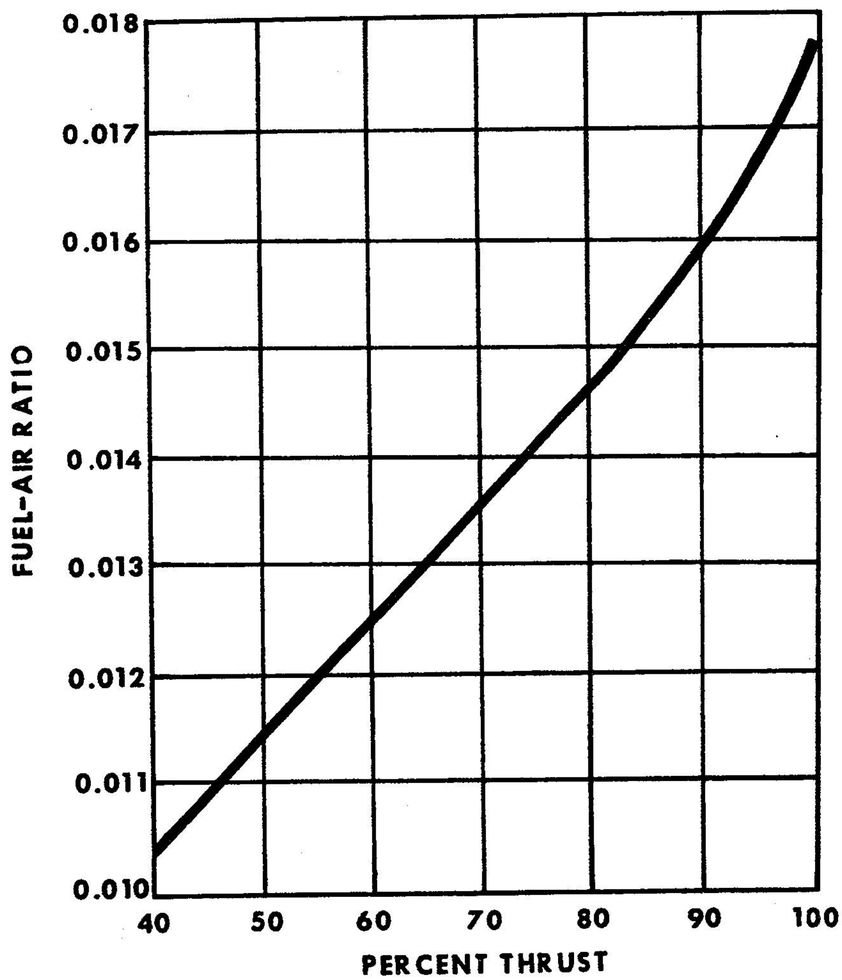


Figure 2-15 Fuel-air Ratio Versus Per Cent Static Thrust in a Centrifugal Turbo-jet Engin

fuel-air ratio actually takes part in combustion. The air, of course, is not only used for combustion but also directly produces propulsion. It should be borne in mind that in the case of a piston engine the combined weight of air used for combustion plus that accelerated by the propellor to produce thrust, will be even higher than in the jet engine for a given thrust at a given aircraft speed.

170 In considering jet engines it may be well to remember that effective propulsive power is a direct multiple of thrust and aircraft speed. Thus, 1 lb of effective thrust at an aircraft speed of 375 mph corresponds to 1 hp and at 600 mph corresponds to 1.6 hp. In considering effective thrust at 375 and 600 mph it must not be assumed that specific fuel and air consumptions at these speeds bear any close relationship to the consumptions obtained at static sea level conditions.

171 In the typical turbo-jet engine discussed above, the compressor absorbs about 10,500 hp at 5000 lb ("Dry Rating") static sea level thrust and at this condition delivers 88 lb of air per sec. The compressor is thus absorbing about 120 hp per lb of air per sec. The turbine develops slightly more power than the main compressor absorbs, the extra power being used up by the cooling compressor, fuel pumps, etc. Neglecting the power used for pumps, etc. the turbine requires about 30 lb of air per hr per hp. Since the engine is using 5600 lb of fuel per hr, the specific fuel consumption of the turbine is about 0.54 lb per hp hr. While the compressor absorbs about 10,500 hp at static sea level conditions, this power will increase in flight at sea level, the increase roughly depending upon the ram. If ram increases the weight of air handled by the compressor by 20%, the power required to drive the compressor will increase by roughly 20%. In the case of this typical turbo-jet engine, in sea level flight at 600 mph with a ramming air intake of average efficiency, the air delivered by the compressor increases by about 30% and the fuel flow by about 22% in comparison with static sea level air delivery and fuel consumption.

172 In the case of a turbo-jet engine, an energy balance may be computed since all the energy of the ingoing fuel will be shown in the jet pipe exit as velocity energy, heat energy of the gases and as unburned fuel. In the case of the above typical turbo-jet an approximate energy balance may be computed for sea level static conditions from the following data:

Air 88 lb sec

Temperature of air entering compressor = 60°F

Fuel 5600 lb hr = 1.556 lb sec

Fuel energy at 18,500 Btu per lb = 28,800

Btu per sec = 40,700 hp. If a combustion efficiency of 98% is assumed, then the total energy release in the combustors is 39,900 hp or 40,000 hp in round figures.

Weight of gas leaving jet nozzle = 88 + 1.556 = 89.56 lb sec
Velocity of gas leaving jet nozzle = 1800 ft sec
Temperature of gas leaving jet nozzle = 548.8°C (1020°F)

173 Assuming 0.25 as the mean specific heat of the gases leaving nozzle is:

(Weight of gases lb per sec) x (temperature rise from compressor inlet to jet pipe exit) x (mean specific heat of gases) and this equals 89.56 x 960 x 0.25 = 21,500 Btu per sec. The added heat energy in the gases (neglecting unburnt fuel) is $\frac{21,500}{0.707}$ = 30,400 hp.

The velocity energy in the gases (see (1), para 124 of this Part) = $\frac{89.56}{64.4} \times (1800)^2$ = 4,500,000 ft lb per sec = $\frac{4,500,000}{550}$ = 8190 hp. Thus, of the 40,000 hp released in the combustors we can account for 30,400 + 8190 or 38,590 hp which corresponds to 94.7% of that in the ingoing fuel.

Thrust (see (2), para 124 of this Part) = $\frac{89.56}{32.2}$ x 1800 = 5010 lb. No horsepower can be assigned to the 5010 lb thrust since the engine is at rest and developing no useful power.

TURBO-PROP ENGINES

174 Fewer data presently available on turbo-props than for turbo-jets and the following is based upon two turbo-prop engines having pressure ratios of between 6 and 7 and both having very efficient axial compressors which are directly connected to the propellor shafts. Both

engines are discussed only in terms of their performance on the test stand at sea level.

175 In the first engine at "full throttle", the compressor absorbs 60% of the power developed by the turbine. The air consumption is 45 lb per hr per propellor shaft hp and the fuel consumption is 0.78 lb per propellor shaft hp hr. This corresponds to a fuel-air ratio of 0.0173. The air consumption is 18 lb per turbine hp hr and the fuel consumption is 0.31 lb per turbine hp hr. In the engine for each hp delivered at the propellor shaft the turbine is developing 2 1/2 hp, and the compressor is absorbing 1 1/2 hp and by simple computation the compressor is absorbing 120 hp per lb of air delivered per sec. The specific fuel and air consumptions for this turbine may be compared with those given above for a typical turbo-jet. The specific consumptions for the turbo-jet are much higher than those of the turbo-prop for the reason that the turbine of the turbo-prop is absorbing a much greater proportion of the energy in the combustion gases. The turbine of the turbo-jet only absorbs sufficient energy to drive the compressor and accessories, leaving the remainder to produce thrust at the jet.

176 The second engine has a somewhat higher pressure ratio and the compressor absorbs 62% of the power developed by the turbine at "full throttle" or take-off power. This engine has considerably better specific fuel consumption than the first engine but actual figures cannot be given. Relative fuel consumption figures (that is, as a percentage of the specific consumption at take-off) are given, however. Figure 2-16 shows the variation of shaft power with rpm, this is not a smooth curve since power is varied by means of both rpm and fuel-air ratio As examples, both rated and take-off power are obtained at the same rpm by increase of fuel-air atio, whereas below rated power both rpm and fuel-air ratio are reduced as the power is reduced. Figure 2-17 shows fuel flow (lb per hr or gal per hr, as a percentage of the flow at take-off power) versus shaft power. It will be noted in Figure 2-17 that the fuel flow, when the engine is near the idle point, is roughly one third of that used at take-off. Figure 2-18 shows relative specific fuel consumption and actual specific air consumption versus power as a percentage of that at take-off. Figure 2-19 shows fuel-air ratio versus shaft power, with power varying against rpm as shown in Figure 2-16.

177 Figures 2-16 to 2-19 inclusive in co junction with the fact that the compressor al sorbs 62% of the turbine power at take-of enable a number of interesting compariso to be made. Figure 2-18 shows that the sp cific air consumption is about 39 lb per hr p shaft hp at take-off power. From this it c be computed that the turbine is using about lb of air per hr per turbine hp and that t compressor is absorbing about 150 hp per of air per sec. It may be said that the specif fuel consumption of the turbine alone is belo 0.3 lb per hr per turbine hp. Figure 2-17 i dicates that "throttling" the engine below abo 50% of take-off power is not an economic proceeding as regards either total or specif fuel consumption. Figure 2-18 shows the ve considerable increase in specific air consum tion as the load is reduced. The relatively hi specific air consumption at part load is to considerable extent responsible for increas of specific fuel consumption as load is reduce This effect is the result of the fact that fue air ratio is reduced as power is reduced (a shown in Figure 2-19). Thus, a large amou of work is going into compressing the air whi the work recovered by expanding this air i reduced since much less than the maximu permissible energy has been added to it b burning fuel. If the engine is considered whe running at take-off rpm and variable fuel-ai ratio, it will be seen that at take-off powe 62% of the fuel is being used to drive the com pressor and 38% to produce power at the pro pellor shaft. On this basis, if the fuel flow i reduced by 38% while maintaining consta rpm, then the turbine will only be developin roughly enough power to drive the compresso and there will be no available power at the pro pellor shaft. By "throttling" the engine by re ducing both rpm and fuel-air ratio the situatio is greatly improved and zero power at the pro pellor shaft is now obtained at about one-thir fuel flow (as shown in Figure 2-17) instead c at about 62% fuel flow.

178 The above indicates that "throttling" turbo-prop by a process similar to that use with a piston engine is not economical in re spect to fuel consumption. Fortunately, how ever, there are two (or possibly more) ef fective ways out of this situation. The first i to really throttle the engine (that is, make i use less air) by increase of altitude while main taining substantially constant fuel-air ratio an rpm. The power absorbed by the compresso will fall off practically in proportion to the at

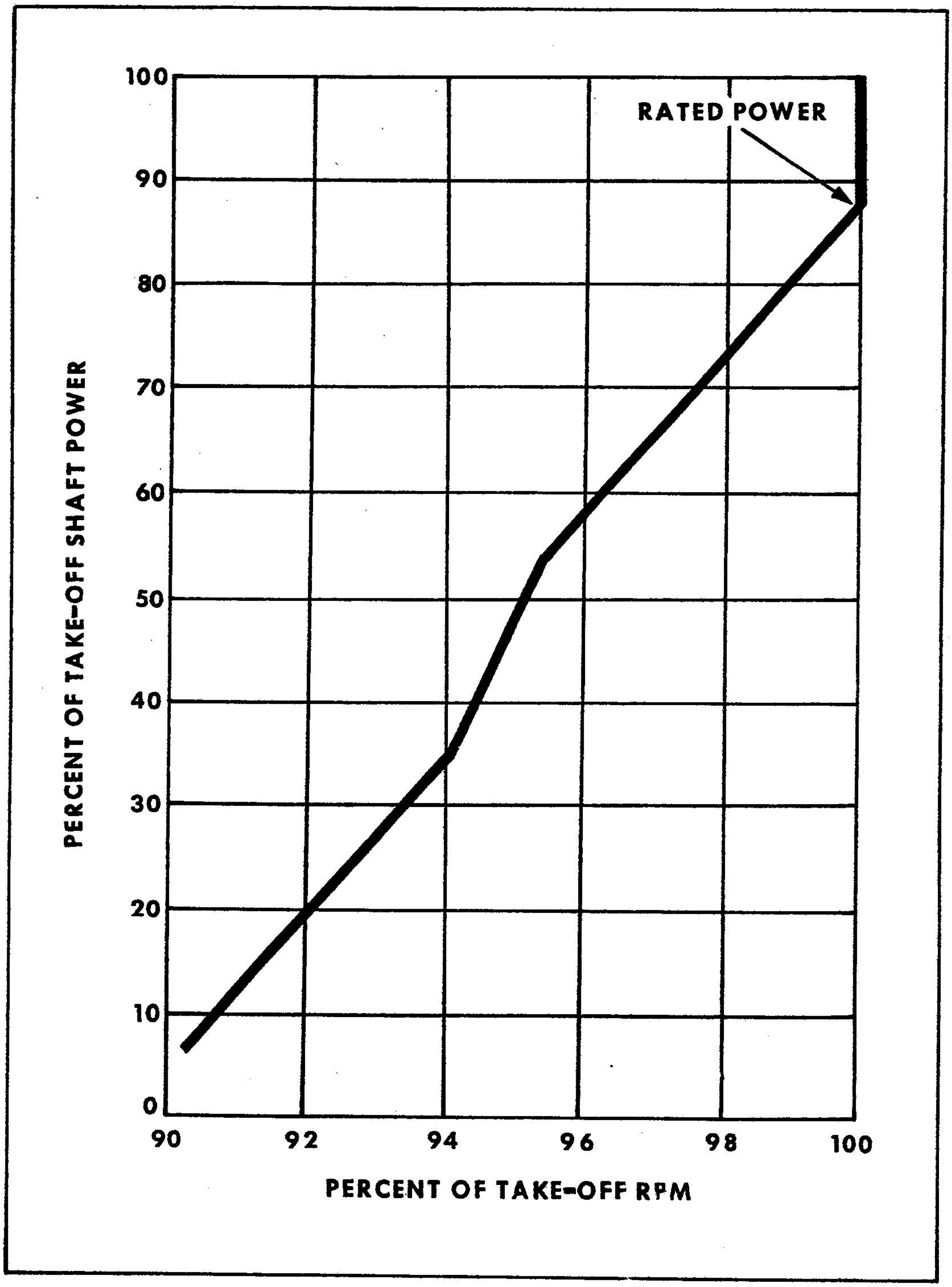


Figure 2-16 Sea-level Test Stand Performance of a Turbo-prop Engine

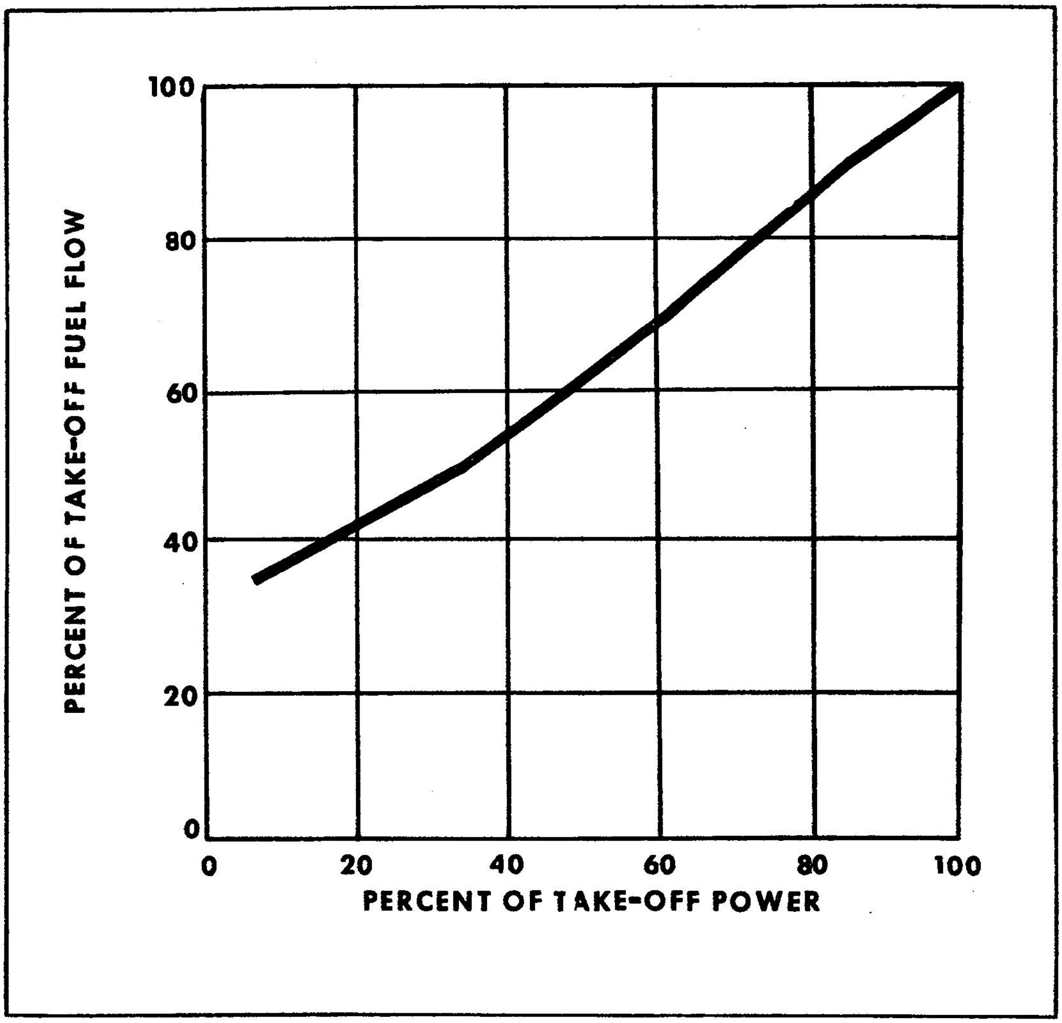


Figure 2-17 Sea-level Test Stand Conditions in a Turbo-prop Engine

mospheric density. Thus, at an altitude where the atmospheric density is only 50% of that at sea-level, the power absorbed will be only about 50% of that at sea-level, while the shaft power will be about 50% (or more) of the sea-level power. Actually, due to the reduction of temperature at altitude, the power absorbed by the compressor will be still lower since it takes less power to compress a pound of cold air to a given pressure ratio than it does to compress a pound of hot air. Furthermore, since the air was colder when it entered the compressor, it will be colder after it is compressed, and the fuel-air ratio can be safely increased to bring the combustion gases back to the limiting temperature allowable at the chosen condition, (the limiting temperatu for take-off is higher than that permitted rated power) and in this manner more pow per lb of air can be recovered in the turbir The second way out of the "throttling" proble consists of a twin turbine engine driving single propellor. By cutting out one of the t engines, the specific fuel consumption at a given altitude is as good at 50% power as it at full power.

179 While it is not connected with the pro lem of "throttling" a turbo-prop engine (in fa rather the reverse), there is an important ir provement of specific fuel consumption in flig which results from the ramming air intak

The ramming air intake increases the over all pressure ratio of the engine. The over-all pressure ratio is the ratio at atmospheric pressure to the pressure at the compressor discharge. If the ramming air intake produces a pressure ratio of 1.2 and the pressure ratio of the compressor is 4, then the over-all ratio is 4.8 to 1. The higher the speed of the air-craft the greater will be the over-all pressure ratio. The higher the over-all pressure ratio the greater is the work available from the gases by expansion through the turbine. While the increase of over-all pressure ratio involves increased total work of compression, a decreased proportion of this work is done by the compressor. Since a decreased proportion of the work of compression is done by the compressor, the compressor absorbs a reduced percentage of the total turbine power and the fuel consumption per shaft horsepower is improved.

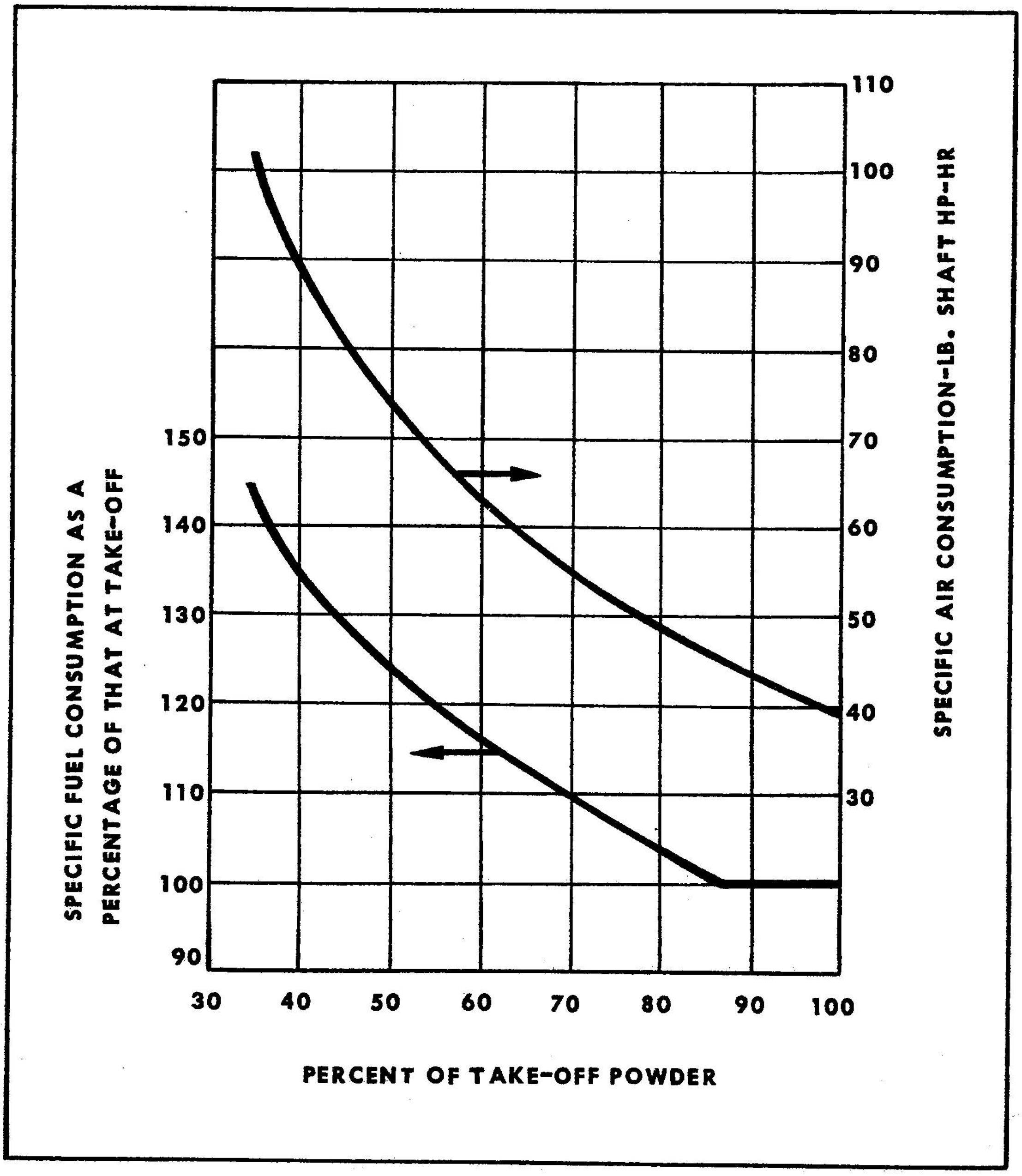


Figure 2-18 Sea-level Test Stand Conditions of a Turbo-prop Engine

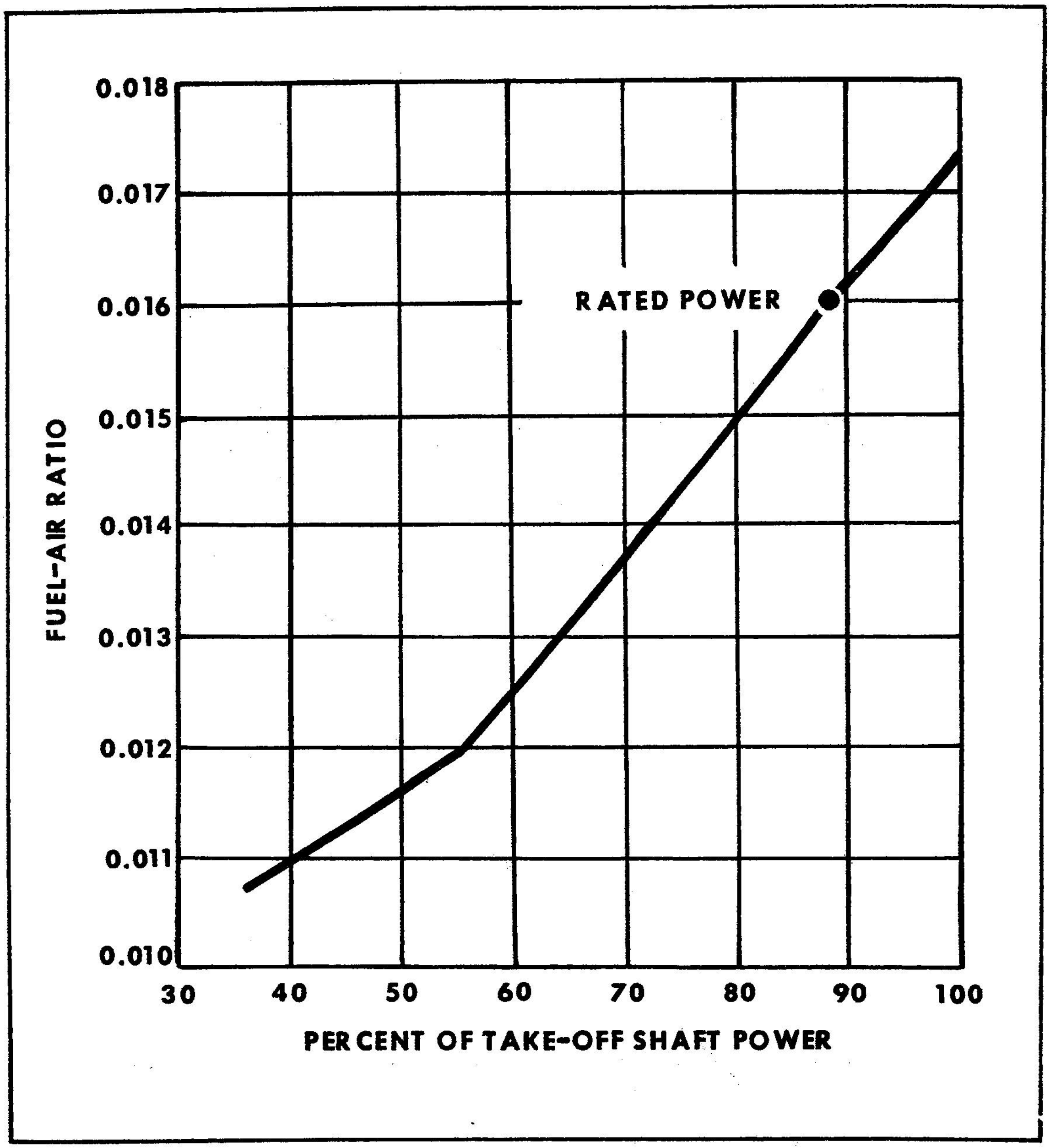


Figure 2-19 Sea-level Test Stand Values of a Turbo-prop Engine

180 The jet effect of the exhaust of the turbo-prop at high aircraft speed and high altitude has a significant effect upon the fuel consumption of the aircraft. The jet effect does not reduce specific fuel consumption per shaft hp but does reduce the consumption per effective thrust hp (effective thrust hp includes net thrust of the propellor and net thrust of the jet).

181 The total "full throttle" air consumptio of 40-45 lb per hr per propellor shaft hp of th turbo-prop may be compared with that of a piston engine. The turbo-prop requires only a small amount of air for cooling accessories jet pipe, etc. It does, however, have a rathe significant requirement of air for oil cooling and this becomes increasingly important wit

very high speeds at very high altitudes, but no estimate of the weight of air required can be given. The turbo-prop, of course, uses a large amount of internal cooling air (roughly three-quarters of the 40-45 lb per shaft hp hr) in order to keep the temperature of the cycle down to a level which the turbine can tolerate. A modern piston engine will use about 6 lb of combustion air per hr per shaft hp and a total of about 40 lb of cooling air per shaft hp hr. This 40 lb per hr includes air for cylinder and oil cooling and air for cooling accessories, etc. Thus, the total air requirement of a piston engine is roughly equal to that of a turbo-prop engine at "full throttle". As the turbo-prop is "throttled" (i.e. as fuel-air ratio is reduced)

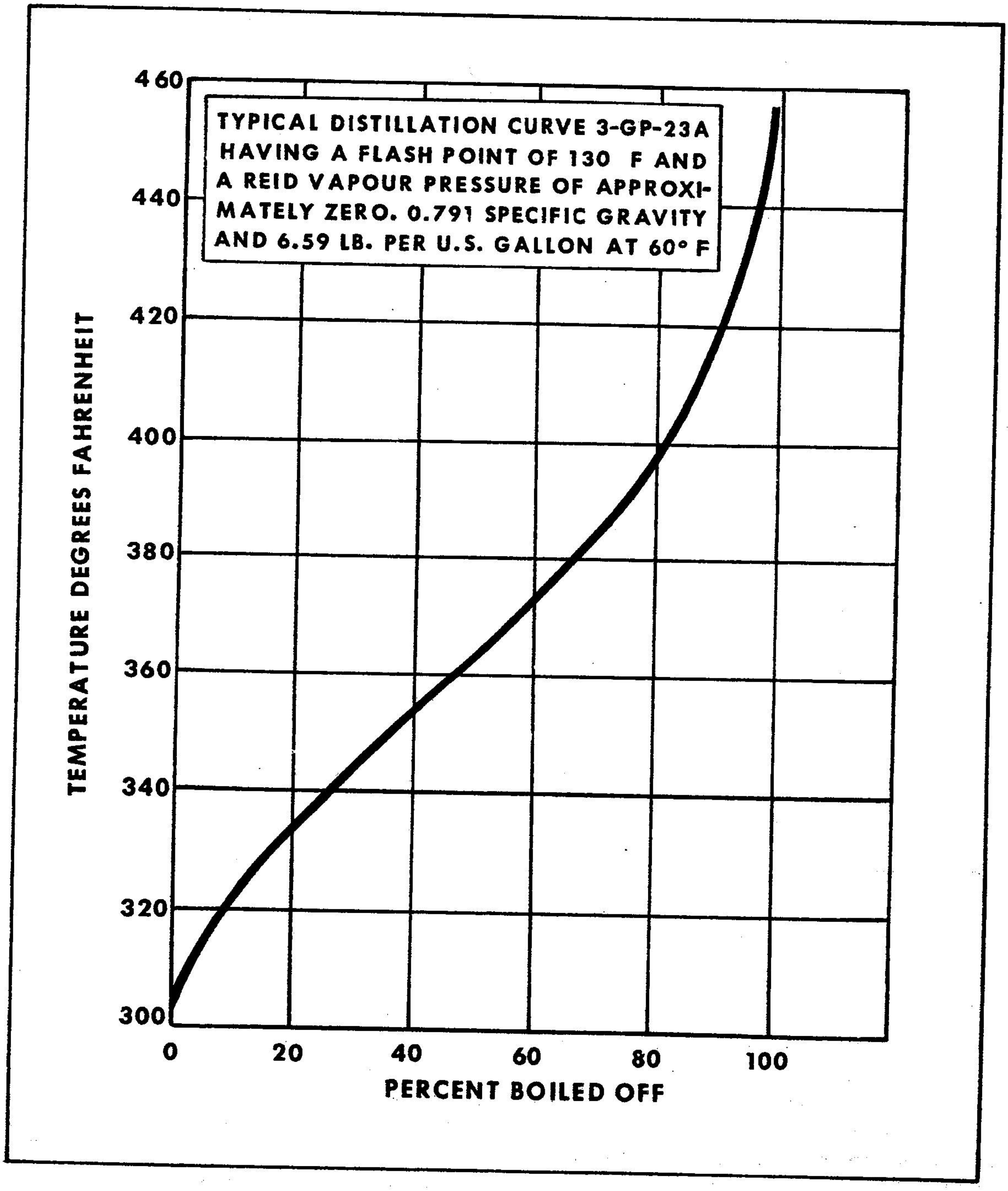


Figure 2-20 Distillation Curve of 3-GP-23A

the comparison with piston engine becomes less favourable. The piston engine, of course, has an increasing specific cooling air demand as hp and fuel-air ratio are simultaneously duced for cruise, but this increase is sm compared to increase with a turbo-prop.

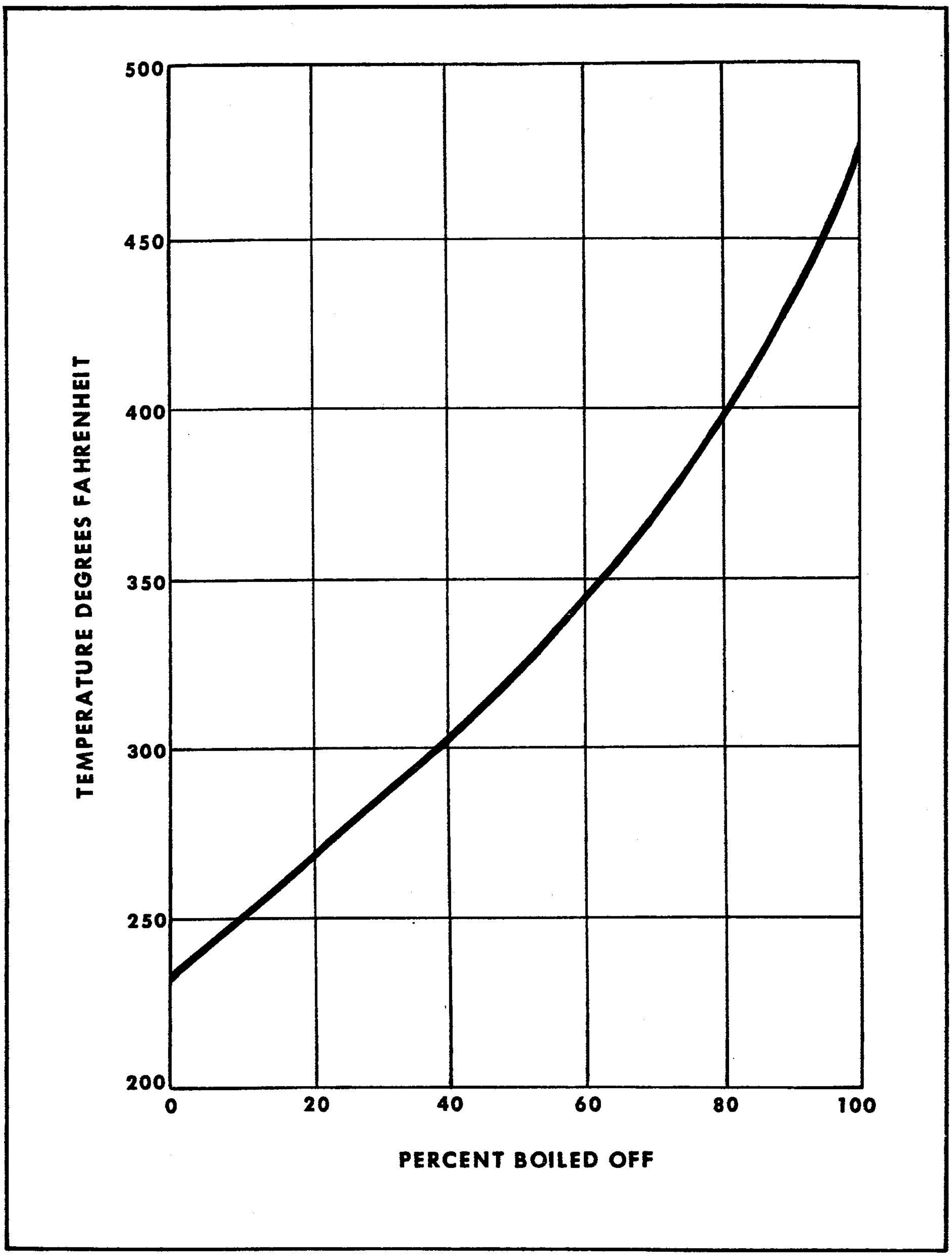


Figure 2-21 Distillation Curve of JP-2

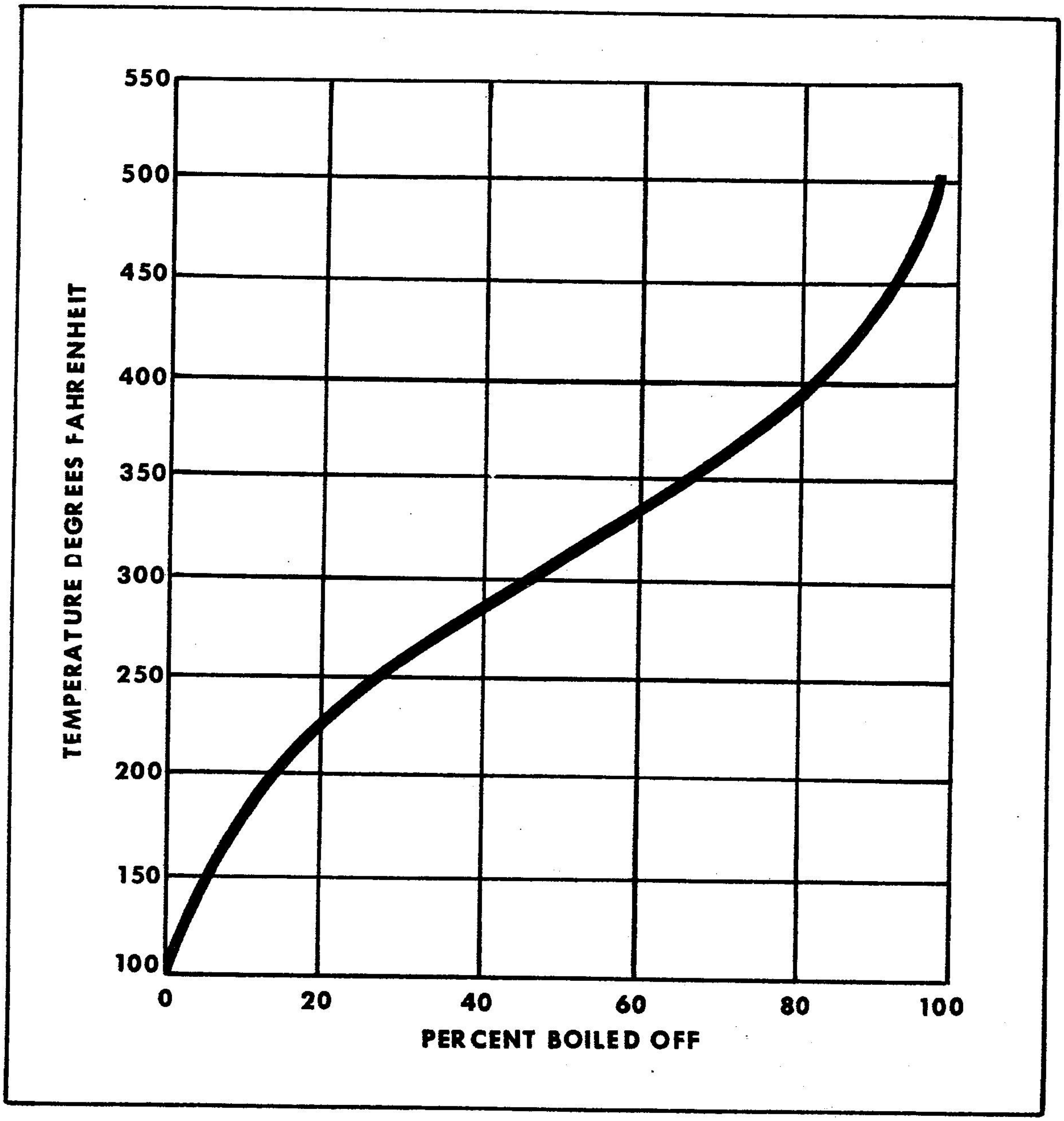


Figure 2-22 Distillation Curve of 3-GP-22

PART 3

DIESEL FUELS

GENERAL

1 Present high speed Diesel fuels are petroleum fractions required to ignite spontaneously when sprayed as atomized liquid into air which has been heated to 500 - 600°C (932-1112° F), by rapid compression. High compression ratios up to 14:1 are required to obtain the high temperatures necessary for the combustion of the fuel in the cylinder, which then provides power to drive the engine.

POUR POINT AND VISCOSITY

2 The pour point and viscosity of Diesel fuels have an important bearing on the operation of Diesel engines. The fuel must remain pumpable at all conditions in which it is to be used. Therefore the pour point must be low enough to meet the frigid temperatures experienced at many stations.

3 The viscosity of Diesel fuel governs the ease of atomization of injected fuel. Excessive viscosity leads to increase in droplet size which lowers the speed of combustion. A minimum viscosity may also be specified because back-leakage in pumps and injectors may occur, when the parts are worn, if the viscosity is too low. This would reduce the power output of the engine.

CETANE NUMBER

4 Cetane number for Diesel fuels corresponds to the Octane number for gasoline. It designates the ignition quality of the fuel and is equivalent to the percentage of cetane, a hydrocarbon liquid, in a reference sample. Cetane has an arbitrary rating of 100. Fuel which has a Cetane number above 500 is considered to be desirable for use in high speed Diesels.

CARBON DEPOSITS IN THE ENGINE

5 The tendency for Diesel engines to form carbon deposits in the combustion chamber, and particularly round the fuel injector nozzles is dependent on both the engine operating conditions and the properties of the fuel. Deposits on injector nozzles increase fuel consumpt and decrease power output, because choking the injector nozzles will upset the even d tribution of the fuel spray. Such deposits m build up into "cones" around the injector nc zles, finally breaking away when they beco unstable. The "cones", having broken aw are obviously undesirable in the engine, and trapped between an exhaust valve and its s may cause pitting or even more severe damag

6 It is normally found that the more vol tile the fuel, the better it is against carbon d position. A carbon residue test, similar to th for lubricating oils, is carried out to pred the tendency for Diesel fuels to form carb deposits, and thus a maximum carbon resid is usually specified.

CLEANLINESS OF THE FUEL

7 It is important that fuels for Diesel e gines are free from solid contaminants. T clearances in injector nozzles are usually ve small, solid contaminants may cause bloc age of these nozzles, or blockage of the filter if these have to cope with large quantities solids. Solid contaminants in the fuel also i crease wear in cylinder bores.

8 Dirty injector nozzles may often be r cognized by continuous black exhaust smok This may be due to carbon deposition arou nozzle, blockages in the nozzle, or solid matt between nozzle valves and their seatings allov ing leakage of fuel. The remedial action is strip and clean the nozzles in accordance wi existing instructions as soon as black exhau smoke is noticed.

9 The corrosive tendencies of the fuel a usually specified. The sulphur content is mo harmful, in certain engines the sulphur con tent of the fuel has a direct bearing on the ra of cylinder wear.

PART 4

SPECIFICATIONS
GASOLINE AUTOMOTIVE (TYPE 1 RED)
3-GP-1A (RCAF REF 34A/2)

PROPERTIES

1 The gasoline covered by this specification is clear, free from undissolved water, and coloured red. The maximum permissible lead content is 3.6 ml of TEL per Imperial gallon, the maximum freezing point is -51.1°C (-60°F), and the maximum sulphur content is 0.15 per cent.

2 The Octane number of Type 1 gasoline is 78 in most areas of Canada. In the Provinces of Saskatchewan, Alberta, that part of British Columbia east of the one hundred and seventeenth meridian, Yukon Territory, and that part of the District of Mackenzie west of the one hundred ana twentieth meridian, a minimum number of 76 is permitted for Type 1.

3 The Reid vapour pressure and oxidation stability of commercial grades may make them unsuitable for military uses, and they are therefore emergency substitutes.

INTENDED USE

4 The gasoline covered by this specifi tion is intended for use in automotive and s tionary engines of the internal combusti spark ignition type requiring a carburant fu It does not apply to materials known as aviat fuel, nor heavier duty fuels in classes kno as kerosene, engine distillate, etc.

FUEL OIL - DIESEL
3-GP-6 (RCAF REF 34A/71)

Properties

5 These fuels are hydrocarbon oils su plied substantially free from water, grit, other foreign matter likely to clog or dama engines. The grade of fuel to be supplied any locality at any one season of the year sh conform to the following tabulation, and unle otherwise specified deliveries are made in a cordance with this tabulation.

	April Through September	October Through March
Martime	Grade 3	Grade 1
Quebec, Northern	Grade 2	Grade 1
Quebec, Southern	Grade 3	Grade 1
Ontario, Northern	Grade 3	Grade 1
Ontario, Southern	Grade 3	Grade 2
Western Provinces	Grade 3	Grade 1
British Columbia, Northern	Grade 3	Grade 1
British Columbia, Southern	Grade 3	Grade 3
North West Territories	Grade 1	Grade 1
Yukon	Grade 1	Grade 1
New Foundland	Grade 2	Grade 2
Labrador	Grade 1	Grade 1

INTENDED USE

6 This specification applies to fuels derived from petroleum and suitable for use in internal combustion engines of the compression-ignition Diesel type.

AVIATION TURBINE FUEL
TYPE 2 - WIDE RANGE
3-GP-22A (RCAF REF 34A/159)

Properties

7 This specification applies to a fuel that is suitable for use in aviation turbine engines. This fuel consists of hydrocarbon compounds (actually a blend of gasoline and kerosene fractions) is clear and free from sediment, undissolved water, dangerous toxic substances, and has a mild odour. The formation of gum is prevented by the addition of approved inhibitors.

INTENDED USE

8 The turbine fuel covered by this specification is intended for use in aviation turbine engines as specified in EO 45-1-2. Since aircraft range is somewhat less with this fuel than with 3-GP-23A fuel, it is quite likely that the specific gravity requirement will be increased and the permissible gravity range reduced.

AVIATION TURBINE FUEL - TYPE 1
3-GP-23A (RCAF REF 34A/158)

Properties

9 This specification applies to a kerosene fuel that is suitable for use in aviation turbine engines. The fuel consists of hydrocarbon compounds, is clear, neutral, free from undissolved water or any suspended matter.

INTENDED USE

10 The turbine fuel covered by this specification is intended for use in aviation turbine engines as specified in EO 45-1-2. Eventually the operation of jet engines on 3-GP-23A fuel will be discontinued and all operations will be performed on 3-GP-22A fuel.

AVIATION GASOLINES
3-GP-25B
GRADE 80 (RCAF REF 34A/186) LEADED, RED
GRADE 80 (RCAF REF 34A/1) LEADED, BLUE
GRADE 91/96 (RCAF REF 34A/79)
GRADE 100/130 (RCAF REF 34A/52)

Properties

11 This specification applies to liquid fuel, of various grades, suitable for use in aircraft engines of the internal combustion, spark ignition type. The fuel consists of hydrocarbon compounds and may have limited amounts of aromatics and ethyl fluid added. Anti-oxidants may be added when required to prevent the formation of gum. The 91/96 grade is dyed blue, the 100/130 grade is dyed green, while the 80 grade may be red or blue.

NOTE

This specification will soon include grade 115/145 now procured to MIL-F-5572 Specification.

INTENDED USE

12 The aviation gasolines covered by this specification are intended for use in Aircraft Reciprocating Engines as specified in EO 45-1-2. In special instances, such as low temperature starts, as specified in relevant EOs, Avgas may be used in aviation turbine engines. RCAF turbine engines may operate on gasoline as specified in EO 45-1-2.

SUMMARY OF RCAF AIRCRAFT
GASOLINE AND TURBINE FUEL
SPECIFICATIONS

13 Specified requirements for aviation gasolines, see Table 4, and for aviation turbine fuels, see Table 5, are subject to change as knowledge grows and requirements increase, and the values given in the tables are for guidance only and should not be used in place of the latest issue of the specification for each grade. In some cases, the specifications may not agree with statements made in this Engineering Order due to subsequent changes in specification requirements.

PROPERTIES OF FUEL COMPONENTS

14 The data given in Table 5 are for reference only and are not intended for study by the reader of this Engineering Order.

15 The use of complex chemical names of compounds and illustration of their molecular structure cannot be avoided if clear identification is to be obtained. The reader will, however, have the data at hand if they are desired.

16 Except for Performance Number data, the values given for the various properties are the best available in the literature; if properties are not exactly known they are so marked. The Performance Number data are only approximate and are not suitable for specification purposes. The values given in many cases are not obtained by officially standardized knock test methods; some of the compounds listed cannot be rated by the current official test methods. The values given are a guide to the usefulness of the compounds in respect to their value from the Performance Number standpoint when added to various grades. Thus, the addition of benzene + 4.0 ml. lead which has a lean Performance Number of 68 and a rich Performance Number of more than 160, to Grade 100/130 can be expected to decrease the lean rating and increase the rich rating, and these expectations are confirmed in practice.

17 However, behaviour of fuels in blends cannot always be predicted from knowledge of the knock properties of the pure components. Thus, a blend of two pure compounds may be better then either component. Addition of a compound with a high lean rating in the absence of lead, may depress the lean rating of Grade 100/130 and this is most likely to be true if lead has only a slight effect upon the added component. When considering the Performance Number data it is well to bear in mind that the Performance Numbers of the grades below 100 are as follows:

Military Grade	Performance Number	
	Lean	Rich
80	58	not specified
91/96	76	88

Grade 80 has no rich Performance Number requirement. There is, however, a corresponding commercial Grade 80/87 having a rich Performance Number requirement of 68.

18 The Performance Number data for normal heptane (Compound 5 of about 22 Performance Number) and triptane (Compound 7) a worthy of comparison since both these con pounds are heptanes (namely seven carbon ato paraffins).

19 The letters used in the structures of th chemical compounds signify chemical elemen as follows:

C equals carbon
H equals hydrogen
O equals oxygen
N equals nitrogen
Br equals bromine
Pb equals lead
S equals sulphur

20 When two carbon atoms are linked with single bar this indicates that those atoms can not take on more hydrogen; when a double ba links the two carbon atoms it indicates th hydrogen can be added by a process known a hydrogenation. Thus, benzene (Compound 1 will take on six hydrogens and become cyclc hexane (Compound 14) and the two di-iso-buty lenes (Compounds 25 and 26) will add two hy drogens and both become iso-octane (Compoun 8). Triptene (Compound 24) can be hydrogenate and becomes triptane (Compound 7).

21 In view of the interest in aromatic nearly all of the aromatic compounds whic can be used in current specification aviatio gasoline are listed in Table 6.

22 The properties of carbon, hydrogen an water are included in Table 6. The relativ heats of combustion of carbon and hydroge show why a high percentage of the latter is de sirable in aviation fuels to secure a high hea of combustion. The latent heat of evaporatio of water when compared to that of hydrocarbon and alcohols explains the usefulness of wate in reducing fuel-air mixture temperature i piston engines and air temperature in turbin engine compressors.

23 Compounds which are either of interes as turbine fuels or which are used in illustrat ing the turbine combustion problem are segre gated in the last portion of Table 6, rather tha being grouped in order as: paraffins, olefins aromatics, etc.

TABLE 4

SUMMARY OF RCAF GASOLINE SPECIFICATIONS *

					3-GP-1T	3-GP-1A		3-GP-1A	
	80	91/96	100/130	115/145	80	Type 1 15 May	Type 2 15 Sept	Type 1 16 Sept	Type 2 14 May
At least 10% evaporated at °F	167	167	167		167	155	155	130	140
At most 40% evaporated at °F	167	167	167			-	-		
At least 50% evaporated at °F	221	221	221		221	255	255	255	255
At most 90% evaporated at °F	-	-	-		-	-	-	-	-
At least 90% evaporated at °F	275	275	275		284	370	370	370	370
Sum of 10% +50% temp. min. °F	307	307	307		307	-	-	-	-
End point max. °F	338	338	338		356	-	-	-	-
Lead ml./Imp. gal. max.	3.0	5.5	5.5		-	3.6	3.6	3.6	3.6
Colour (1)	Blue	Blue	Green		White	Red	Other than Red	Red	Other than Red
Freezing point max. °F	-76	-76	-76		-76	-60	-60	-60	-60
Octane number lean min.	80	91	100		80)				
Performance number lean min.	(58.3)	(76)	100		)	See Part 4 of			
Octane number rich min.	-	96	-		-)	this EO			
Performance number rich min.	-	(87.5)	130		-)				
Heat value Btu per lb. min.	18700	18700	18700		18700	-	-	-	-
Sulphur per cent by weight max.	0.05	0.05	0.05		0.05	0.15	0.15	0.15	0.15
Inhibitors permitted (3)	Yes	Yes	Yes		Yes	-	-	-	-
Existent gum mg/100 ml. max.	3.0	3.0	3.0		4.0	7.0	7.0	7.0	7.0
Copper dish res. mg/100 ml. max.	-	-	-		-	-	-	-	-
Accelerated gum (5 hrs) mg/100 ml. max.	-	-	-		6.0)				
Accelerated gum (16 hrs) mg/100 ml. max.	6.0	6.0	6.0		-)	Oxidation Stability 240 minutes minimum			
Precipitate (5 hrs) mg/100 ml. max.	-	-	-		-	-	-	-	-
Precipitate (16 hrs) mg/100 ml. max.	2.0	2.0	2.0		-	-	-	-	-
Corrosion copper strip	None	None	None		-	Pass	Pass	Pass	Pass
Water tolerance permitted ml.	2.0	2.0	2.0		2.0	-	-	-	-
Reid vapour press. lb. sq. in. max. (4)	7.0	7.0	7.0		7.0	10.0	10.0	13.0	13.0
Reid vapour press. lb. sq. in. min.	5.5	5.5	5.5		-	-	-	-	-
Aromatic amines permitted	No	No	No		No)				
Aromatic permitted (5)	Yes	Yes	Yes		Yes)	Not Stipulated			
Distillation loss per cent max.	1.5	1.5	1.5		1.5	-	-	-	-

(1) If unleaded shall be white, +20 Saybolt (min.). If it contains 0.6 mls TEL it is coloured red.

(2) Dye concentrations are not specified directly for military fuel but finished fuel must be within minimum and maximum military colour standards. Types of dyes permitted are specified.

(3) Inhibitors may be added to the extent required to prevent formation of excessive precipitate or excessive gum during the oxygen bomb test. Not more than 0.25 pound of approved inhibitor may be used for each 5000 Imperial gallons of finished fuel blend for the 16 hr test or not more than one-half this quantity for the 5 hr test. Several inhibitors are approved for RCAF use.

(4) Except that a vapour pressure of one psi greater for 1-GP-1A will be permitted at the refinery, or at delivery from railway tank cars.

(5) Aromatic content limited by heating value requirement.

* This summary is for general information only. Latest detailed specifications should be obtained from AMCHQ when quality control is involved.

TABLE 5

SUMMARY OF RCAF AVIATION TURBINE FUEL SPECIFICATIONS *

Specification Nominal Grade	3-GP-23A Type 1	3-GP-22 (Cancelled)	3-GP-22A Type 2
Flash point, min. °F	103.0	-	-
Reid vapour press. psi min.	-	5.0	2.0
Reid vapour press. psi max.	-	7.0	3.0
Initial boiling point min. °F	-	-	-
10% evaporated point, max. °F	-	-	250.0
90% evaporated point, min. °F	-	400.0	-
End point, max. °F	572.0	600.0	550.0
Colour	White	White	-
Saybolt colour, max.	+12.0	-	-
Freezing point, max. °F	-55.0	-76.0	-76.0
Sulphur per cent by wt. max.	0.20	0.50	0.40
Mercaptans, per cent by wt. max.	-	0.005	0.005
Inhibitors permitted (1)	No	Yes	Yes
Residue mg/100 ml. max. (Air Jet Evap'n)	6.0	10.0	10.0
Accelerated gum (7.0 hrs) mg/100 ml. max.	-	-	-
Accelerated gum (16.0 hrs) mg/100 ml. max.	8.0	20.0	20.0
Corrosion, copper strip	None	None	None
Water tolerance permitted mls	None	1	1
Specific gravity (60/60) max. (3) °API		63	58
Specific gravity (60/60) min. (2) °API	-	45	40
Viscosity at -40°F, centistokes max.	15.0	-	-
Viscosity at 100°F, centistokes min.	-	-	-
Aromatics % by vol. max.	22.0	25.0	25.0
Bromine No. max.	3.0	30.0	30.0
Heating value (lower or net) Btu/lb. min.	18,300	18,400	18,400

(1) Inhibitors may be added to the extent required (max. 1.25 lb. approved inhibitor for each 5000 Imperial gallons of finished fuel) to prevent formation of excessive gum during the oxygen bomb test. Several inhibitors are approved for use.

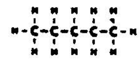
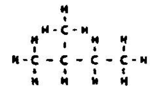
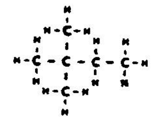
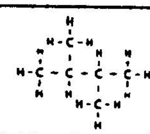
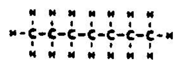
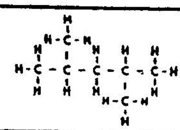
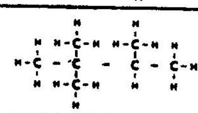
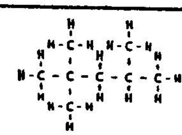
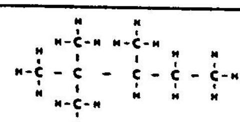
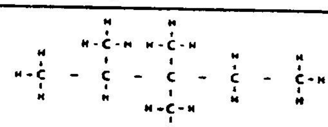
(2) $\frac{\text{Density of fuel at } 60°F}{\text{Density of water at } 60°F}$

* This summary is for general information only. Latest detailed specifications should be obtained from AMCHQ when quality control is involved.

TABLE 6

PROPERTIES OF FUEL COMPONENTS

TABLE 6

TYPE OF COMPOUND	NO	COMPLETE NAME	STRUCTURE	PERCENT HYDROGEN	PERCENT CARBON
PARAFFIN	1	NORMAL PENTANE		16.8	83.2
PARAFFIN	2	ISOPENTANE OR 2-METHYLBUTANE		16.8	83.2
PARAFFIN	3	NEOHEXANE OR 2,2-DIMETHYLBUTANE		16.4	83.6
PARAFFIN	4	2,3-DIMETHYLBUTANE		16.4	83.6
PARAFFIN	5	NORMAL HEPTANE		16.1	83.9
PARAFFIN	6	2,4-DIMETHYLPENTANE		16.1	83.9
PARAFFIN	7	TRIPTANE OR 2,2,3-TRIMETHYLBUTANE		16.1	83.9
PARAFFIN	8	ISOOCTANE (OCTANE) OR 2,2,4-TRIMETHYL-PENTANE		15.9	84.1
PARAFFIN	9	2,2,3-TRIMETHYL-PENTANE		15.9	84.1
PARAFFIN	10	2,3,3-TRIMETHYL-PENTANE		15.9	84.1

1. Lower heating value which does not allow for heat due to condensation of steam formed during combustion. 2545 Btu equals one horsepower hour.
2. Approximate values.
3. Current rich mixture knock test methods do not assign Performance Numbers to alcohols due to their low heats of combustion. However, alcohols, if tested at very high specific fuel consumptions, have very high Performance Numbers. When blended with water the three alcohols listed all have very high Performance Numbers and very high resistance to preignition.

BOILING (7) POINT °F.	REID VAPOUR PRESSURE LB./SQ. IN.	LATENT HEAT OF EVAPORATION BTU PER LB.	FREEZING POINT °F.	HEATING VALUE BTU PER LB. (1)	BTU PER U.S. GAL. AT 68° F.	SPECIFIC GRAVITY AT 68° F.	WEIGHT PER U.S. GAL. LB. AT 68° F	KNOCK VALUE PERFORMANCE NUMBERS (2)			
								NO LEAD		LEAD 4 ML.	
								LEAN	RICH	LEAN	RICH
97	16	154	−201	19,300	101,000	0.627	5.23	41	41	63	63
82	22	146	−256	19,300	100,000	0.621	5.17	76	—	120	130
122	10	131	−148	19,200	104,000	0.650	5.42	78	—	130	130
136	8	136	−199	19,200	106,000	0.663	5.52	85	—	140	>160
209	1.7	136	−131	19,200	110,000	0.685	5.71	ZERO O.N.	ZERO O.N. (5)	50 O.N. (5)	50 O.N. (5)
177	3.5	127	−183	19,100	107,000	0.674	5.61	62	62	95	95
178	3.5	124	− 13	19,100	110,000	0.691	5.76	140	200	200	300
211	1.8	117	−161	19,100	110,000	0.693	5.77	100	100	153	153
230	1.2	121	−170	19,100	114,000	0.717	5.98	100	120	150	>160 (6)
239	0.9	123	−149	19,100	116,000	0.727	6.06	100	120	150	>160

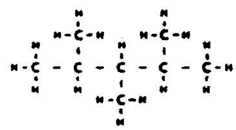
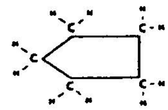
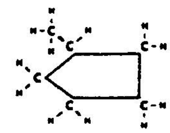
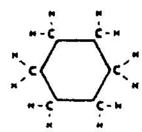
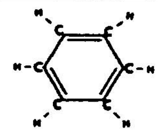
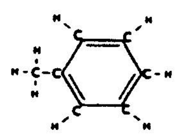
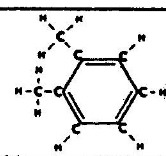
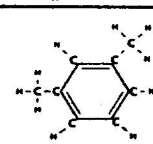
Average maximum values. Straight-run gasoline used in Grade 73 may have a Performance Number of only 40 before the addition of lead (one ml.).

All values in Performance Numbers except normal heptane. Zero octane number corresponds to a Performance Number of about 22.

> 160 means above 160. < 75 means below 75.

At atmospheric pressure.

TABLE 6 (CONTINUED)

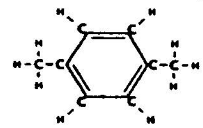
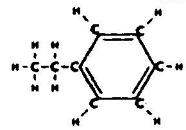
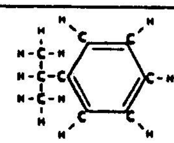
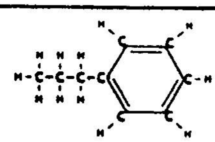
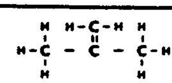
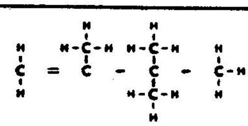
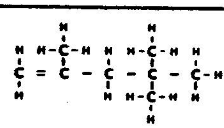
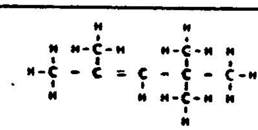
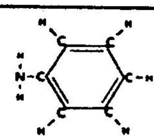
TYPE OF COMPOUND	NO.	COMPLETE NAME	STRUCTURE	PERCENT HYDROGEN	PERCENT CARBON
PARAFFIN	11	2,3,4-TRIMETHYL-PENTANE		15.9	84.1
CYCLIC PARAFFIN	12	CYCLOPENTANE		14.4	85.6
CYCLIC PARAFFIN	13	METHYLCYCLOPENTANE		14.4	85.6
CYCLIC PARAFFIN	14	CYCLOHEXANE		14.4	85.6
AROMATIC	15	BENZENE OR BENZOL		7.7	92.3
AROMATIC	16	TOLUENE OR TOLUOL		8.8	91.2
AROMATIC	17	ORTHO-XYLENE OR 1,2-DIMETHYLBENZENE		9.5	90.5
AROMATIC	18	META-XYLENE OR 1,3-DIMETHYLBENZENE		9.5	90.5

1. Lower heating value which does not allow for heat due to condensation of steam formed during combustion. 2545 Btu equals one horsepower hour.
2. Approximate values.
3. Current rich mixture knock test methods do not assign Performance Numbers to alcohols due to their low heats of combustion. However, alcohols, if tested at very high specific fuel consumptions, have very high Performance Numbers. When blended with water the three alcohols listed all have very high Performance Numbers and very high resistance to preignition.

BOILING (7) POINT ° F.	REID VAPOUR PRESSURE LB./SQ. IN.	LATENT HEAT OF EVAPORATION BTU PER LB.	FREEZING POINT ° F.	HEATING VALUE BTU PER LB. (1)	BTU PER U. S. GAL. AT 68° F.	SPECIFIC GRAVITY AT 68° F.	WEIGHT PER U. S. GAL. LB. AT 68° F.	KNOCK VALUE PERFORMANCE NUMBERS (2)			
								NO LEAD		LEAD 4 ML.	
								LEAN	RICH	LEAN	RICH
236	1.0	123	−165	19,100	115,000	0.720	6.00	100	120	150	>160
121	10.5	167	−137	18,800	117,000	0.746	6.22	65	>100	100	>160
161	4.8	148	−224	18,800	118,000	0.750	6.25	58	—	88	140
177	3.3	154	+ 44	18,700	122,000	0.780	6.50	55	—	84	130
176	3.2	169	+ 42	17,300	127,000	0.881	7.34	68	>160	68	>160
231	1.2	156	−139	17,400	126,000	0.869	7.23	93	>160	95	>160
292	0.3	149	− 13	17,500	129,000	0.882	7.35	85	85	100	100
282	0.35	147	− 54	17,500	126,000	0.866	7.21	100	>160	>100	>160

4. Average maximum values. Straight-run gasoline used in Grade 73 may have a Performance Number of only 40 before the addition of lead (one ml.).
5. All values in Performance Numbers except normal heptane. Zero octane number corresponds to a Performance Number of about 22.
6. > 160 means above 160. < 75 means below 75.
7. At atmospheric pressure.

TABLE 6 (CONTINUED)

TYPE OF COMPOUND	NO.	COMPLETE NAME	STRUCTURE	PERCENT HYDROGEN	PERCENT CARBON
AROMATIC	19	PARA-XYLENE OR 1,4-DIMETHYLBENZENE		9.5	90.5
AROMATIC	20	ETHYLBENZENE		9.5	90.5
AROMATIC	21	CUMENE OR ISOPROPYLBENZENE		10.1	89.9
AROMATIC	22	NORMAL PROPYL BENZENE		10.1	89.9
OLEFIN	23	ISO-BUTYLENE OR 2-METHYLPROPENE		14.4	85.6
OLEFIN	24	2,3,3-TRIMETHYL-1-BUTENE (TRIPTENE)		14.4	85.6
OLEFIN	25	DIISOBUTYLENE OR 2,4,4-TRIMETHYL -1-PENTENE		14.4	85.6
OLEFIN	26	DIISOBUTYLENE OR 2,4,4-TRIMETHYL -2-PENTENE		14.4	85.6
AROMATIC AMINE AND ANTIKNOCK	27	ANILINE		7.6	77.4

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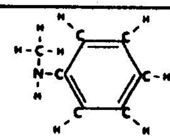
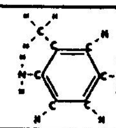
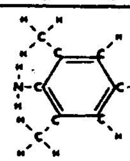
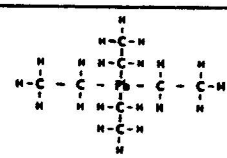
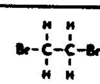
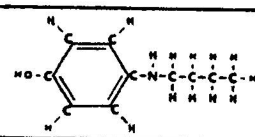
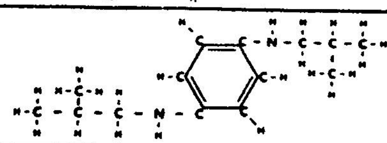
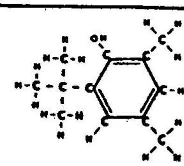
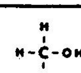
2. Approximate values.
3. Current rich mixture knock test methods do not assign Performance Numbers to alcohols due to their low heats of combustion. However, alcohols, if tested at very high specific fuel consumptions, have very high Performance Numbers. When blended with water the three alcohols listed all have very high Performance Numbers and very high resistance to preignition.

BOILING (7) POINT °F.	REID VAPOUR PRESSURE LB./SQ. IN.	LATENT HEAT OF EVAPORATION BTU PER LB.	FREEZING POINT °F.	HEATING VALUE BTU PER LB. (1)	BTU PER U. S. GAL. AT 68° F.	SPECIFIC GRAVITY AT 68° F.	WEIGHT PER U. S. GAL. LB. AT 68° F.	KNOCK VALUE PERFORMANCE NUMBERS (2)			
								NO LEAD		LEAD 4 ML.	
								LEAN	RICH	LEAN	RICH
281	0.35	146	+ 56	17,500	126,000	0.863	7.19	100	> 160	> 100	> 160
277	0.4	146	−139	17,600	127,000	0.869	7.24	93	> 160	100	> 160
306	0.2	134	−141	17,700	127,000	0.864	7.19	78	> 160	93	> 160
319	0.15	137	−147	17,700	127,000	0.864	7.19	78	> 160	93	> 160
20	65	169	−221	19,400	96,000	0.595	4.96	—	—	—	—
172	3.6	124	−169	19,100	112,000	0.706	5.88	75	—	84	—
215	1.6	—	−136	19,000	113,000	0.716	5.97	64	—	85	> 160
221	1.4	—	−160	19,000	114,000	0.722	6.02	64	—	85	> 160
364	0.04	187	+ 21	15,000	128,000	1.024	8.53	—	—	—	—

4. Average maximum values. Straight-run gasoline used in Grade 73 may have a Performance Number of only 40 before the addition of lead (one ml.).
5. All values in Performance Numbers except normal heptane. Zero octane number corresponds to a Performance Number of about 22.
6. > 160 means above 160. < 75 means below 75.
7. At atmospheric pressure.

TABLE 6 (CONTINUED)

TYPE OF COMPOUND	NO.	COMPLETE NAME	STRUCTURE	PERCENT HYDROGEN	PERCENT CARBON
AROMATIC AMINE AND ANTIKNOCK	28	MONOMETHYL ANILINE OR N-METHYLANILINE		8.5	78.5
AROMATIC AMINE AND ANTIKNOCK	29	2,4-XYLIDINE		9.2	79.3
AROMATIC AMINE AND ANTIKNOCK	30	2,6-XYLIDINE		9.2	79.3
ANTIKNOCK	31	TETRAETHYLLEAD		6.2	29.7
ORGANIC HALIDE	32	ETHYLENE DIBROMIDE (1,2-DIBROMOETHANE)		2.1	12.8
INHIBITOR	33	NORMAL-BUTYL-PARA-AMINO-PHENOL		—	—
INHIBITOR	34	DI-SECONDARY-BUTYL-PARA-PHENYLENE DIAMINE		—	—
INHIBITOR	35	DI-METHYL-TERTIARY-BUTYL PHENOL		—	—
ALCOHOL	36	METHANOL (WOOD ALCOHOL)		12.6	37.5

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2. Approximate values.
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BOILING (7) POINT °F	REID VAPOUR PRESSURE LB/SQ. IN.	LATENT HEAT OF EVAPORATION BTU PER LB	FREEZING POINT °F.	HEATING VALUE BTU PER LB. (1)	BTU PER U.S. GAL. AT 68° F.	SPECIFIC GRAVITY AT 68° F.	WEIGHT PER U.S. GAL. LB. AT 68° F	KNOCK VALUE PERFORMANCE NUMBERS (2)			
								NO LEAD		LEAD 4 ML.	
								LEAN	RICH	LEAN	RICH
384	0.02	172	− 71	15,600	128,000	0.988	8.23	—	—	—	—
420	0.005	150	—	15,600	127,000	0.976	8.13	—	—	—	—
422	0.005	150	—	15,600	127,000	0.981	8.17	—	—	—	—
388 DE-COMP	0.02	60 (2)	−202	7,800	108,000	1.656	13.8	—	—	—	—
269	0.5	83	+ 50	—	—	2.185	18.2	—	—	—	—
500 (2)	—	—	+157	—	—	—	—	—	—	—	—
500 (2)	—	—	+144 (2)	—	—	—	—	—	—	—	—
480 (2)	—	—	+ 72	—	—	—	—	—	—	—	—
148	4.5	473	−144	8,600	57,000	0.794	6.62	75	(3)	< 75	(3)

4. Average maximum values. Straight-run gasoline used in Grade 73 may have a Performance Number of only 40 before the addition of lead (one ml.).
5. All values in Performance Numbers except normal heptane. Zero octane number corresponds to a Performance Number of about 22.
6. > 160 means above 160. < 75 means below 75.
7. At atmospheric pressure.

TABLE 6 (CONTINUED)

TYPE OF COMPOUND	NO	COMPLETE NAME	STRUCTURE	PERCENT HYDROGEN	PERCENT CARBON
ALCOHOL	37	ETHANOL (GRAIN ALCOHOL)	H H H-C-C-OH H H	13.1	52.1
ALCOHOL	38	ISOPROPANOL (ISOPROPYL ALCOHOL)	H OH H H-C-C-C-H H H H	13.4	60.0
WATER	39	WATER	H-O-H	11.2	—
AMMONIA	40	AMMONIA (GAS)	H H-N-H	17.8	—
HYDROCARBON PARAFFIN + CYCLIC PARAFFIN PLUS AROMATIC	41	STRAIGHT RUN GASOLINE (AVIATION)		15.5	84.5
HYDROCARBON PARAFFIN + CYCLIC PARAFFIN PLUS AROMATIC	42	CATALYTICALLY CRACKED GASOLINE (AVIATION)		15	85
HYDROCARBON PARAFFIN ALMOST ENTIRELY	43	ALKYLATE (MOSTLY OCTANES)		15.8	84.2
CARBON	44	CARBON (SOLID)	C	—	100
HYDROGEN	45	HYDROGEN (GAS)	H-H	100	—

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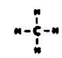
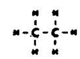
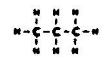
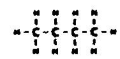
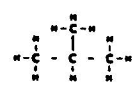
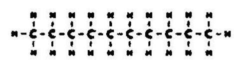
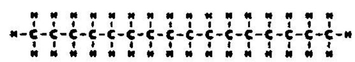
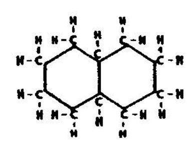
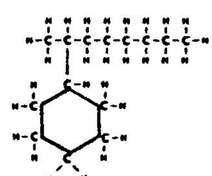
BOILING (7) POINT °F.	REID VAPOUR PRESSURE LB./SQ. IN.	LATENT HEAT OF EVAPORATION BTU PER LB.	FREEZING POINT °F.	HEATING VALUE BTU PER LB. (1)	BTU PER U.S. GAL. AT 68° F.	SPECIFIC GRAVITY AT 68° F.	WEIGHT PER U.S. GAL. LB. AT 68° F	KNOCK VALUE PERFORMANCE NUMBERS (2)			
								NO LEAD		LEAD 4 ML.	
								LEAN	RICH	LEAN	RICH
173	2.3	370	−174	11,500	76,000	0.790	6.58	75	(3)	<75	(3)
180	1.8	290	−129	13,100	86,000	0.786	6.55	75	(3)	<75	(3)
212	0.95	970	+ 32	0	0	1.000	8.33	—	—	—	—
−28	—	—	−108	—	—	GAS	GAS	—	—	—	—
110 — 300	2 TO 7	140 (2)	<−76	19,000	115,000	0.68-0.74	6	54 (4)	61 (4)	78 (4)	93 (4)
110 — 300	2 TO 7	140 (2)	<−76	19,000	115,000	0.70-0.74	6	61 (4)	85 (4)	93 (4)	130 (4)
200 — 300	ABOUT 1.5	125 (2)	<−76	19,000	115,000	—	—	76 (4)	92 (4)	120 (4)	140 (4)
—	—	—	—	14,100	—	—	—	—	—	—	—
—	—	—	—	52,000	—	GAS	GAS	—	—	—	—

4. Average maximum values. Straight-run gasoline used in Grade 73 may have a Performance Number of only 40 before the addition of lead (one ml.).
5. All values in Performance Numbers except normal heptane. Zero octane number corresponds to a Performance Number of about 22.
6. > 160 means above 160. < 75 means below 75.
7. At atmospheric pressure.

TABLE 6 (CONTINUED)

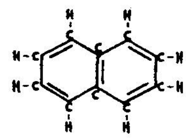
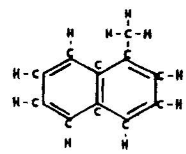
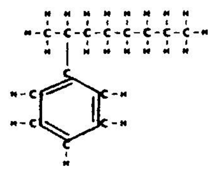
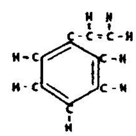
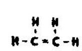
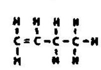
TYPE OF COMPOUND	NO.	COMPLETE NAME	STRUCTURE	PERCENT HYDROGEN	PERCENT CARBON
PARAFFIN	46	METHANE		25.1	74.9
PARAFFIN	47	ETHANE		20.0	80.0
PARAFFIN	48	PROPANE		18.3	81.7
PARAFFIN	49	NORMAL BUTANE		17.3	82.7
PARAFFIN	50	ISOBUTANE		17.3	82.7
PARAFFIN	51	NORMAL DECANE		15.6	84.4
PARAFFIN	52	CETANE		15.1	84.9
CYCLIC PARAFFIN OR NAPHTHENE	53	DECALIN[9]		13.1	86.9
CYCLIC PARAFFIN OR NAPHTHENE	54	2-CYCLOHEXYL -OCTANE		14.4	85.6

1. Lower heating value which does not allow for heat due to condensation of steam formed during combustion. 2545 Btu equals one horsepower hour.
2. Approximate values.
7. At atmospheric pressure.

H/C RATIO	BOILING (7) POINT °F.	REID VAPOUR PRESSURE LB./SQ. IN.	LATENT HEAT OF EVAPORATION BTU PER LB.	FREEZING POINT °F.	HEATING VALUE BTU PER LB. (1)	BTU PER U. S. GAL. AT 68° F.	SPECIFIC GRAVITY AT 68° F.	WEIGHT PER U.S. GAL. LB. AT 68° F.	REMARKS
.336	−259	—	219	−296	21,500	—	GAS	GAS	Most important constituent of natural gas.
.252	−128	—	210	−298	20,400	—	GAS	GAS	Second most important constituent of natural gas.
.224	−44	—	183	−306	19,800	—	GAS	GAS	Extracted mainly from natural gas. Used for domestic purposes as bottled gas.
.210	31	—	165	−217	19,500	94,000	0.580(8)	4.83(8)	Found in natural gas. Used for domestic purposes.
.210	11	—	158	−255	19,500	91,000	0.558(8)	4.65(8)	Found in natural gas. Used to make alkylate.
.185	345	0.06	119	−21	19,000	116,000	0.731	6.09	Straight chain. Found in kerosene.
.178	547	<0.001	98	+65	18,900	122,000	0.774	6.45	Straight chain. May be found in kerosene. Used in cetane number scale for rating Diesel fuels.
.151	374	0.04 (2)	135	−40	20,000	140,000	0.88	7.4	Example of high boiling naphthene.
.168	504 (2)	<0.001	135 (2)	<−70	—	—	0.825	6.88	Example of high boiling naphthene.

8. Under sufficient pressure to maintain the liquid state at 68°F.
9. Properties shown are a mixture of the two forms *cis* and *trans*, which are present at moderate temperatures.

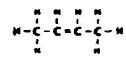
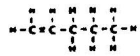
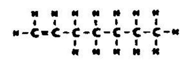
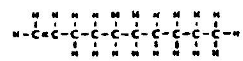
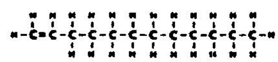
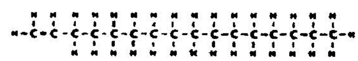
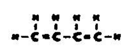
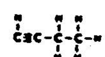
TABLE 6 (CONTINUED)

TYPE OF COMPOUND	NO.	COMPLETE NAME	STRUCTURE	PERCENT HYDROGEN	PERCENT CARBON
AROMATIC	55	NAPHTHALENE (MOTH BALLS)		6.3	93.7
AROMATIC	56	ALPHA-METHYL -NAPHTHALENE		7.1	92.9
AROMATIC	57	2-PHENYL-OCTANE		11.6	88.4
AROMATIC OLEFIN	58	STYRENE		7.7	92.3
OLEFIN	59	ETHYLENE		14.4	85.6
OLEFIN	60	BUTYLENE-1 1-BUTENE		14.4	85.6

1. Lower heating value which does not allow for heat due to condensation of steam formed during combustion. 2545 Btu equals one horsepower ho
2. Approximate values.
7. At atmospheric pressure.

H/C RATIO	BOILING (7) POINT ° F.	REID VAPOUR PRESSURE LB./SQ. IN.	LATENT HEAT OF EVAPORATION BTU PER LB.	FREEZING POINT ° F.	HEATING VALUE BTU PER LB. (1)	BTU PER U. S. GAL. AT 68° F.	SPECIFIC GRAVITY AT 68° F.	WEIGHT PER U. S. GAL. LB. AT 68° F.	REMARKS
.067	424	SOLID	—	+176	16,700	—	SOLID	SOLID	Not found in petroleum fuels. Most important use is in manufacture of plastics.
.076	473	0.003	140	−23	16,700 (2)	140,000 (2)	1.022	8.51	Can occur in fuels. Used in cetane number scale used for rating Diesel fuels. Example of high boiling aromatic with low H/C ratio.
.131	464	0.001	139	−38	18,200	130,000	0.859	7.15	Example of high boiling aromatic with high H/C ratio.
.084	293	0.3	152	−23	17,400	132,000	0.908	7.56	Can occur in fuel in small quantities. Used for synthetic rubber and in plastics.
.168	−155	—	208	−272	20,300	—	GAS	GAS	Gas—used in manufacture of ethyl alcohol and other chemical uses.
.168	+21	62	168	−302	19,500	97,000	0.596	4.97	Gas—used in manufacture of alkylate. Used in motor gasoline.

TABLE 6 (CONTINUED)

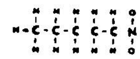
TYPE OF COMPOUND	NO.	COMPLETE NAME	STRUCTURE	PERCENT HYDROGEN	PERCENT CARBON
OLEFIN	61	BUTYLENE-2 CIS-2-BUTENE[10]		14.4	85.6
OLEFIN	62	1-PENTENE		14.4	85.6
OLEFIN	63	1-HEPTENE		14.4	85.6
OLEFIN	64	1-DECENE		14.4	85.6
OLEFIN	65	1-DODECENE		14.4	85.6
OLEFIN	66	CETENE OR 1-HEXADECENE		14.4	85.6
DIOLEFIN	67	1,3-BUTADIENE		11.2	88.8
ACETYLENE	68	ACETYLENE	H−C≡C−H	7.7	92.3
ACETYLENE	69	1-BUTYNE		11.2	88.8

1. Lower heating value which does not allow for heat due to condensation of steam formed during combustion. 2545 Btu equals one horsepower hour.
2. Approximate values.
7. At atmospheric pressure.

H/C RATIO	BOILING (7) POINT °F	REID VAPOUR PRESSURE LB/SQ. IN	LATENT HEAT OF EVAPORATION BTU PER LB.	FREEZING POINT ° F.	HEATING VALUE BTU PER LB. (1)	BTU PER U. S. GAL AT 68° F.	SPECIFIC GRAVITY AT 68° F.	WEIGHT PER U. S. GAL. LB. AT 68° F.	REMARKS
.168	+39	46	179	−218	19,400	101,000	0.622	5.19	Gas—used in manufacture of alkylate. Used in motor gasoline.
.168	+86	19	154	−265	19,300	104,000	0.642	5.35	Found in motor gasoline.
.168	201	2.0	148	−182	19,200	112,000	0.698	5.82	Found in motor gasoline.
.168	339	0.09	131	−98	19,100	118,000	0.742	6.18	Straight chain. Can occur in cracked motor gasoline or cracked kerosene.
.168	416	0.015	123	−32	19,100	121,000	0.759	6.33	Straight chain. Can occur in cracked kerosene.
.168	545	<0.001	112	+39	19,000	124,000	0.783	6.52	Straight chain. Can occur in cracked kerosene.
.126	24	59	178	−164	19,000	98,000	0.622	5.18	Used with styrene in a widely used type of synthetic rubber.
.084	−119[11]	—	—	−114	20,700	—	GAS	GAS	Produced from calcium carbide. Used for welding and cutting.
.126	+48	38	186	−194	19,600	106,000	0.65	5.4	—

10. The properties of trans-2-butene are similar except that the freezing point is 60° higher.
11. The temperature at (or above) which the solid vaporizes directly at atmospheric pressure without becoming a liquid. For example dry ice (solid carbon dioxide) vaporizes directly at (or above)—109°F. at atmospheric pressure.

TABLE 6 (CONTINUED)

TYPE OF COMPOUND	NO	COMPLETE NAME	STRUCTURE	PERCENT HYDROGEN	PERCENT CARBON
ORGANIC NITRATE	70	**AMYL NITRATE**		9.5	51.3
ORGANIC SULFUR COMPOUND	71	**BUTYL MERCAPTAN**		11.2	53.3
	72	**SULFUR**	S	—	—
	73	**HYDROGEN SULFIDE**	H–S–H	5.9	—

1. Lower heating value which does not allow for heat due to condensation of steam formed during combustion. 2545 Btu equals one horsepower hour.
2. Approximate values.
7. At atmospheric pressure.

H/C RATIO	BOILING (7) POINT F.	REID VAPOUR PRESSURE LB./SQ. IN.	LATENT HEAT OF EVAPORATION BTU PER LB.	FREEZING POINT ° F.	HEATING VALUE BTU PER LB. (1)	BTU PER U. S. GAL. AT 68° F.	SPECIFIC GRAVITY AT 68° F.	WEIGHT PER U. S. GAL. LB. AT 68° F.	REMARKS
.185	305	0.18	121	−139	—	—	0.999	8.32	Used to improve combustion in Diesel engines.
.210	208	0.9	151	−177	15,000 (2)	105,000 (2)	0.836	6.97	Oil of skunk. Similar compounds found in petroleum.
—	832	—	—	+235	3,980	—	SOLID	SOLID	
—	−77	—	—	−122	6,500	—	GAS	GAS	Found in petroleum and natural gas.