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Aviation Fuel Problems

at High Altitudes and High Aircraft Speeds

- by -

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SUMMARY

Much useful data has appeared over recent years concerning the problems incurred by continued increases in operational altitudes and aircraft speeds. This report is an attempt to correlate a representative amount of these data, and to present them in a form suitable both for general information and for project design reference. Frequent references are made to the literature as guides to additional information. Some of the work has formed the basis of research activities at Cranfield.

Note: Imperial Gallons are used throughout.

1 Imperial Gallon = 1.20094 United States Gallons

1 United States Gallon = 0.83268 Imperial Gallons.

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AT HIGH ALTITUDES AND HIGH AIRCRAFT SPEEDS

1. Introduction

Aircraft operation at high altitudes and forward speeds sets severe
problems regarding fuel quality, with resulting complications in aircraft
design, and limitations in performance. The correlation of up-to-date
information on fuel behaviour under these conditions should prove helpful
at this stage, both towards the appreciation of these problems, and as a
reference work for project design purposes

The final specification of aviation fuel properties is essentially
a compromise, in view of the many conflicting requirements. Details of
current Ministry of Supply specifications, given in table 1, indicate the
two basic types of aviation fuel, namely gasolines for piston engines, and
kerosines for gas turbines and other continuous-flow combustors. The
rapid growth of the gas turbine engine in an era geared to the quantity
production of gasoline would, in the event of an emergency, have resulted
in an acute shortage of kerosine fuel. This led to the adoption of wide-cut
gasoline, produced from gasoline and kerosine components, which is used
largely in service aircraft. A kerosine of high flash point is specified
for naval aircraft carriers, in order to meet shipboard safety requirements.
An additional specialised fuel is the low freezing kerosine. American
civil and service specifications are designated by the symbols ASTM and
JP respectively, and their equivalence (with a few minor differences) to
British fuels is indicated in table 1.

The proportion of each fuel directly obtainable from the parent
crude oil can be gauged roughly from the extent of the distillation
temperature range. It will be shown that certain of the properties
necessary for high-speed high-altitude flight impose limits upon the
distillation range of the particular fuel, and hence upon its availability.
In order to compare fuel properties, it is convenient to select some
representative property to form a basis of comparison. Specific gravity
provides such a basis, and the variations with specific gravity in a number
of relevant properties are shown in Fig. 1. It is interesting to note
that, in modern turbine-powered aircraft, fuel quality requirements are
set to a very large degree by the aircraft fuel system rather than the
engine.

2. Fuel System Capacity

The fuel load, expressed as a fraction of take-off weight, ranges
from about 5% in the light piston-engined aircraft, to about 45% in the
long-range jet transport. In all airborne vehicles, mass is a vital
factor, so that the maximum energy content is required per pound of fuel
carried. In the case of piston-engined aircraft, the engine exerts
an over-riding requirement upon fuel type, and gasoline fuels of high

antiknock quality are essential. However, reference to Fig. 1 shows that these fuels also exhibit the highest heating value/lb. for all the petroleum-based liquid fuels available. Hence, gasolines satisfy both engine and aircraft-loading requirements.

With the advent of the high-speed turbojet aircraft, the heating value/gallon has become equally significant, since aerodynamic design stipulates thin wing sections, and these restrict fuel stowage space. Fig. 1 shows that heating value/gallon increases with specific gravity, so that the volume-limited turbojet aircraft is more suited to a heavy fuel in the petroleum range. The use of gas oil has been examined by Sharp (Ref. 2) who finds that, when compared with kerosine, the capacity payload range is reduced by 2 to 7% due to anti-freeze precautions, but the extreme range (full tanks and reduced payload) may be increased by about 8%.

Refrigeration prior to fuelling has been proposed as one means of increasing the fuel load in a given volumetric capacity. This system would be expensive and inflexible, but has been used for distance record purposes (Ref. 3), where an additional 4% mass was supplied to an aircraft by pre-chilling from 80 to 20°F. (27 to -7°C.) with solid CO_2. For gasoline, this represents a rise in specific gravity from 0.70 to 0.73 approximately (Fig. 2).

Generally, both forms of expressing energy content are important for high-speed aircraft equipped with air-breathing propulsive units, and this has led to the derivation of a 'performance index' expressed as the ratio between the products of these two heating values for the fuel in question and for aviation kerosine, i.e.

$$\text{Performance index} = \frac{\text{CHU/lb. x CHU/gallon}}{K},$$

where K for aviation kerosine is 840×10^6 approximately, in consistent units. Fig. 3 shows performance index values of typical petroleum-based fuels, together with some 'chemical' fuels of current interest.

3. Low Temperature Problems

Statistical data are now available regarding the frequency of occurrence of low atmospheric temperatures, and Fig. 4 indicates the minimum ambient temperatures recorded during winter months within the greater part of the northern hemisphere. The ICAN temperature curve is included for comparison. Information has also recently been made available on the rate at which fuel cools after take-off. For a given rate of climb, this depends upon the thermal insulation of the fuel tanks, i.e. whether the tanks are independent units fitted inside or outside the aircraft, or formed from compartments in the airframe structure, with or without flexible lining. The effectiveness of various thermal insulating materials is given by Sharp (Ref. 2).

Fuel temperature curves, based on results obtained during Comet flight tests, are shown in Fig. 5. These indicate that the cooling rate of fuel is less than the rate of reduction in ambient temperature, and that the fuel temperature stabilises at a level approximately 25 C^o above ambient when the flight speed is about 465 m.p.h. This is slightly greater than that expected from kinetic heating,[M] and is due to incidental effects such as the proximity of engines and warm air ducts.

In general, the minimum fuel temperature likely to be met in civil aviation is considered to be -55°C, e.g. -80°C ambient plus 25 C^o of kinetic heating at 500 m.p.h., although the worst case is represented by the moderate-speed high-altitude aircraft such as the Britannia, in which fuel temperatures as low as -58°C have been recorded (Ref. 5). Reduction in fuel temperature leads progressively to the formation of ice and wax, and lower operating altitudes must be accepted on the rare occasions when the minimum temperatures obtain.

3.1. Ice Formation

Water is invariably present in fuels due to contact with the atmosphere during storage and during inward venting on descent. Some water dissolves in the fuel, and Fig. 6 shows the variation with temperature of water solubility. Any additional free water exists as a suspension, ultimately settling in the tank bottom, and promoting corrosion. Cooling causes a precipitation of excess dissolved water; a reduction from 15 to -10°C, for example, releases about $\frac{1}{2}$ pint of water from 1000 gallons of fuel. Slow cooling normally permits the precipitated water droplets to reach the surface and escape to atmosphere. In rapid chilling, on the other hand, the precipitated water agglomerates and adds to the free water content.

Cooling below 0°C causes the free water to freeze into ice crystals. Supercooling may occur down to -60°C, but impact or contamination then causes instant freezing of water and some hydrocarbon hydrates. Slow cooling results in larger crystals with a greater tendency to settlement. Rapidly cooled water droplets and crystals of less than 5μ size, however, have a very slow settling rate, and are carried forward to the flowmeter and low-pressure filters. A loose network of ice particles builds up on the filter surfaces, resulting in an increased pressure differential and, eventually, complete blockage. Bypassing the blocked filter is not recommended, since the small guard filter fitted to the engine fuel pump can become ice-blocked despite the presence of engine heat.

[M] Kinetic temperature rise $= \left(\dfrac{\text{Air speed in m.p.h.}}{100}\right)^2 C^o$ approximately

3.2. Prevention of Filter Icing

The standard test for water tolerance (maximum volume of water which can be dissolved by a dried sample of fuel) serves as a measure of the concentration of water-soluble constituents, such as alcohol, and ensures the suitability of fuel supplies. Fuelling techniques are controlled rigidly as a precaution against the delivery of free water. These controls include the use of efficient water separators in the distribution system, and the periodic checking of water settlement in the ground storage tanks, together with draining as necessary after adequate settling time.

Free water concentrations down to about 0.02% w. are **detectable** visually (see Ref. 8), but recently a simple water detecting method has been introduced for field use, capable of indicating the presence of free water at concentrations as low as 0.003% w. (Ref. 9). This figure was selected on the basis that current airborne fuel heaters can accept no more than a total water concentration of about 0.02% w., and that about 0.014% w. can be expected to exist in solution under initial fuelling conditions. This leaves a maximum permissible free-water concentration of 0.006% w., which is now detectable by the new Shell method of taking a sample through chemically treated paper fitted on the end of a plastic syringe.

Since the possibility exists of unsafe water concentrations, preventative measures must be taken to avoid filter blockage by ice. In arctic operation, the fuel can be allowed to cool below $0^{\circ}C$ in the storage tanks, and the ice crystals removed by means of large efficient filters during aircraft refuelling. Refrigeration prior to fuelling is not recommended, as outlined in paragraph 2.

3.2.1. Anti-Freeze Agents

One method of ice protection is the use of anti-freeze materials to retain the liquid phase at low temperatures. Solid anti-freeze agents could be contained in a replaceable canister within the fuel system, whereas liquid agents could be either injected into the fuel stream at a given filter pressure differential, or added initially to the bulk fuel. Shell (Refs. 10 and 11) found such solids as chromium trioxide, zinc chloride, calcium chloride, and calcium nitrate to have successful anti-freeze action but to attack metals and/or rubbers. The light alcohols (methanol, ethanol, and isopropanol) act as anti-freeze liquids, and filters can be de-iced within a few seconds after injection. The bulk addition of 0.4% v. of methanol to kerosine with a given free-water concentration has been found to prevent ice formation at temperatures above $-50^{\circ}C$. Ethanol and iso-propanol are less effective.

A methanol concentration of 0.1% v. is sufficient in the complete absence of free water and, in any case, a concentration greater than about 0.15% v. would reduce the flash point of typical kerosine below the specified minimum of $100^{\circ}F$. (See Fig. 7). Also, methanol is relatively

insoluble in kerosine, so that efficient mixing is required initially.
Furthermore, the separation of aqueous methanol from the bulk fuel leads
to corrosion and deterioration of adhesive materials, and to short-
circuiting of certain types of electronic fuel contents gauges. In felt
filters, aqueous methanol tends to accumulate, and any subsequent use of
non-additive fuel dissolves away the methanol and could lead to sudden
ice blockage. British Petroleum has now produced an anti-freeze fluid
which avoids the above-mentioned difficulties, and has proved satisfactory
down to -35°C in a 0.5% v. addition to a kerosine containing 0.027% v.
total water (See ref. 8).

3.2.2. Fuel Heating

An alternative approach is to heat the fuel immediately upstream
of the filter when the pressure differential becomes excessive. This
method has proved to be reliable, the heat being provided by hot air
tapped from the last stage of the compressor of a main gas turbine engine.
Automatic heat selection can be arranged and, in practice, the fuel can
be heated through 40 C° in about 30 seconds. Extraneous heating effects
due to the proximity of wing de-icing systems have been found helpful,
but such systems are not yet capable of giving complete or continuous
protection to the fuel filter.

3.2.3. Filter Design

An additional measure of protection lies in the design of the
filter. Shel results (Ref. 12) show benefits from preliminary filtration
with a 100 mesh gauze situated upstream of the low-pressure filter, and
the suggestion is made also that the filter area necessary to cope with
the water passed during the longest anticipated flight may not be greatly
in excess of standard areas currently used. Research is also in progress
with sintered metal filters, and with hydrophobic surface treatments.

3.2.4. Air Dehydration

Shell research (Ref. 12) suggests that dissolved air collects
around water droplets and assists their passage to the surface where
they vaporise. This effect is noted when the fuel is stirred vigorously,
and the introduction of dry air to the agitated contents of a fuel tank
appears to be a possible solution of filter ice-blockage.

3.3. Fuel Freezing

On cooling, fuels continue to behave as Newtonian fluids (i.e.
viscosity independent of shear stress), and their viscosity increases
in the normal way until an additional rise occurs due to the precipitation
of wax crystals (Fig. 8). This condition is represented by the freezing
point (the temperature at which crystals diappear on warming, the sample
having been chilled with stirring), which is approximately equal to the
cloud point (the temperature at which crystals appear, the sample being

chilled without stirring). Since fuels are mixtures of many different hydrocarbons, there is no single freezing point, and the quantity of solid material increases on further cooling. This produces a slurry of fuel and wax, which remains mobile until apparent solidification eventually sets in at lower temperatures. This condition is represented by the pour point (the temperature 5 F° above that at which no movement of the surface occurs when held vertically, the sample being chilled without stirring), although pumping is still possible below the pour point if sufficient force is applied.

In the semi-solid condition, fuels exhibit the property of thixotropy; that is, mechanical agitation causes a reversion to the normal Newtonian fluid state (see photographs in Ref. 13). Continued stirring prevents the crystals from interlocking to form a wax matrix, and the normal viscosity increase only is found on further cooling.

3.4. Prevention of Wax Formation

With hydrocarbon fuels, wax formation at low temperatures is inevitable. Nevertheless, certain steps can be taken by fuel suppliers and aircraft designers to combat this difficulty. It has become clear that no current laboratory test can predict the minimum temperature of pumpability. The lowest temperature at which the contents of a fuel tank can be evacuated is found to lie between about 3 and 15 C° below the conventional freezing point, depending upon fuel type. A more representative test technique is, therefore, necessary, and Strawson (Ref. 5) gives details of the new Thornton Cold Flow Test in which the quantity of fuel remaining in a chamber is measured after flow has been permitted to take place into a lower chamber over a controlled period (e.g. 10 seconds) and at a controlled low temperature. The interconnecting orifice is large, so that the quantity of fuel escaping depends primarily upon the yield value of the wax matrix rather than the apparent viscosity. A hold-up in excess of, say, 30% can be taken as a flow failure. The different low temperature events for a typical kerosine are represented in Fig. 9.

3.4.1. Fuel Quality Control

The minimum operating fuel temperature expected has been seen to be $-55^{\circ}C$. Gasolines and wide-cut gasolines meet this condition satisfactorily with a specified freezing point of $-60^{\circ}C$, but kerosine (D.Eng.R.D.2482, Avtur) is specified down to $-40^{\circ}C$ only. This situation led in 1955 to the supply, and in 1957 to the specification, of a low freezing kerosine (D.Eng.R.D.2494, Avtur/50) with a freezing point not above $-50^{\circ}C$. (See Table 1). This requirement is met by limiting the proportions of heavy fractions, and Fig. 10 shows the effect of final boiling point on freezing point. Hence, as indicated in paragraph 1, anti-freeze requirements set a limit upon fuel availability.

3.4.2. Fuel Additives

The pour-point depressant type of additive can be very effective in the case of heavy hydrocarbons, such as lubricating oils, but little effect has been noticeable when applied to kerosine. Strawson (Ref. 5) suggests that this is due largely to the insensitivity of the pour point tests, and reports a reduction of 15 C$^{\circ}$ in the pumpability limit of a kerosine, as measured by the Thornton Cold Flow method, when 1% of an additive was incorporated. The action of promising additives was seen to vary widely between fuel types.

3.4.3. Fuel Heating

Fuel in the pipelines can be heated to prevent blockage, as discussed in paragraph 3.2.1., and Sharp (Ref. 2) has made an assessment of the effect of fuel tank heating requirements upon aircraft economics.

3.4.4. Tank Insulation

Fuel freezing within the tanks can be alleviated by means of thermal insulation (See Ref. 2). Penalties of weight and bulk make this system unattractive, but it is interesting to note that the thermal conductivity of frozen kerosine is similar to that of rubber, and that the solidified layer growing on the tank walls provides a significant insulating effect (Ref. 13). The rate of growth of the solidified layer is shown in Fig. 11. The fuel in the layer is recovered easily when the ambient temperature rises, but the condition is serious in the case of wax build up in static fuel lines.

3.4.5. Fuel Agitation

It may become possible to exploit the thixotropic nature of hydrocarbon fuels as a means of depressing the minimum operating temperature to well below the pour point. Shell (Ref. 13) found that a combination of tank rocking and booster pump recycling lowered the pumpability limit of fuels by 8 to 11 C$^{\circ}$. However, development work would probably be necessary for each individual design of fuel tank.

4. High Temperature Problems

In the case of stationary fuel tanks subjected to high ambient temperatures for prolonged periods, vaporisation may account for a significant loss of the more volatile fractions. Although the quantitative loss might not be serious, fuel quality may be affected to the extent of difficult starting under subsequent low temperature conditions.

The much higher levels of temperature incurred by kinetic heating at high aircraft speeds give rise to very severe problems of boiling (see paragraph 5.2) and stability. The curves in Fig. 12 indicate the

variation of air stagnation temperatures with flight speed. The vapour pressure curves given in Fig. 13 show the marked rise at the higher temperatures. The vapour pressure of kerosine, for example, which is almost negligible (approximately 0.15 p.s.i.) at the standard test temperature of 100°F. (37.8°C), rises to no less than 25 p.s.i. at a temperature of 200°C, corresponding to a Mach number of 2.0 at 10,000 ft altitude. The problem is intensified when fuel is used as a convenient heat sink for purposes of cooling engine oil and aircraft equipment at supersonic aircraft speeds, the surrounding air being too hot to act as a coolant.

In recent years, the elevated temperatures at supersonic speeds have proved to be sufficient to cause oxidation and degradation of the fuel resulting in the formation of an insoluble sediment which tends to restriction and blockage of the fuel flow (see photographs in Ref. 17).

At higher levels of temperature ($> 250^\circ$C), sufficient thermal energy may be present for the fuel oxidation reactions to lead to spontaneous ignition. The standard ASTM laboratory test consists of assessing the minimum temperature at which fuel droplets will ignite spontaneously when introduced into a heated flask of air at atmospheric pressure. The more complex molecules are more easily ruptured when exposed to thermal activity, and Fig. 14 shows the general reduction in ignition level with increase in specific gravity. Ignition temperatures vary inversely with pressure. In the event of spontaneous ignition temperature becoming a limiting specification requirement, fuels of low specific gravity will be required, and the use of inhibiting additives may be necessary together with a limit imposed upon tank pressurisation.

Purging the oxygen from the tank free space would prevent spontaneous ignition, but fuel molecules are liable to crack into light molecules and carbon if the temperature rises much above the normal distillation limit of 370°C.

4.1. Fuel Quality Control

Fuel degradation is a recent problem, and no existing test technique has been found suitable for the prediction of thermal stability in aircraft fuel systems. In parallel with tests conducted on a full-scale mock-up fuel system, Esso (Ref. 17) are developing a flow test apparatus incorporating a fuel heater and a heated filter. This is known as the ERDCO rig, and thermal stability is assessed on the time required to reach a certain pressure differential across the filter. A similar test technique, known as the CFR Fuel Coker test, is quoted in some American fuel specifications.

The development of assessment techniques of this kind has made possible the determination of the most suitable types of fuel, and the most satisfactory processes of refining. Segregation of thermally stable fuel stocks thus becomes a possibility, although this causes

additional complications and expense. American specifications now include a thermally-stable wide-cut fuel (JP 6) for gas-turbine operation at Mach 2.0, and a thermally-stable heavy kerosine of 0.9 specific gravity (RJ 1) suited to a high-speed ramjet aircraft.

The influence of additives upon thermal stability is being investigated, but experience with conventional oxidation inhibitors has shown an <u>increased</u> tendency to deposit formation. In the case of one experimental additive (Ref. 17), no chemical difference was found between deposits, but the physical nature was changed from small gummy particles to larger crystalline structures which had less tendency to filter blockage.

4.2. Aircraft Design Factors

The remarks applied to the insulation of aircraft fuel tanks for the prevention of heat loss and fuel freezing apply equally here, the object in this case being the prevention of heat gain (see Ref. 16). Fuel cooling in flight is difficult, in view of the statements made earlier. The provision of refrigerating equipment within the aircraft is not impracticable, but the cooling services could not be expected to extend much beyond the needs of the crew and certain items of vital electronic equipment. Esso results (Ref. 17) suggest that degradation is inhibited by controlling the contact between fuel and oxygen. This entails the removal of dissolved air, and the provision of inert gas blanketing in the fuel tanks.

5. Low Pressure Problems

Ambient pressure falls at altitude, as indicated by the ICAN curve in Fig. 15. In a freely vented tank, these pressures are exerted on the surface of the liquid fuel, and reduction in pressure leads progressively to the release of dissolved air and to fuel boiling.

5.1. Air Release

Hydrocarbon fuels contain a small quantity of dissolved atmospheric gases, which are released slowly on climbing to low-pressure altitudes (e.g. 1 ft.^{3}/minute released from 100 gallons of gasoline at a climb rate of 10,000 ft./minute). Since the solubility of oxygen is greater than that of nitrogen, the released 'air' is oxygen-rich (see paragraph 6.1). The volume of air involved is not great (Fig. 16), and can normally be handled without difficulty. However, supersaturation can occur, with consequent foaming when agitated. The released air is saturated with fuel vapour, but the loss of vapour caused by air release is not serious.

5.2. Fuel Boiling

Fuel commences to boil when the vapour pressure exerted by the fuel reaches the level of the imposed pressure. Since fuels are mixtures of many different hydrocarbons, there is no single boiling point, and the vapour pressure is the mean of those exerted by the individual components.

As the imposed pressure falls, progressive boiling occurs until the vapour pressure of the least volatile component is reached. Fuel boiling is responsible for serious loss of fuel through tank vents, and for vapour lock in the pipelines.

If the imposed pressure is held constant, boiling ceases when the mean vapour pressure of the remaining components falls below this level. The fuel is then said to have 'weathered'. Since vaporisation involves the absorption of latent heat, the boiling process results in a cooling effect upon the remaining components, which reduces their mean vapour pressure and so eases the situation. Values of latent heat and thermal capacity do not differ greatly between hydrocarbon fuels, and a temperature drop of $1.7 \, C^\circ/\%$ weight loss is found to be reasonably common (Ref. 19).

5.2.1. Boiling Altitudes

The vapour pressures of the components, and hence of the fuel, are a function of temperature, so that the boiling altitude is determined by the temperature of the fuel, as shown in Fig. 17. The altitude variation of vapour pressure for aviation gasoline is included in Fig. 15. The rapid climb case is represented by the constant fuel temperature line of $15 \, ^\circ C$, and compared with the slow climb case where the fuel temperature follows the ICAN values. In practice, conditions would probably lie somewhere between these two curves, biassed towards the constant temperature line due to the low rate of cooling. Boiling commences at the intersection point, and would cease if the curves crossed again at a higher altitude.

5.2.2. Boiling Losses

Smith (Ref. 20) gives curves for 100/130 Avgas showing the values of fuel boiling losses obtained by calculation (Fig. 18). The reduction in the extent of loss due to self-cooling is clearly evident. As shown in the figure, the authors compare their results with those obtained from a flight test with an aircraft using similar fuel. Losses of 7% w. are seen to be possible at an altitude of 50,000 ft. with an initial fuel temperature of $15 \, ^\circ C$, and as great as 20% w. with an initial temperature of $50 \, ^\circ C$. Derry et al (Ref. 19) have checked the following expression :-

$$W = X \ (H - H_b),$$

where W = % w. fuel loss at altitude H,

H_b = boiling altitude, in thousands of feet,

and found that $X = 1.970/(S + 1.937)$, where S is the slope of the ASTM distillation curve between the 5% and W% recovery points, in $F^\circ/\%$. The value of X was found to vary from 0.53 for 100/130 Avgas to 0.2 for Avtag.

Curves of boiling losses for turbine fuels are given by Shellard (Ref.21)

for initial fuel temperatures up to 70°C. In view of the elevated temperatures resulting from kinetic heating, Shell has recently produced experimental results for the boiling losses of aviation turbine fuels subjected to temperature levels above 200°C. Fig. 19 shows these losses for Avtag, Avtur, and Avcat.

5.2.3. Preventive Measures

Fuel vapour pressure is the fundamental property controlling boiling at altitude, so that selection of a low vapour pressure fuel is essential for high altitude flight. Avtur (vapour pressure approximately 0.15 p.s.i. at 100°F) is, therefore, more attractive than Avtag (3.0 p.s.i.) or Avgas (7.0 p.s.i.). Since a low vapour pressure requirement sets a limit on the proportion of volatile fractions permissible, altitude boiling is seen to be another of those problems which restrict distillation range, and hence fuel availability.

The next logical approach is to increase the tank pressure as high as practicable above ambient in order to delay the onset of fuel boiling until greater altitudes are reached. Strength and weight considerations normally limit the degree of pressurisation to about 3 or 4 p.s.i. The effect of pressurisation on boiling altitude is included in Fig. 17. It is interesting to note that a significant degree of self pressurisation is incurred if the size of the tank venting system is inadequate. Arklay (Ref. 23) found that a 2 in. diameter vent hole, with no external pipe, is sufficiently small to create a pressure differential of 1 p.s.i. in a 300 gallon Avgas tank climbing at 3,000 ft./minute. Derry et al (Ref. 19) found that the theoretical linear speed of the vapour escaping through a 2 in. diameter vent at 60,000 ft. altitude was no less than 1300 m.p.h. for 100 gallons of 7 p.s.i. vapour pressure fuel at 10,000 ft./minute rate of climb. The authors also give details of the extent of refrigeration necessary to prevent boiling at 60,000 ft. altitude. A 2 p.s.i. vapour pressure fuel, for example, requires the extraction of approximately 25,000 C.H.U. per 1000 gallons.

Vent design is also important from considerations of foaming and slugging. Sudden releases of dissolved air or of vapour can project foam, or even slugs of liquid fuel, into the vent pipe, considerably increasing the overall loss of fuel. Exploratory tests carried out by Derry show these phenomena to be more prone with full tanks, but to be reduced by the presence of a film of adsorbed gas on the inner surface of the tank. Details of tank pressurisation equipment are given in Ref. 24. Research is also in progress on the condensation of fuel tank vapours.

6. Inflammability Problems

Within certain ranges of temperature and pressure, the air-vapour mixture produced above the liquid fuel in aircraft fuel tanks will support combustion, and will burn explosively on the addition of the necessary energy for local ignition. This energy may be provided if the tank is pierced by incendiary missiles, or by metallic particles which are hot, or which spark when striking internal baffles. The variations in fuel temperature and pressure, discussed in earlier paragraphs, give rise to changes in the inflammability range for each aviation fuel.

The condition leading to tank explosion are similar to those obtaining during a laboratory determination of flash point (the temperature level to which the sample of liquid fuel must be raised at atmospheric pressure in order to provide sufficient vapour to flash momentarily when exposed to a naked flame). Since the flash point may be taken as the weak inflammability temperature limit, it is an indication of volatility, so that flash points are expected to show a close relationship with temperature levels of distillation. This is apparent in Fig. 1, the lighter fuels having a flash point well below ambient, and hence not measurable under standard conditions of test. The close relationship between flash point and the 10% distillation temperature is shown clearly in Fig. 20.

The weak inflammable mixture obtaining at the flash point is a fuel vapour concentration of about 1.3% v., and this holds reasonably constant over the whole range of hydrocarbon aviation fuels. A complementary limiting condition is visualised when just sufficient oxygen is available for a momentary flash, and this occurs at a rich fuel vapour concentration of about 7.0% v. for the hydrocarbon aviation fuels. These two limits, therefore, encompass a mixture range of inflammability which, on the temperature scale, is about 30 C$^{\circ}$. The 'upper' flash points, which are not normally measured in the laboratory test, are included in Fig. 1. It is seen that fuels of about 3.0 p.s.i. vapour pressure are inflammable under ambient conditions, whereas those of higher vapour pressure are too rich to ignite, and those of lower vapour pressure are too weak.

Mixture limits of inflammability show little variation with reduced pressure, but the temperature limits reduce progressively since vaporisation takes place more easily. Eventually a pressure level is reached (approximately 200 mm Hg. = 32,600 ft. altitude) at which the inflammable mixture range begins to shrink, the movement of the rich limit being particularly marked. At a pressure of about 50 mm Hg. (= 61,500 ft. altitude), depending upon the energy of the igniting agent, the mixture range reduces to zero. Similar trends are found in the inflammable temperature limits for hydrocarbon fuels; those shown in Fig. 21 are derived from numerous full-scale static tests in aircraft fuel tanks. These curves show that the vulnerability of aircraft fuel tanks to explosion depends upon the initial fuel temperature, together with the rate of climb and subsequent behaviour in the air. Kerosine, for example, would be the safer fuel to use when operating with a low ground temperature and rate of climb, such

as a heavy transport aircraft in the arctic, and gasoline preferable for a high-speed aircraft in the tropics. This conclusion is in direct opposition to that based upon heating values. Operational fuel temperature curves have been compared with inflammable temperature zones by Ogston (Ref. 27), as indicated in Fig. 22.

Inspection of the lower limit values at sea level in Fig. 21 shows them to be about 7 C° below the respective flash points determined in the laboratory. This disagreement is due to differences in geometry and scale, and to heterogeneity of air-vapour mixtures within the free space (See Fig. 5 of Ref. 28). The conventional flash point is, therefore, no precise criterion of explosion safety in an aircraft fuel tank.

Lightning would present a considerable hazard in the event of inadequate bonding. Operational experience shows that lightning strikes occur mainly at sharply curved surfaces, as at the tips of wings and tailplanes (See Fig. 7 of Ref. 28). By testing model fuel tanks with artificial-lightning-generator facilities, Robb et al (Ref. 29) show that ignition of fuel is likely only when the tank wall is punctured, and that aluminium-alloy walls in excess of 0.081 in. thickness are not normally punctured when exposed to representative discharges. Lightning strikes of greater magnitude, or damage of greater confinement, would still be dangerous. A major proportion of strikes in service is shown to have occurred within the temperature range -10 to + 10°C, and the low altitude range of 6,000 to 14,000 ft. Fig. 21 shows Avtag to be the most hazardous fuel under these conditions.

Static electricity presents another possible source of ignition. The charges build up either by the passage of water or dust particles over the surface of the aircraft, or by the proximity of electrically charged clouds. Again, bonding provides an adequate safeguard, except in the remote possibility of static charges being generated due to motion of the fuel within the tank.

6.1. Inflammability Beyond Equilibrium Limits

The temperature limit boundaries of Fig. 21 enclose the equilibrium danger areas, but explosion is also possible beyond both limits under the following circumstances. When liquid fuels are sprayed into the air, the greatly increased surface area results in a correspondingly increased rate of vaporisation, and a greater effective volatility. Explosion thus also becomes possible beyond the low temperature side of the normal boundary curve, and may occur when a missile enters a tank and causes the liquid fuel to splash. Explosion on the high temperature side of these boundaries is possible when the oxygen content of the air in the mixture is increased. On climbing, oxygen-rich 'air' is released (see paragraph 5.1), the oxygen content being about 33% v. instead of the normal atmospheric value of 21% v. This displaces the boundary curve bodily through about 10 C° in the high temperature direction (See Ref. 30). On diving, the ingress of atmoshperic air through the tank vents provides explosive mixtures at

temperatures higher than the normal boundary values. This follows as the fuel vapour, normally too rich to burn, diffuses relatively slowly into the incoming air, and creates near the vent a region of mixture whose strength gradates into the weak explosive range. When atmospheric air is used as the pressurising fluid to prevent fuel boiling at altitude, the lower effective altitude within the tank brings the operating condition down towards the explosive range during operation on the high temperature side of the boundary. These four effect are illustrated for aviation kerosine in Fig. 23. It is evident, therefore, that the many factors involved make it difficult to find completely safe operating conditions for any aviation fuel.

6.2. Preventive Measures

It is apparent that some kind of effective and continuous protection against tank explosion is very desirable, particularly when flying within the explosion boundaries. The fuel quality required depends upon flight speed; a high flash point is needed for low-speed high-altitude flight, and a low flash point when flight speed is sufficient to incur appreciable kinetic heating. Armour-plated fuel tanks are impracticable, but two main approaches exist, i.e. suppressing incipient explosions, and purging oxygen from the free space.

6.2.1. Explosion Suppression

In all ignition processes, a finite period of time elapses between the application of energy and the initiation of flame. If the delay period is adequate, the incipient explosion can be sensed and then suppressed. The upper curve in Fig. 24 shows the normal growth in pressure immediately prior to an explosion of a fuel-air mixture in a confined space. The lower curve indicates the pressure levels reached at the instants when the detector operates and when the suppressant fluid is discharged into the tank contents. In existing systems, the total pressure rise is limited to about 3 p.s.i. only (Ref. 31). The incipient explosion may be detected by means of either a pressure-sensitive capsule, or a photocell. Fuel itself may be used as the suppressant fluid since the resulting enrichment precludes combustion. In this case, the tank contents are not contaminated.

6.2.2. Inert Gas Purging

A prerequisite to ignition is an adequate concentration of oxygen, and tests show that ignition is not possible when the oxygen concentration of the 'air' in an air-fuel mixture falls from the normal atmospheric value of 21% v. to about 12% v., i.e. still considerably above zero (see Ref. 30). It is practicable, therefore, to carry gaseous nitrogen in order to purge the contents of the tank vapour space, and to reduce their oxygen concentration below the danger limit. Additional nitrogen is needed on the release of oxygen-rich air on climbing, and to deal with the incoming air on descent. Hence, nitrogen purging offers a means of continuous explosion safety at any altitude or condition of flight, but

it entails considerable weight penalties to cover a flight of any appreciable duration. A recent development of British Oxygen Aro Equipment Ltd., is a purging system comprising a high-vacuum insulated container storing liquid nitrogen, which is injected into the compressor bleed air used to pressurise the fuel tanks (Ref. 32).

An alternative source of purging fluid, which offers great attractions of low weight and availability, is the combustion efflux from the main propulsive engines. In the gas turbine engine, the mixture strength in the primary zone of the combustion chambers should be very nearly stoichiometric, and the oxygen concentration negligible. Tests have shown that fuel-cooled probes located in fixed positions in the primary zone will sample gases with an oxygen concentration not exceeding 6% v. over a wide range of engine operating conditions (Ref. 33). The sampled gases, cooled and dried, are found to be suitable as a purging fluid over all conditions of flight, with the possible exception of diving with the main engine idling. In view of this limitation, it may be more satisfactory to provide a separate combustor within the aircraft for purposes of producing inert purging gases. A very close control must be maintained over the oxygen concentration of the output gases, but the duties of such a system could be combined with those of an aircraft heater.

7.   Conclusions

It is evident from the foregoing discussions that fuel requirements conflict, and that a compromise must be drawn when setting limits for fuel specifications. The fuel requirements, together with additional measures of protection, can be correlated by considering separately the conditions obtaining at high altitude, and at high aircraft speed, as in Tables 2A and 2B, and by means of a composite diagram as in Fig. 25. The effects of aircraft operation under these two conditions may be summarised as follows :-

(i)   High Altitude Flight. This incurs problems of filter blockage by
      ice and wax, fuel foaming and boiling losses, and possibilities
      of tank explosion with high flash point (kerosine) fuels at low
      aircraft speeds. The low ambient temperatures asist in preventing
      thermal degradation and boiling loss in high-speed aircraft.

(ii) High Speed Flight. This incurs problems of fuel stowage space, fuel
      boiling loss, filter blockage by thermal degradation products, and
      possibilities of tank explosion with low flash point (gasoline)
      fuels, and at higher temperatures, with high specific gravity fuels.
      The kinetic heating assists in preventing filter blockage by ice
      and wax.

In the hydrocarbon range, an application is seen to be appropriate to each significant fuel property. Using specific gravity again as the main distinguishing property, the picture appears as follows :-

(i) Low Specific Gravity Hydrocarbon Fuels

High heating values per pound	All aircraft applications
Low freezing points	Low speed, high altitude
High vapour pressures	Low speed, low altitude
Low flash points	High speed, high altitude

(ii) High Specific Gravity Hydrocarbon Fuels

High heating values per gallon	High speed
High freezing points	High speed, low altitude
Low vapour pressures	High speed, high altitude
High flash points	Low speed, high altitude

With regard to the additional measures for combating these problems, the following summarising notes show certain techniques to be effective in dealing with more than one problem :-

(a) Fuel Additives. These offer possibilities of suppressing filter blockage due to ice, wax and thermal degradation products, and also the possibilities of tank freezing, and tank explosion due to spontaneous ignition at very high flight speeds with pressurised tanks.

(b) Fuel Heating. Although imposing penalties of weight and complication, this is a practicable system of preventing filter blockage by ice and wax. It is achieved by means of a heat exchanger fed with hot air from the compressor of a main gas turbine engine.

(c) Fuel Cooling. This is a difficult and expensive process, but it would permit the carriage of a greater mass of fuel in a given volumetric capacity, and the filtration of ice crystals during fuelling. It would also assist in the prevention of boiling losses, and of filter blockage by thermal degradation products.

(d) Fuel Agitation. This assists in preventing filter blockage by ice and wax, and loss of fuel by foaming and slugging initiated by sudden air release. It also assists thermal stability at high aircraft speeds. It could be achieved by continued recycling with the booster pumps, in conjunction with suitable baffles in the tanks.

(e) Fuel Pressurisation. This prevents boiling losses at high altitude and at high aircraft speeds, and can be achieved by tapping the compressor of a main gas-turbine engine. If an inert gas is used as the pressurising fluid, this renders the tanks continuously safe from explosion under all conditions, and assists thermal stability. The standard practice of fitting booster pumps at the tank outlets minimises problems of vapour lock in the pipelines.

(f) <u>Tank Insulation.</u> This prevents filter blockage by ice and wax, and the excessive build up of wax on the tank walls, in low-speed aircraft at high altitude. It also improves thermal stability in high-speed aircraft.

(g) <u>Explosion Suppression.</u> This reduces the possibility of tank explosion under all conditions, but is limited to a single operation during a given flight.

The demands for higher and faster flight can be expected to become more pressing, and the magnitude of the problems outlined above to be correspondingly increased. One exception may be the problem of filter blockage by ice and wax, since ambient temperatures are not likely to fall further, whereas aircraft speeds will continue to rise, and the effect of kinetic heating to increase. An overall result will be an increased trend from hydrocarbon to specially tailored 'chemical' fuels.

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APPENDIX

STANDARD LABORATORY TESTS QUOTED

Para.	Property	I.P.* No.	A.S.T.M.* No.
1.	Distillation	123/55	D86-53
1.	Specific Gravity	59/55	D1298-54
2.	Calorific Value	12/53	D240-50
3.2.	Water Tolerance	98/44	D1094-53
3.3.	Kinematic Viscosity	71/55	D445-53
3.3.	Freezing Point	16/44	D910-53
3.3.	Cloud Point	15/55	D97-47
3.3.	Pour Point	15/55	D97-47
4.	Vapour Pressure	69/55	D323-52
4.	Autogenous Ignition Temperature	-	D286-30
6.	Flash Point	33/55	D56-52

* These test procedures are nominally equivalent, but certain minor differences exist.

British test techniques are detailed in the current edition of "Standard Methods for Testing Petroleum and its Products". The Institute of Petroleum, 26, Portland Place, London, W.1., and American techniques in the current edition of "ASTM Standards on Petroleum Products and Lubricants". American Society for Testing Materials, 1916, Race Street, Philadelphia 3, Pa., United States of America.

Fuel specifications normally indicate the methods to be adopted.

PROPERTY \ TYPE	GASOLINES (1) (AVGAS)	WIDE-CUT GASOLINE (AVTAG)	KEROSINE (2) (AVTUR)	HIGH FLASH KEROSINE (AVCAT)
D.Eng.R.D. No. & date	2485 1/12/54	2486 1/12/54	2482 1/3/57	2488 1/12/55
U.S. Equivalent	–	A.S.T.M. Type B (JP4)	A.S.T.M. Type A	JP 5
Specific Gravity	Not Limited	0.751 to 0.802	0.775 to 0.825	0.788 to 0.845
Distillation f.b.p. Residue, % Loss, %	≤ 10% & ≥ 40% at 75°C ≤ 50% at 105°C ≤ 90% at 135°C (10 + 50)% ≤ 135 C° ≥ 170°C ≥ 1.5 ≥ 1.5	≤ 20% at 143°C ≤ 50% at 188°C ≤ 90% at 243°C – ≥ 1.5 ≥ 1.5	≤ 20% at 200°C ≥ 300.0°C ≥ 2.0 ≥ 1.5	10% at ≥ 204°C ≥ 288°C ≥ 1.5 ≥ 1.5
Lower Heating Value B.Th.U. per lb.	≤ 18,700 (≤ 18,900 for 115/145)	≤ 18,400	≤ 18,300	≤ 18,300
Water Tolerance ml.	2	1	1	1
Freezing Point °C	Not above –60	Not above –60	Not above –40	Not above –40
Vapour Pressure at 100°F, in p.s.i.	≤ 5.5 and ≥ 7.0	≤ 2.0 and ≥ 3.0	–	–
Flash Point °F	–	–	≤ 100	≤ 140
Kinematic Viscosity	–	–	≥ 6 cs. at 0°F	≥ 16.5 cs. at –30°F
Aromatic Content	–	≥ 25% Vol.	≥ 20% Vol.	≥ 25% Vol.
Bromine Number	–	≥ 5	≥ 5	≥ 5
Total Sulphur, wt.%	≥ 0.05	≥ 0.40	≥ 0.20	≥ 0.40
Total Acidity mgm. KOH/gm. fuel	–	≥ 0.10	–	≥ 0.10
Existent Gum/100 ml. Accel. Gum/100 ml.	≥ 3.0 mgm. ≥ 6.0 mgm.	≥ 7.0 mgm. ≥ 14.0 mgm.	≥ 3.0 mgm. ≥ 6.0 mgm.	≥ 7.0 mgm. ≥ 14.0 mgm

Notes   (1)   Includes 5 grades: 73/80 (both colourless), 91/96 (blue), 100/130 (green), & 115/145 (purple).
         (2)   Avtur/50, D.Eng.R.D.2494 is identical to 2482 but freezing point not above –50°C. J.P.1 freezing point not above –60°C.   J.P.6 is thermally stable.

CONDITIONS	EFFECT	FUEL REQUIREMENT	ADDITIONAL MEASURES
Low ambient temperature	Dissolved water precipitates. Free water freezes. Filter blockage.	Water content minimised. (Negligible difference between fuels).	Pre-refrigeration and filtration. Anti-freeze agents. Fuel heating. High-speed flight. Upstream mesh filter. Increased filter area. Fuel agitation with dry air.
	Fuel freezes progressively. Tank contents fail to flow. Filter blockage.	Low freezing point (Low S.G.). Low pour point (Low S.G.)	Fuel tank heating. High speed flight. Tank insulation. Fuel agitation (thixotropy).
Low ambient pressure	Dissolved air released. Foaming.	(Negligible difference between fuels).	Fuel agitation.
	Fuel boils. Vapour loss. Vapour lock.	Low vapour pressure (High S.G.).	Tank pressurisation. Booster pump.
Low ambient temperature and pressure	Level of explosion temperature range reduces.	High flash point (High S.G.).	Explosion suppression. Inert gas purging.

TABLE 2B   FUEL CONSIDERATIONS IN HIGH-SPEED FLIGHT

CONDITIONS	EFFECT	FUEL REQUIREMENT	ADDITIONAL MEASURES
Thin wing sections	Fuel stowage capacity reduced.	High heating value per gallon. (High S.G., and chemical fuels).	External tanks. Pre-chilling.
Kinetic heating	Vapour pressures rises appreciably. Vapour loss.	Low vapour pressure (High S.G.).	Tank pressurisation.
	Sediment forms. Filter blockage.	Thermal stability. (High paraffinic, and low aromatic content).	Segregation of satisfactory fuel stocks. Selection of suitable refining processes. Additives. Tank insulation. Fuel cooling. Removal of dissolved air (agitation). Inert gas blanketing.
	Fuel temperature reaches explosion range.	Low flash point (Low S.G.).	Explosion suppression. Inert gas purging.
	Fuel temperature approaches spontaneous-ignition level.	High spontaneous-ignition temperature (Low S.G.).	Ignition suppression additives.
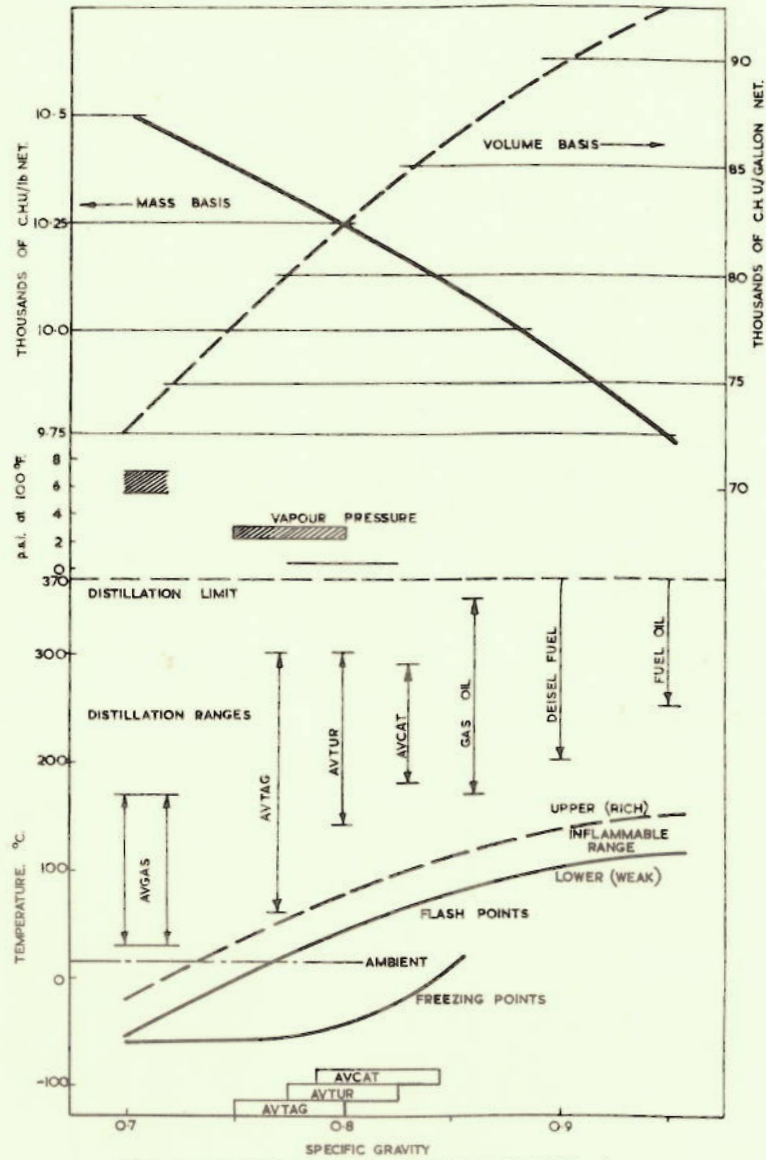
FIG. I. TYPICAL VALUES SHOWING TRENDS IN
FUEL PROPERTIES (REF. I.)
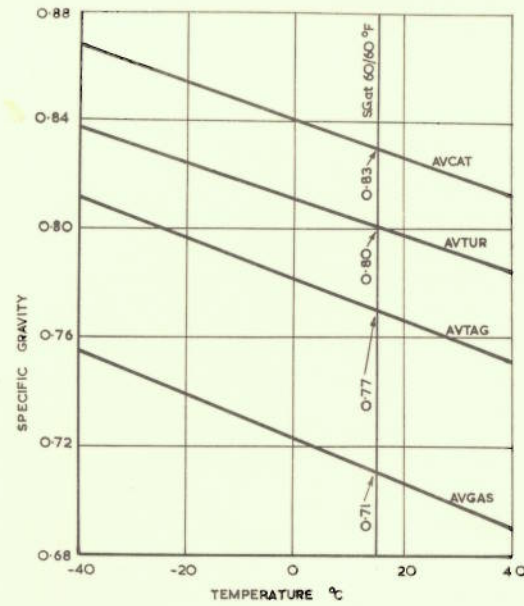
FIG. 2. TEMPERATURE VARIATIONS IN SPECIFIC GRAVITY FOR TYPICAL AVIATION FUELS (REF 7)

FIG. 3. VALUES OF PERFORMANCE INDEX (REF. 4)

FIG. 4. ALTITUDE TEMPERATURES (DERIVED FROM REF.5)
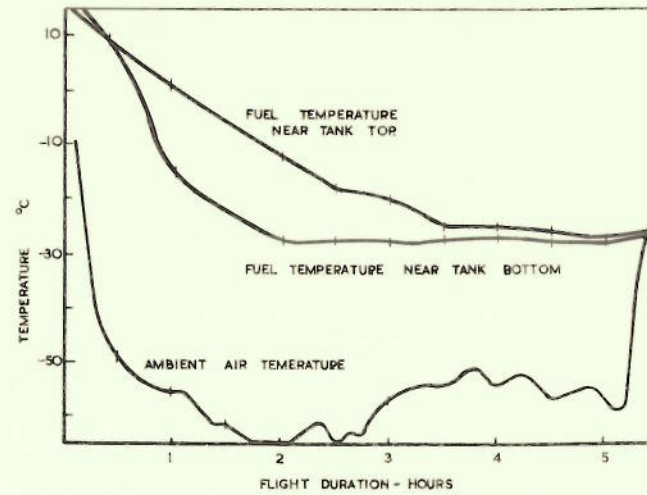
FIG. 5. COMET FUEL TEMPERATURES (DERIVED FROM REF. 6)
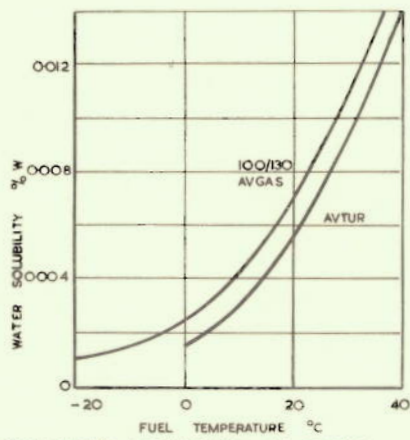
FIG. 6. WATER SOLUBILITY IN FUELS
[REF. 7.]
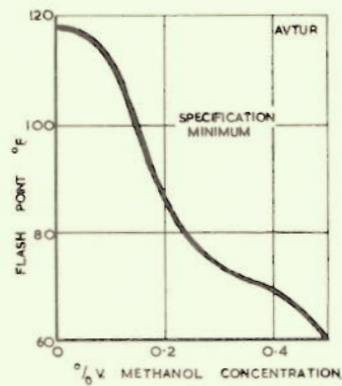
FIG. 7. EFFECT OF MENTHANOL
ON FLASH POINT OF KEROSINE.
(REF 12)
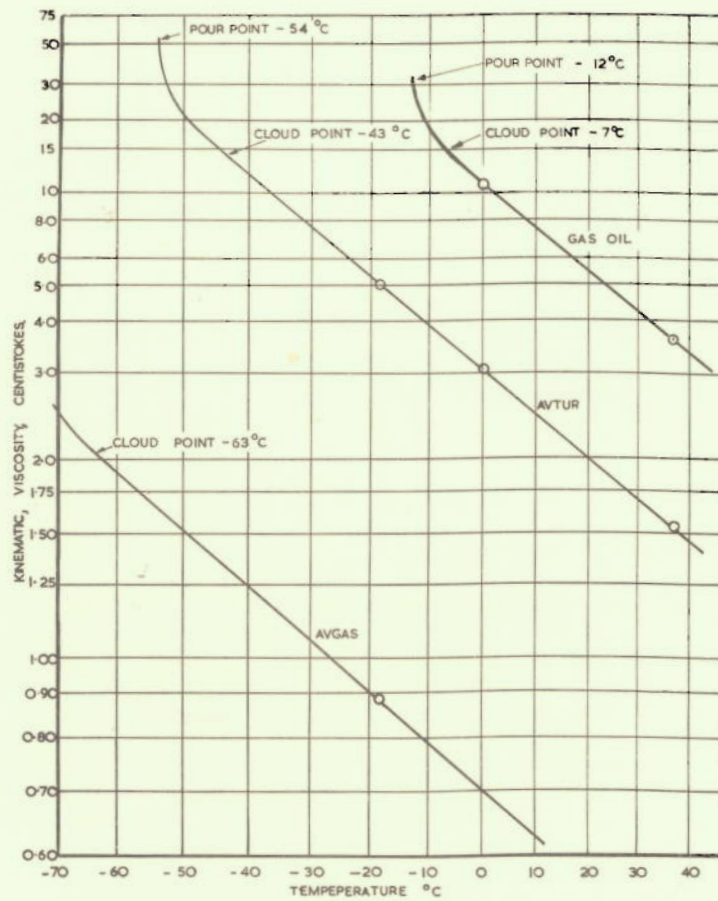
FIG. 8. TEMPERATURE VARIATION OF FUEL VISCOSITY [DERIVED FROM REF. 10]
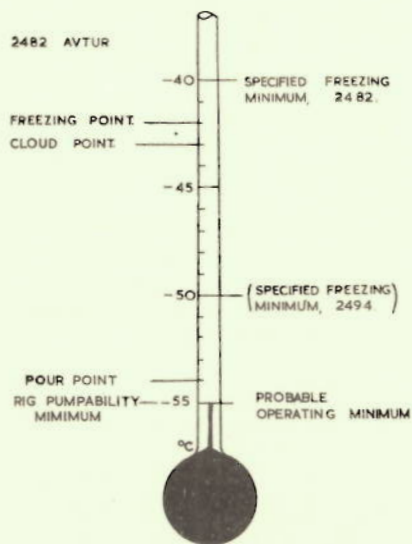
FIG. 9. LOW TEMPERATURE EVENTS WITH TYPICAL AVTUR

2482 AVTUR

SPECIFIED FREEZING MINIMUM, 2482.
FREEZING POINT
CLOUD POINT
(SPECIFIED FREEZING MINIMUM, 2494)
POUR POINT
RIG PUMPABILITY MINIMUM
PROBABLE OPERATING MINIMUM
°C
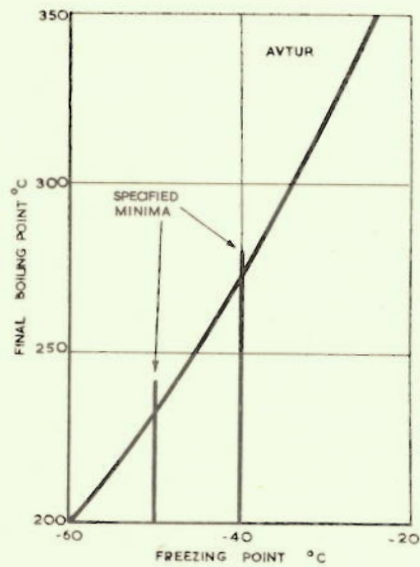
FIG. 10 EFFECT OF FINAL BOILING POINT ON FREEZING POINT [REF. 14]

AVTUR

SPECIFIED MINIMA

FINAL BOILING POINT °C

FREEZING POINT °C
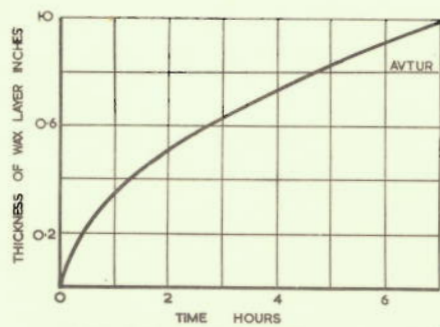
FIG II GROWTH RATE OF WAX LAYER [REF 13]

THICKNESS OF WAX LAYER INCHES

AVTUR

TIME HOURS
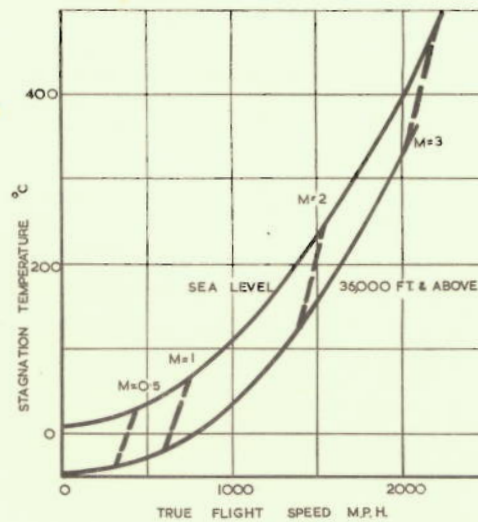
FIG. 12. VARIATION OF STAGNATION TEMP. WITH FLIGHT SPEED. [REF. 15.]

STAGNATION TEMPERATURE °C

M=3
M=2
SEA LEVEL
36,000 FT & ABOVE
M=1
M=0·5

TRUE FLIGHT SPEED M.P.H.
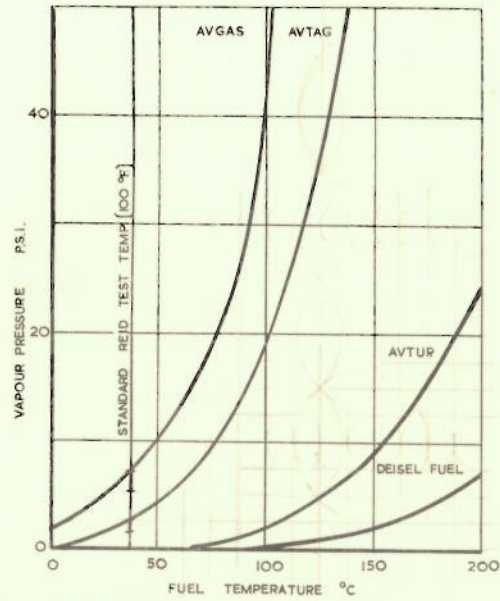
FIG. 13. VARIATION OF FUEL VAPOUR
PRESSURE WITH TEMPERATURE [REF.16 & 7.]
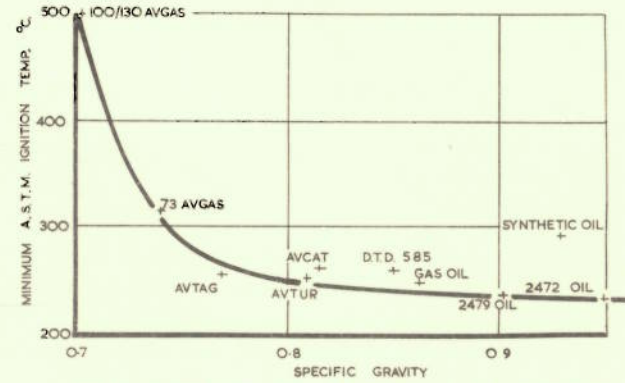
FIG.14. VARIATION IN MINIMUM A.S.T.M. IGNITION
TEMPERATURE WITH SPECIFIC GRAVITY [REF.18.]
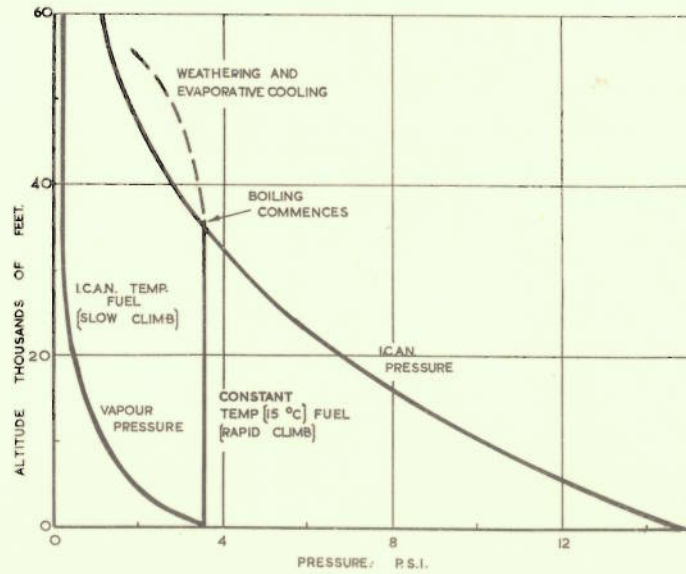
FIG 15 ALTITUDE VARIATION OF ATMOSPHERIC PRESSURE
AND OF AVGAS VAPOUR PRESSURE
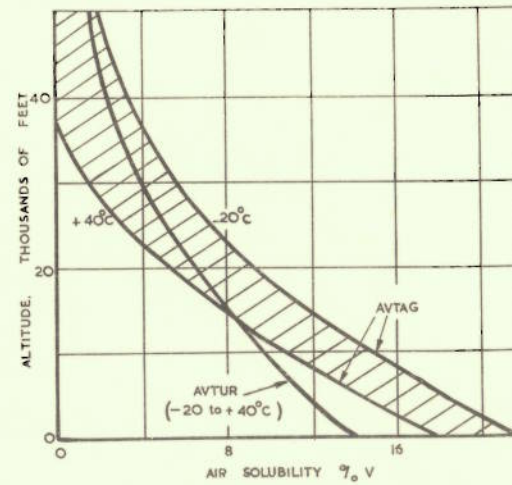
FIG.16. AIR SOLUBILITY IN FUELS [REF. 6]
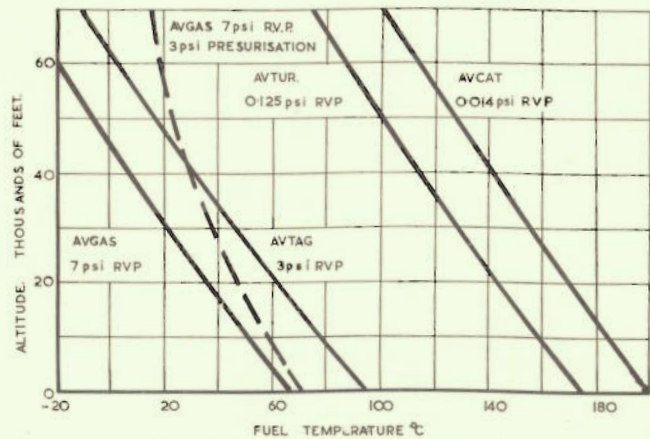
FIG. 17. FUEL BOILING ALTITUDES [DERIVED FROM REF. 22]

FIG. 18. BOILING LOSSES WITH 100/130 AVGAS SHOWING
SELF-COOLING EFFECTS [REF. 20]

FIG. 19. BOILING LOSSES WITH AVTAG, AVTUR, & AVCAT [REF. 22]
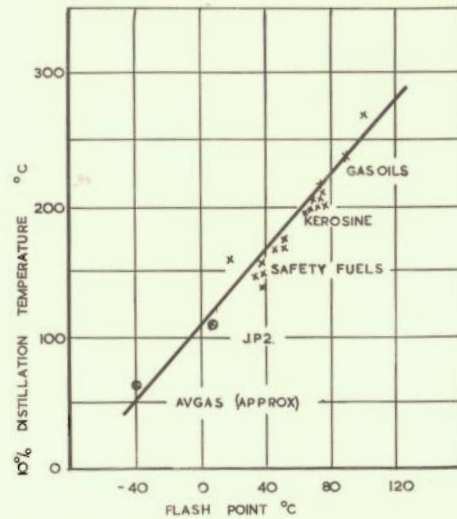
FIG. 20. CORRELATION BETWEEN FLASH
POINT AND VOLATILITY. [REF. 25.]
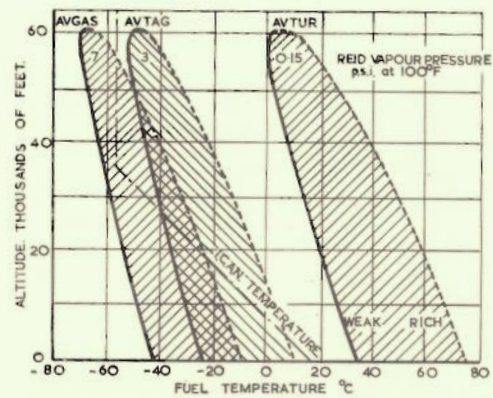
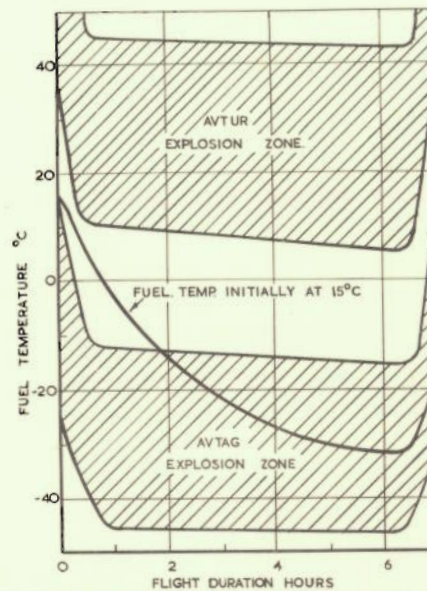FIG. 21. EXPLOSIVE LIMIT TEMPERATURE BOUNDARIES FOR AVIATION FUELS [REF. 26]

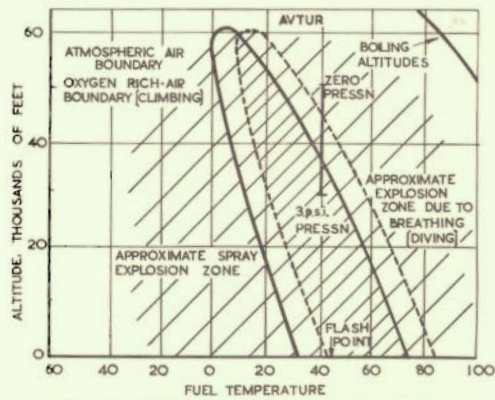FIG. 22 FUEL TEMPERATURE AND EXPLOSION ZONES FOR 40,000 FEET CRUISE [REF. 27]

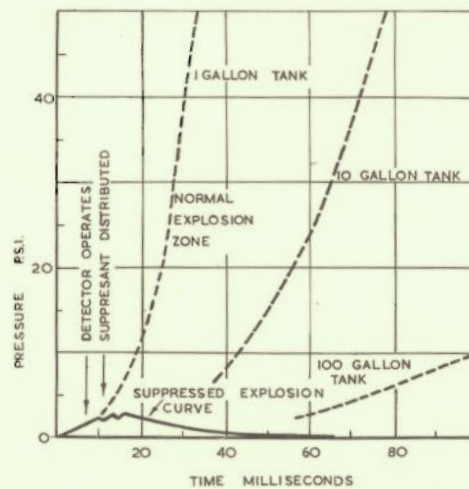FIG. 23. ADDITIONAL EXPLOSIVE ZONES FOR AVTUR [REF. 30]

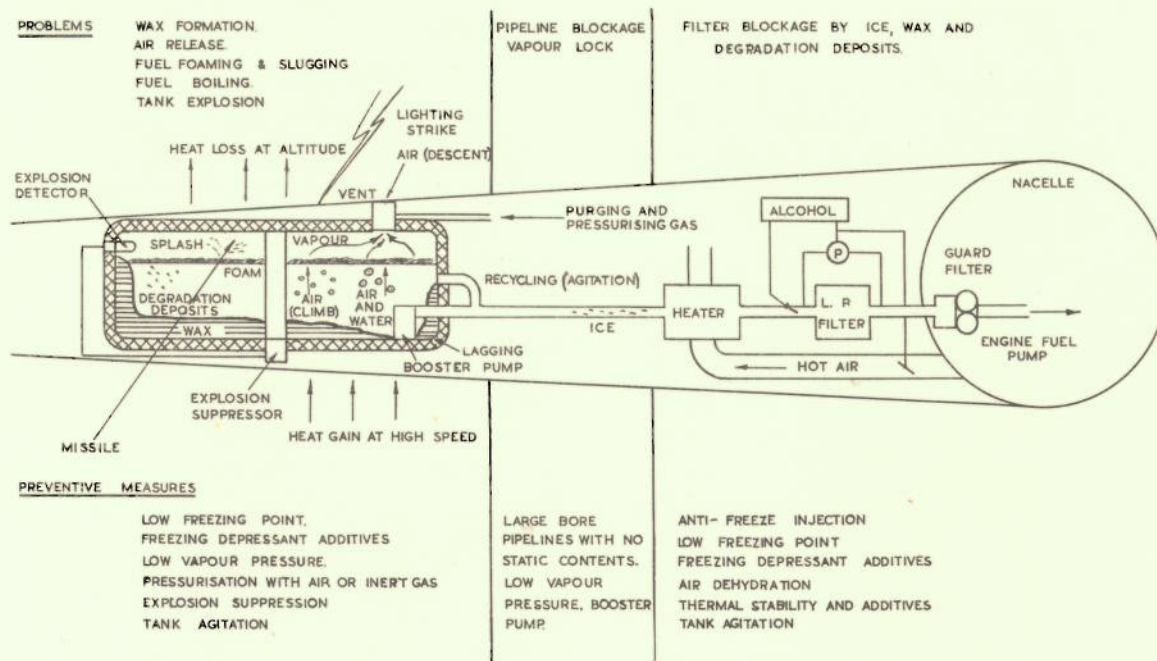FIG. 24. EXPLOSION PRESSURE CURVES. [REF. 31.]

FIG. 25. DIAGRAMMATIC REPRESENTATION OF AIRCRAFT FUEL SYSTEM SHOWING FUEL PROBLEMS AND PREVENTIVE MEASURES