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The Protection of Aircraft Fuel Tanks Against Explosion
Hazards using Inert Combustion Products

-by-

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SUMMARY

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 ignition. Although the danger zone for each type of aviation fuel can be clearly defined under equilibrium conditions, the many transient factors involved in practice make it difficult to find completely safe operating conditions for any fuel.

A war-time approach to the solution was the continuous purging of the tank free space with nitrogen to reduce the oxygen content of the admixed air below the minimum permissible for combustion. In order to avoid the weight and bulk of air-borne nitrogen storage equipment, combustion products have been suggested as an alternative and continuously-available supply of inert gases. The source of these gases may be either the primary zone of some combustion chambers of the main gas-turbine engines, or a separate inert gas generator located within the aircraft.

This report describes experiments made on sampling from the primary zone of a Derwent I chamber, and on the testing of various automatic control devices suitable for an inert gas generator. The conclusions drawn from the results are that both systems of purge gas supply are feasible, and that the critical condition will be the high altitude dive with engine idling, when the purge gas requirement is a maximum, and the supply a minimum.

This report is based on sections of a thesis submitted by F/Lt. Cadman in June 1953, and a thesis submitted by S/Ldr. Murchie in June 1954, as part of the requirements for the award of the Diploma of The College of Aeronautics. The investigations were made under the supervision of Mr. Goodger.

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1. The Explosion Problem, and Safety Requirements

1.1. Introduction

The fire hazard in aviation is a problem which has called for continued research, and the advances in aircraft design and fuel handling techniques have done much, in civil aviation, to reduce fire to a fairly remote possibility. In military aviation, however, fire initiated by enemy action is the direct cause of most aircraft losses, and further active development is therefore vital.

The general problem can be subdivided into the various aspects of airframe and engine fires occurring in the air or on the ground, and includes the initiation of fires within the aircraft fuel tanks. This latter aspect is particularly serious in that it almost invariably leads to explosion and the total loss of the aircraft. The conditions under which such disasters may occur, together with a possible method of protection, form the basis of this report.

As in all combustion processes, explosion is only possible when the two requirements of ignition energy and inflammable mixture strength are met. Sufficient energy for ignition may be provided if the tank is pierced by incendiary missiles, or by metallic particles which may spark on striking internal baffles. The strength of the vapour-air mixture above the liquid fuel in an aircraft fuel tank is influenced by a number of factors and, under certain circumstances, lies within the inflammable range for the fuel.

As it is impracticable to counteract completely the ignition danger by means of extensive armour-plating, recent development work on explosion safety has proceeded mainly upon the following alternative lines.-

- (a) Using nitrogen for continuously purging the vapour-air mixture in order to render it inert. Where necessary, the nitrogen also acts as the pressurising fluid.
- (b) Projecting extinguishant into the vapour as soon as a small rise in tank pressure indicates an incipient explosion.

The explosion suppression method has been shown to be markedly effective but, being a single shot system, cannot be reset for repeated use. The nitrogen purging system has been developed to give explosion safety for the tanks of large aircraft, but is unsuitable for small aircraft due to the bulk of equipment required. In order to overcome this drawback, combustion products have been suggested as an alternative and continuously-available supply of inert gas. The source of these gases may be either the primary zone of some combustion chambers

of the main gas turbine engines, or a separate combustor, automatically-controlled to operate at or near stoichiometric conditions, located within the aircraft. The design of a separate combustor for inert gas purging is described by Hill (ref. 1), but little information has been found regarding primary zone sampling. It was decided at the College of Aeronautics, therefore, to investigate the possibilities of both methods of inert gas production.

1.2. Explosive Limits in Aircraft Fuel Tanks

Most published results for the inflammable limit mixtures of fuel vapour in air (or oxygen) relate to homogeneous conditions within spheres (ref. 2) or cylindrical tubes (ref. 3). For the hydrocarbons contained in average commercial fuels, the inflammable range extends from approximately 1.2 to 7.0 per cent by volume of fuel vapour in the mixture with air at atmospheric pressure and temperature, and these limits gradually approach each other as the temperature level is reduced. Reduction in pressure has little effect until a pressure level of about 200 m.m. mercury (= 32,600 ft. I.C.A.N.) is reached, after which the limits approach each other to meet at a minimum pressure of about 50 m.m. mercury (= 61,500 ft.), depending upon the energy of the igniting agent.

Results have now been presented (ref. 4) to effect the calculation of weak and rich explosive limit mixtures for aviation gasoline in aircraft fuel tanks together with the temperatures at which these mixtures occur. Further results have been presented in the form of curves (fig. 1) showing the variation of the limit temperatures with altitude for most aviation fuels (ref. 5). The conditions leading to a tank explosion are similar to those obtaining during a laboratory determination of flash point, when an igniting flame is introduced into the vapour space above the liquid surface. However, complete agreement between laboratory and tank tests cannot be expected, due to differences in dimensions and scale, and it is noticeable that the lower explosion limit temperatures at sea-level are some 7°C below the respective flash point values. The conventional flash point is thus no true criterion of safety from explosion in a tank containing undisturbed fuel and air.

These temperature curves show that the vulnerability of aircraft tanks to explosion depends upon the initial fuel temperature, together with the rate of climb and subsequent behaviour in the air. For example, kerosine would be the safer fuel to use when operating with a low ground temperature and rate of climb (e.g. heavy bomber in the arctic), and gasoline preferable for a high-speed aircraft in the tropics. This is in direct opposition to the high specific gravity requirement for the modern high performance fighter aircraft in which stowage space is at a premium.

Nominally, these temperature limit boundaries 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, the effect being to displace the boundary curves bodily in the high temperature direction. As hydrocarbon fuels absorb atmospheric gases, and the solubility of oxygen is greater than that of nitrogen, the release of oxygen-rich 'air' at altitude displaces the explosion boundaries in fig. 1 through about 10°C. The ingress of atmospheric air through the tank vents when diving into zones of higher pressure also 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. The above three effects are illustrated for aviation kerosine in fig. 2. When atmospheric air is used as the pressurising fluid to prevent fuel boiling at altitude, the lowered effective altitude within the tank brings the operating conditions down towards the explosive range during operation on the high temperature side of the boundary, (ref. 6).

It is evident, therefore, that the many factors involved make it difficult to find completely safe operating conditions for any aviation fuel, and effective and continuous protection of some kind is essential when flying under conditions likely to lead to tank explosion.

1.3. Combustion Products as a Possible Inerting Fluid

It is not necessary to remove completely the oxygen from air in order to inhibit combustion, and results from ref. 7 show that the oxygen content of air need be reduced only to 12.1 per cent by volume to give inertness (fig. 3). This figure also shows that inert exhaust gases (85 per cent N_2 and 15 per cent CO_2) from an automobile engine are more effective than pure nitrogen in suppressing combustion, the minimum oxygen content being 13.4 per cent. However, as free nitrogen is likely to be present in addition to that contained in the combustion products, the 12.1 per cent limit should be used as the safety threshold. The first requirement for any inerting gas, therefore, is that its oxygen content should be appreciably less than 12.1 per cent so that the oxygen content of the 'air' portion of the purged

mixture does not exceed this figure, when allowing for air release, tank breathing, and so on. An arbitrary maximum of 6 per cent has been assumed in the tests at Cranfield.

The theoretical concentration curves for dry exhaust gases show the oxygen content to be well below this limit even with mixtures considerably weaker than stoichiometric (fig. 4). It appears practicable, therefore, to produce engine exhaust gases of a nature suitable for tank purging. As the aim in the design of gas turbine combustors is to burn the fuel almost completely within the primary zone, a continuous source of these gases immediately becomes apparent. Accordingly, tests were carried out with a single gas turbine combustor in order to determine the nature and rate of flow of primary zone samples. Secondly, checks were made on the effectiveness of various automatic mixture control devices, in order to determine the most promising system for application to a combustor working independently from the main engine combustion system.

1.4. Flow Requirements for Purged Tanks

In a climbing aircraft, the purge gas flow requirements of a fuel tank are dictated by the release of oxygen-rich air from the fuel. Requirements for equilibrium conditions can be calculated from a knowledge of the rate of air release and the maximum permissible oxygen content, although a higher purge rate would be desirable in practice in order to cover the sudden releases of air due to supersaturation.

Of the data available on the saturation content of air in hydrocarbon fuels, the expressions from ref. 8 are convenient, giving rates of air release for a given volume of fuel at a given rate of climb. These expressions have been used in Appendix A to determine the flow rates of combustion products required to render inert the free space above 100 gallons of aviation kerosine, climbing at 5,000 ft./min. The combustion products are assumed to contain 6 per cent by volume of oxygen, and the requirements are shown in fig. 5A for diluting the released air to 12.1 per cent (the safety threshold), and to 10 per cent. The nitrogen threshold curve is included for comparison. These gas flows are likely to be more than adequate to occupy the space left by the liquid fuel consumed during the climb.

In the descent case, a tank free-space of 100 gallons is taken as a basis and, as kerosine exerts a very low vapour pressure, particularly at the low temperatures at altitude, the space can be assumed to contain air only, with its oxygen content limited to 12.1 per cent due to previous purging. With increasing air density on descent, this air is compressed into a smaller volume, the volume change being occupied by both purge gas and inhaled air. For the threshold condition, the proportion of

these two incoming fluids must be such that their total oxygen content also equals 12.1 per cent. The purge gas and nitrogen requirement curves for descent are shown in fig. 5B.

2. Tapping the Main Engine

The two major problems presenting themselves when considering sampling from the primary zone of combustion chambers are the high temperature (1600°C.) involved, and the possible changes in combustion pattern occasioned by variations in the many controlling factors. Even when a suitable cooled probe is developed and located to sample gases of acceptable oxygen content at a given condition, the need is recognised for exhaustive tests at other conditions to ensure that the maximum permissible oxygen content is still not exceeded. In addition, the presence of the probe must not in itself seriously affect the combustion process or the main gas flow. Further, the sampled gases must be sufficiently cooled, and the condensed water disposed of.

The equipment available for these tests consisted of a Derwent I combustion chamber, which was considered to be reasonably similar in design to current chambers, together with associated air and fuel supply systems, igniter plug and booster coil, and an Orsat apparatus for the absorption of oxygen from the samples, (fig.6)(ref.9). Air was delivered to the test rig from a Bristol Hercules type supercharger, the air temperature at the chamber inlet being about 40°C. The chamber discharged directly to atmosphere, so that no control of chamber pressure was available. Aviation kerosine to specification D.Eng.R.D. 2482 was used throughout the tests.

In order to reproduce an actual running condition, it was necessary to select one at which the combustion chamber pressure equals the sea-level atmospheric value. The maximum altitude at which this condition holds was estimated to be 38,000 ft. with an aircraft speed of 500 m.p.h., a chamber mass flow of about 1.5 lb/sec., and an air/fuel ratio slightly richer than 60/1. In order to study the effects of changing both air/fuel ratio at constant mass flow, and mass flow at constant air/fuel ratio, the following test conditions were selected.-

- | | | | | | | |
|-----|---------------|---|--------------|----------------|---|------|
| (A) | Air mass flow | = | 1.5 lb/sec., | air/fuel ratio | = | 60/1 |
| (B) | ' | ' | ' | ' | ' | ' |
| (C) | ' | ' | ' | ' | ' | ' |
| (D) | ' | ' | ' | ' | ' | ' |

The weakest mixture used in this type of chamber under steady running conditions in practice is 90/1, and the same

burner pressure was used for tests B and C. Test D was considered to be severe, as the low fuel pressure involved could lead to poor atomisation, unburnt fuel, and a high oxygen content of the primary gases. As the oxygen absorbing agent (potassium hydroxide) in the Orsat apparatus also absorbs carbon dioxide, it was necessary to analyse the samples first for carbon dioxide and then for oxygen. When likely sources of inert gas were discovered, the gas samples were also analysed for carbon monoxide. In order to save time, it was decided to record results to the nearest 0.5 per cent of the total sample, and to the nearest 0.1 per cent when the result was less than 1 per cent.

2.1. Exploratory Sampling with Water-Cooled Probe

In order to derive an overall picture of the gas concentration within the chamber, a water-cooled probe was designed for insertion from the chamber outlet. The probe consisted of two concentric stainless-steel tubes, the inner sampling tube of $\frac{1}{8}$ in. I/D, and the outer jacketing tube of $\frac{1}{2}$ in. O/D. Mains water was fed into the rear end of the jacketing tube and was allowed to spray out through two 2n.n. I/D pipes situated near the sampling end, the pipes being carried rearwards to discharge about 6in. downstream of the sampling orifice. This water, which served to cool the probe mounting bracket, was therefore unlikely to affect the combustion process of the sampled gases. The mounting bracket was located 5in. to the rear of the chamber outlet, and adjustment was possible for sampling from any point within the central horizontal plane of the chamber, subject to the limits provided by the flame tube walls.

A typical result from this test series is shown in fig.7, and the most promising region for further investigation is seen to lie on the chamber axis just upstream of the secondary air dilution holes.

2.2. Sampling with Uncooled Probe

Having located the regions of low oxygen content, it was decided to make more thorough investigations using a probe more nearly resembling the type visualised for a permanent installation. A probe was designed for insertion through the side of the chamber, in a radial direction normal to the chamber axis in order to minimise the length exposed to the hot gases. As violent cooling of the sample might result in chilling the combustion reactions, and a higher oxygen content, the $\frac{1}{2}$ in. O/D stainless steel probe was uncooled, the gases being passed through a cooling coil before reaching the Orsat. The probe was marked with a scale at $\frac{1}{2}$ in. intervals to show the penetration into the chamber, and three sampling holes were drilled into the chamber at axial intervals of $2.1/4$ in. The sampling holes in both the air casing and flame

tube were blanked off when not in use.

The results obtained are shown in fig. 8 and the conclusions, which confirm those drawn from the previous water-cooled probe tests, are as follows.-

- (a) At constant air mass flow, the low-oxygen zone decreases in size with increase in air/fuel ratio. (figs. 8A and B).
- (b) At constant air/fuel ratio, the low-oxygen zone decreases with decrease in air mass flow. This follows as the reduced temperature level lowers the combustion efficiency. (figs. 8A and C).
- (c) The fuel burner pressure directly controls the width and length of the low oxygen zone, and appears to be the main governing factor. (figs. 8A and B).
- (d) The carbon monoxide concentration increases with increasing fuel pressure and decreasing air/fuel ratio, the maximum concentrations being located near the burner. As a check on the combustion danger of this carbon monoxide when in the fuel tank, fig. 9 was studied and replotted as fig. 9A. This indicates that the inflammable region requires gas concentrations which are unlikely to be encountered in samples taken from the test chamber.
- (e) The beneficial reduction in oxygen content obtained by not cooling the probe is negligible. Although the life of the uncooled probe was sufficient for the tests described, the metallurgical problems would be severe, and probe cooling is recommended in a practical installation.

2.3. Sampling in Combustion Chamber Dome Head

In view of the temperature difficulties anticipated in connection with a permanently installed gas pick-up in the chamber immediately forward of the secondary air holes, it was decided to investigate the possibility of obtaining suitable gas from the dome head of the chamber adjacent to the spray nozzle. It was realised, however, that considerable quantities of carbon monoxide and unburnt fuel might be picked up, and that the presence of the probe might adversely affect the fuel spray pattern. Fig. 10 shows a typical result which indicates that gases of 6 per cent maximum oxygen concentration could be obtained with a probe penetration of 1in, as against about 2½in. in the previous side-probe tests, at a temperature not exceeding 520°C, (see next section). However, the carbon monoxide concentration was in the region of 9 per cent and appreciable quantities of unburnt fuel were found to accumulate in the liquid trap included in the gas sampling system. This method of approach was therefore abandoned.

2.4. Temperature traverses in the Low Oxygen Zones

In order to evaluate the magnitude of the probe cooling problem, temperature traverses were made in the more promising zones of low oxygen content. As temperatures up to 1700°C were to be expected, a thermocouple of platinum/platinum 13 per cent rhodium was used, capable of satisfactory operation up to 1770°C. The thermocouple was mounted in a stainless steel tube of 5/32in. I/D and 1/4in. O/D, and was shielded from radiation effects. About 95 per cent of the dynamic temperature rise was expected to be indicated, but this effect was found to be very small in the present tests. Compensating leads were used to connect to a cold junction and a Negretti and Zambra Null Reading Potentiometer. The operating conditions used were similar to those in the sampling tests. Any errors in reading caused by evaporative cooling or catalysis were no doubt swamped by the difference between the test air inlet temperature of 40°C and the calculated engine temperature, at 38,000 ft., of 118°C. As an approximation, this difference could be added to the measured temperatures, so that the temperature peak, measured as 1475°C, would probably be 1553°C in practice.

The typical result in fig. 11 shows the temperature distribution patterns to bear a close resemblance to the oxygen distribution patterns, the maximum temperatures occurring in the low oxygen zones. It is also to be noted that the probe should be located as far downstream (i.e. as near the secondary holes) as possible. As the width of the high temperature zone increased with fuel pressure, and as the probe would have to penetrate to the chamber axis for sampling at low fuel pressure, the greater part of the probe length would be subjected to high temperature at high fuel pressures.

2.5. The Practical Fuel-Cooled Probe

As many heat-resisting materials suffer from thermal shock, it was decided to revert to liquid cooling for the practical probe, and to use as coolant the fuel destined for the chamber, rather than call for special water or air cooling systems. The design of the stainless steel probe is shown in fig. 12, and provision was made to measure the flow of the fuel and its temperature on entering and leaving the probe. The probe was located in the rear (downstream) of the three sampling positions provided, with the sampling orifice at the chamber axis. The temperature rise of the cooling fuel is as shown in fig. 13, and the flow was found experimentally to be suitably turbulent above a rate of about 1 ft.³/hour. This was considered to be preferable to laminar flow, where the formation of 'dead' zones might lead to hot spots. A light straw discolouration on the upstream outer surface of the probe showed that the skin temperature had not exceeded about 300°C.

No suction pump was available to simulate tank conditions at altitude, and the sampled gases discharged directly to atmosphere. By using the expressions for fluid flow given in ref. 10, a spot calculation was made for the flow of inert gases through the 5/32in. bore probe and gas delivery system serving a freely-vented tank in an aircraft operating at the standard 38,000 ft. full power condition. A pressure drop of 2 p.s.i. was assumed in the system, and the successive approximations to the gas velocity gave a gas delivery rate of about 7 ft.³/min. In a given system, the gas delivery rate will vary with the cross-sectional area of the probe and the pressure difference across the system. As the pressure in the combustion chamber falls at a greater rate than that in the fuel tank, the effect of increasing altitude is a reduction in the gas delivery rate. As the maximum purge requirement occurs at the maximum operating altitude, this becomes the most critical condition to be considered in the design.

2.6. Sampling with the Fuel-Cooled Probe

As a final practical check on the suitability of the design and location of the fuel-cooled probe, gas samples were taken and analysed using various probe penetrations. The results confirmed those obtained from previous sampling tests in the same zones, and showed maximum concentrations of 6 per cent oxygen and 3 per cent carbon monoxide to be easily obtainable. The optimum location of the sampling orifice was found to be within 1/4in. of the chamber axis. By violently cooling the sampled gases with liquid oxygen, the water and unburnt fuel were condensed and measured as 0.062 and 0.0057 lb. respectively per lb. of sampled gas. Removal of these fluids from the purge gas would be essential in practice. General conclusions regarding the method of primary zone sampling for the supply of inert purge gases are given at the end of the report, and notes on a proposed installation are included in Appendix B.

3. The Separate Inert Gas Producer

For large aircraft with large tank capacity, a separate combustor may be more suitable, and could be accommodated more easily than in a smaller aircraft. The advantages of such a scheme are the greater flexibility of operation, the closer control over the oxygen content, and the utilisation of the heat extracted from the inert gases for general heating purposes. In this latter connection, it is interesting to note that a current type of space heater consuming 4 gallons of fuel per hour would produce stoichiometric inert gases at the rate of about 100 ft.³/min.

If the main engine compressors are used for the air supply, the separate combustor will suffer from the same disad-

vantage as the probe system, in that the inert gas delivery will depend upon the engine operating conditions, and insufficient gas may be available in the dive with engine idling. The problem could be eased, at the expense of added complication, by fitting the combustor with its own compressor, which may be driven from the main engine through a variable-speed gearbox, or from the combustor itself.

The automatic control of air/fuel ratio within the combustor is best effected by sensing the output, rather than the input, conditions in order to eliminate any effects of increased oxygen content due to combustion inefficiency. Fig. 4 shows that an operating air/fuel ratio range from about 13/1 and 21/1 is permissible, although closer control may be desirable in practice. Various properties of the combustion products were examined in order to determine the most convenient property for the indication of air/fuel ratio and, through a suitable relay device, for the necessary control of fuel and/or air supplies (ref. 11).

3.1. Thermal Conductivity

The thermal conductivity values of the individual combustion products are of the same order, except that of carbon dioxide, which is lower, and of hydrogen, which is very much higher. By means of Salamon's formula, involving the partial volumes of the individual products, the mean thermal conductivity values can be found for the varying concentrations shown in fig. 4, and are plotted in fig. 14. This curve is for the exhaust products from a gasoline, but curves for other hydrocarbon fuels do not vary appreciably.

The form of the curve in fig. 14 shows that an air/fuel ratio indicator working on the thermal conductivity principle would reverse its reading on passing through the stoichiometric mixture, and that its sensitivity would be highest on the rich side. The Cambridge Mixture Indicator, as used in certain piston-engined aircraft, employs this principle, and a continuous measurement of thermal conductivity is made from the cooling effect on a heated wire contained in a Wheatstone bridge circuit. As indicated above, the use of the instrument is restricted to mixtures richer than stoichiometric, but a rich working range is permissible from the inert gas point of view. If the output signal of such an instrument can be made to operate a relay control device, it is clear that a method of automatically controlling the air/fuel ratio values of rich mixtures will be available.

In order to test the effectiveness of a thermal conductivity control system, a combustor of some type is necessary, arranged so that the exhaust gases can be continuously sampled, and the fuel input to a given air flow mechanically controlled. The most convenient choice of combustor was the Fedden single-cylinder spark-ignition sleeve-valve engine which, although

burning gasoline type fuels only, was already equipped with an exhaust sampling system and a fuel-injection pump controllable by a rack. The existing instrumentation included, in addition, means of accurately measuring air and fuel mass flows, and an Orsat exhaust gas analyser.

The electrical output of the Cambridge thermal conductivity instrument was first determined over the rich mixture range (fig. 15), the air/fuel ratio values being obtained from individual readings of air and fuel mass flow. Gas analysis results were found to bear out quite well the theoretical values shown in fig. 4. The presence of oxygen on the rich side of stoichiometric is usual in practice, due to dissociation and incomplete mixing, and is of importance in this connection.

The controlling system designed to operate on the output signal from the Cambridge instrument consisted of an adapted German electric-furnace temperature controller feeding to a 24 volt D.C. compound-wound miniature motor (fig. 16). The furnace controller had been designed to receive the output from a thermocouple, in order to switch on or off the furnace input power, and was unsuitable for aeronautical use, but it was readily available and lent itself to experimental purposes. The miniature motor was geared down in a 1500/1 ratio to give a linear speed range for the pump rack from 0.013 to 0.050 inches per minute. In general, the minimum speed was desirable in order to minimise hunting. The direction of rotation of the motor was determined by a twin gang relay, controlled by the output from the Cambridge instrument.

Results from a typical test run are shown in fig. 17 where it is seen that control has been effective to within ± 0.15 units of air/fuel ratio, and that equilibrium was again reached 3.5 minutes after making a manual adjustment of the controller from 11.23/1 to 10.63/1.

3.2. Combustion Temperature

When a fuel-air mixture is burnt in a chamber, the temperature resulting from the combustion is a function mainly of the heat released by the burning mixture, and the heat absorbed by the combustion products. With no losses through the chamber walls, these two quantities of heat are equal, and the temperature may be determined from the quantities of products produced and their individual values of specific heat. If combustion is considered as an irreversible process, the maximum temperature will occur at the stoichiometric mixture, where the absence of excess air or fuel gives a maximum heat release, and enables the heat to be absorbed by the minimum number of products to the maximum extent.

However, above a temperature level of about $2,000^{\circ}\text{C}$, the combustion process begins to reverse, and the products dissociate into carbon monoxide and hydrogen. Less released heat is thus available for heating the products, and the resulting combustion temperature is lower. Once the temperature drops below the $2,000^{\circ}\text{C}$ level, recombination of the dissociated products occurs, and the combustion may be subsequently completed. The maximum temperature attained during the complete process, however, will be less than that attainable had dissociation not occurred. The dissociation curve of combustion temperature versus air/fuel ratio thus lies below that obtained when ignoring dissociation and, because of differences in gradient of the latter, the peak of the dissociation curve is displaced towards the rich side of stoichiometric. Fig. 18 has been obtained from calculations for an air-benzene mixture burnt in the cylinder of a spark-ignition engine, and shows the effects of dissociation on the temperature-mixture curve.

It is evident from this figure that an appreciable temperature gradient exists on both sides of the peak, so that a sensitive method of mixture control appears possible. Use has been made of this temperature variation in piston engine work for the development of sparking plugs and for investigations into mixture distribution. In the Rabezzana and Kalmar method of test, one sparking plug in each cylinder has a thermocouple fitted into a drilling in the central electrode, in order to measure the electrode temperature at a point $1/8$ in. from the tip. On running the engine, the thermocouples indicate the mean temperature level in each cylinder, and these temperatures are sufficiently sensitive to the overall engine mixture setting for the determination of individual cylinder mixture strength, (ref. 12).

A sparking plug fitted with a chromel-alumel thermocouple was used in the Fedden single-cylinder engine, and the resulting temperature-mixture curve is shown in fig. 19. The temperature range of nearly 300°C infers a variation in thermocouple output of some 12 mV, which is sufficient to operate a controlling mechanism. This type of instrument would be more satisfactory for controlling on the weak side of stoichiometric where the temperature gradient is steeper, and where the conditions are sufficiently removed from the temperature peak to avoid reversed action.

The Cambridge instrument used in the control circuit previously described was replaced by the thermocouple sparking plug, and similar test runs were carried out. The test results given in fig. 20 show that control was maintained to within ± 0.3 units of air/fuel ratio during the test, the large number of motor reversals indicating the high degree of sensitivity.

3.3. Exhaust Gas Density

The curve of exhaust gas density, as in fig. 21 for a 100/130 grade aviation gasoline, shows a marked variation over the rich side of stoichiometric and very little change on the weak. Theoretically, therefore, exhaust density offers a means of air/fuel ratio measurement and control, in a similar manner to thermal conductivity. However, measurement of gas density is at present only possible by means of laboratory type instruments, insufficiently robust for airborne installation, and no further experimental work in this direction was undertaken.

3.4. Oxygen Paramagnetism

For purposes of tank purging, the most important constituent of the combustion products is oxygen, and it happens that oxygen is the only constituent exhibiting paramagnetism. The remaining constituents are diamagnetic, i.e. magnetic flux passes more easily through a vacuum than through these gaseous constituents. Fig. 22 shows the overall magnetic properties of the exhaust gases from 100/130 grade aviation gasoline, indicating a large gradient over the weak range. From the purging aspect, therefore, a control system operating on the paramagnetic principle would appear to be ideal, and experimental work was initiated on two oxygen-sensing devices, employing this principle in different ways. Although neither instrument was fully successful, a brief description is given of the lines of approach.

In the first, magnetic, method, a constant magnetic field was arranged so that the oxygen attracted to it would pass over a heated spiral in a Wheatstone bridge circuit, the cooling effect giving a measure of the oxygen flow. The instrument embodied a circulatory passage for the gases, and thus differed from that described in ref. 13. The instrument was calibrated using known mixtures of nitrogen and oxygen. Apart from the instability caused through heating effects of the electro-magnet used, the response was found to be linear only down to 30 per cent oxygen, beyond which great inaccuracy arose. As oxygen contents no higher than about 6 per cent are required, this type of instrument was abandoned.

In the second, magnetic-capacitive, method, a magnetic circuit was constructed incorporating two gas gaps. The exhaust gases flowed through the first gap, the amount of magnetic flux passing across the gap depending upon the oxygen content, and controlling the attraction exerted across the poles of the second, air, gap. This second gap was designed in the form of a vane-type capacitor fitted on the end of a cantilever within the magnetic circuit. The measurement of capacitance change in the air gap should thus provide a measure of the oxygen content of the exhaust gases. Due mainly to constant 'drift' of the instrument,

and to the excessive amplification necessary with an instrument of this type, this aspect of the investigations was also abandoned.

4. Conclusions

The general conclusions that can be drawn from the considerations of inert gas supply, and of tank requirements, are as follows.-

4.1. Primary Zone Sampling

(a) Inert gases containing a maximum of 6 per cent oxygen by volume are obtainable from a fixed point within the primary zone of a Derwent I combustion chamber over a wide range of operating conditions.

(b) For the temperatures and mass flows existing in the Derwent I chamber, the probe could be suitably cooled by means of the fuel subsequently burnt in the chamber.

(c) The sampled gases need to be cooled before introduction into the tanks, and the condensed water and unburnt fuel to be removed. The gas cooling could be effected by means of the fuel destined for one of the other combustion chambers.

(d) For the rates of climb and descent considered, the required purge gas flow rates are of the same order, and the curves of variation with altitude are of similar form. The occurrence of the maximum requirement at altitude, where the minimum delivery is available, confirms that the system should be designed for both climbing and descending at the maximum operational altitude. In fact, the most critical condition will be the dive at high altitude with the engine idling, when the purge requirement is high and the gas delivery at its minimum.

4.2. Separate Inert Gas Producer

(a) Automatic control to within ± 0.3 units of air/fuel ratio is obtainable over the rich range by means of a thermal conductivity type of control gear.

(b) Automatic control to similar accuracy is obtainable over the weak range by means of a combustion temperature type of control gear. This method is probably more promising, although high temperature problems may be incurred in the design of a suitable thermocouple.

- (c) Both the above methods are independent of exhaust gas pressure, temperature and mass flow.
- (d) The use of exhaust gas density, or of oxygen volume content, is not recommended, for the reasons stated in the text.

Conclusion

The general conclusion that can be drawn from the comparison of these two methods, and of their requirements, are as follows:

4.1. Exhaust Gas Sampling

(a) The gas samples containing a mixture of 5 per cent oxygen by volume are obtainable from a fixed point within the exhaust gas of a turbine engine over a wide range of operating conditions.

(b) For the temperature and mass flow existing in the turbine engine, the probe could be suitably cooled by means of the fuel immediately burnt in the chamber.

(c) The required gases need to be cooled before introduction into the water, and the condensed water and exhaust fuel to be removed. The gas cooling could be effected by means of the fuel distilled for use of the other combustion chamber.

(d) For the range of air and exhaust densities, the required purge gas flow rates are of the order, and the curves of variation with altitude are of similar form. The occurrence of the maximum requirement at altitude, where the minimum delivery is available, suggests that the system should be designed for both altitude and decreasing as the turbine engine altitude. In fact, the most critical condition will be the flow at high altitude with the engine idling, when the purge requirement is high and the gas delivery at its minimum.

4.2. Turbine Fuel Gas Pressure

(a) Turbine control is obtainable to within ± 0.5 units of dynamic ratio is obtainable over the whole range by means of a thermal control valve type of control gear.

(b) Turbine control is obtainable to within ± 0.5 units of dynamic ratio over the whole range by means of a combustion temperature type of control gear. This method is probably more promising, although high temperature problems may be involved in the design of a suitable thermocouple.

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Trans. A.S.M.E., Vol. 70, 1948, pp.211-6.

APPENDIX A

Calculation of Purge Gas Flow Requirements

1. CLIMB

From reference 8,

$$X = 129 R k \left(\frac{5.258}{44,307-H} \right), \text{ when } H < 11,000 \text{ metres, and}$$

$$X = 129 R k \frac{(1.578)}{10^4}, \text{ when } H > 11,000 \text{ metres, where}$$

X = rate of air release in ft³/min. from 100/Imp. gallons at 60°F and at the pressure appropriate to the altitude H in metres.

R = rate of climb (= 5000 ft./min. = 1524 metres/min. in this case)

k = solubility coefficient } = vol. percentage gas dissolved in liquid/gas partial pressure, = 0.018 per cent/n.m. Hg. for kerosine.

Purging with Nitrogen

Total oxygen content of released air and purging gas

$$= 0.121 = \frac{0.326 X}{X + \text{purge volume}}$$

Thus, $\frac{\text{Purge volume}}{X} = \frac{0.205}{0.121} = \underline{1.7}$

i.e. 1 volume of released air is required to be diluted with 1.7 volumes of nitrogen.

Purging with combustion products

$$\text{Total oxygen content} = 0.121 = \frac{0.326 X + 0.06(\text{Purge volume})}{X + \text{Purge volume}}$$

Thus, $\frac{\text{Purge volume}}{X} = \frac{0.205}{0.061} = \underline{3.36}$

For improved safety, the oxygen content may be purged to 10 per cent, then

$$\frac{\text{Purge volume}}{X} = \frac{0.226}{0.040} = \underline{5.65}$$

2. DESCENT

Purging with nitrogen

$$\begin{aligned} &\text{Total oxygen content of added gases} \\ &= 0.121 = \frac{0.21 (\text{inhaled air volume})}{\text{volume change of original air}} \end{aligned}$$

But inhaled air volume = volume change of original air - purge gas volume

Thus, Purge gas volume = $\underline{0.0679 (\text{Vol. change of original air}), ft}^3$.

Purging with combustion products

$$\begin{aligned} &\text{Total oxygen content of added gases} \\ &= \frac{0.21 (\text{inhaled air vol.}) + 0.06 (\text{purge gas vol.})}{\text{Volume change of original air}} \end{aligned}$$

Thus, Purge gas volume = $\underline{0.095 (\text{Vol. change of original air}), ft}^3$.

For 10 per cent oxygen,

Purge gas volume = $\underline{0.118 (\text{Vol. change of original air}), ft}^3$.

APPENDIX B

Notes on a Proposed chamber probe Installation

A schematic layout of a complete purging system is shown in fig. 23, and notes on the individual components are given below.

1. Fuel-cooled probe, and gas cooler

Results have shown sufficient heat capacity to be available in the fuel destined for one chamber to cool the probe, and in a further, equal, quantity of fuel to cool the sampled gas to 200°C. The probe and cooler should therefore form a single unit incorporating the two separate fuel flows. The temperature of the cooling fuel may be low at altitude, and the gas cooler should thus be of the parallel, rather than the contraflow, type in order to avoid condensation and freezing in the outlet gas. The high pressure difference existing between the fuel and gas passages suggests a tube design for adequate strength. Calculations show that a 3/8in. I/D gas tube would require a developed length of about 11 ft. to bring the gas temperature down to 200°C.

2. On-off Cock

This has been introduced so that the purging system may be turned off if, at idling speed, the purge gas becomes insufficiently inert, or the fuel flow unable to cool the probe. The cock could be controlled by either a direct interlink with the throttle, or a servo system operated by fuel pressure.

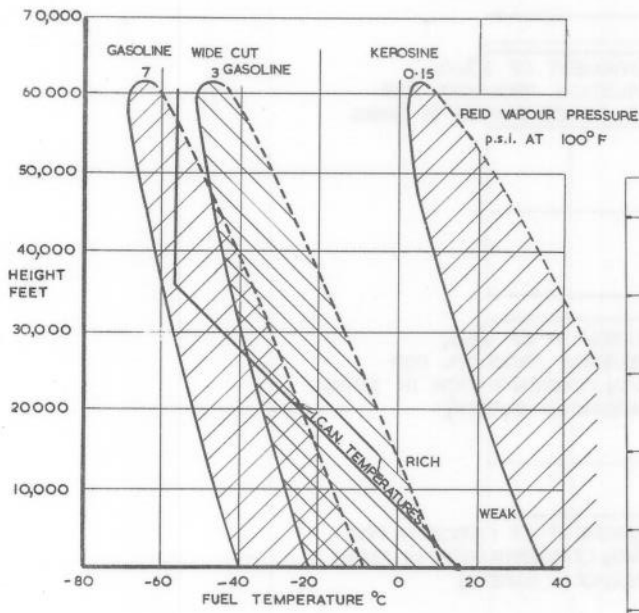
3. Condenser

In order to prevent the accumulation of condensed water in the fuel tanks, the condenser temperature must be at least as low as that in the tanks. This suggests as cooling medium the fuel feeding from the tanks to the engine. The condenser must be able to dispose of the condensate, or to retain it without impeding the gas flow. The condenser should be suitably located in relation to the engine heat to prevent the formation of ice. Lagging and/or filtration may also be necessary.

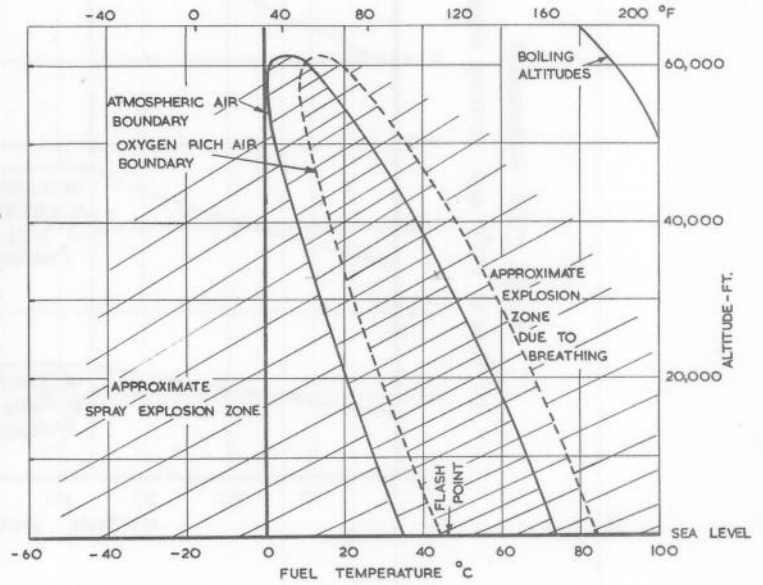
4. Control Valve, and Fuel Tank Vents

Many alternative valve and vent arrangements are possible, but a valve of some type is essential to control the flow rate of the purge gas, to prevent return flow, and to maintain the required degree of pressurisation within the tanks. Any reduction in gas pressure effected by this valve will also assist in drying the flow of purge gas. In addition, the valve may be specially designed to permit maximum purging of the oxygen-rich air during the climb, and, in a sustained flight at constant altitude, to maintain the

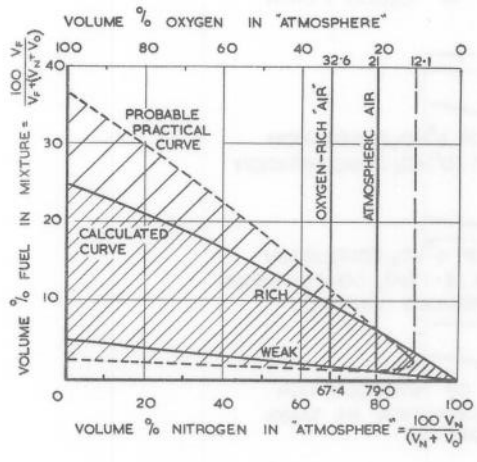
tank pressure with purge gas at a slightly lower pressure level than the setting of the tank vent. This would obviate the otherwise continuous purge flow, which is unnecessary at constant altitude. The tank vents, which would probably be of conventional design, should be located as far as possible from the purge gas inlet to obtain a maximum purging effect throughout the tank free space.



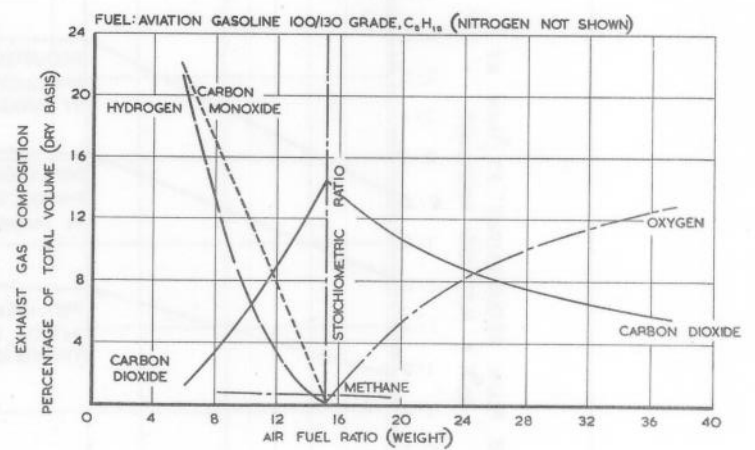
ALTITUDE TEMPERATURE BOUNDARIES
FIG. 1



ADDITIONAL DANGER ZONES FOR KEROSENE
FIG. 2



MINIMUM OXYGEN COMBUSTION LIMIT FOR
GASOLINE
FIG. 3



THEORETICAL EXHAUST GAS CURVES FOR
100/130 AVIATION GASOLINE
FIG. 4

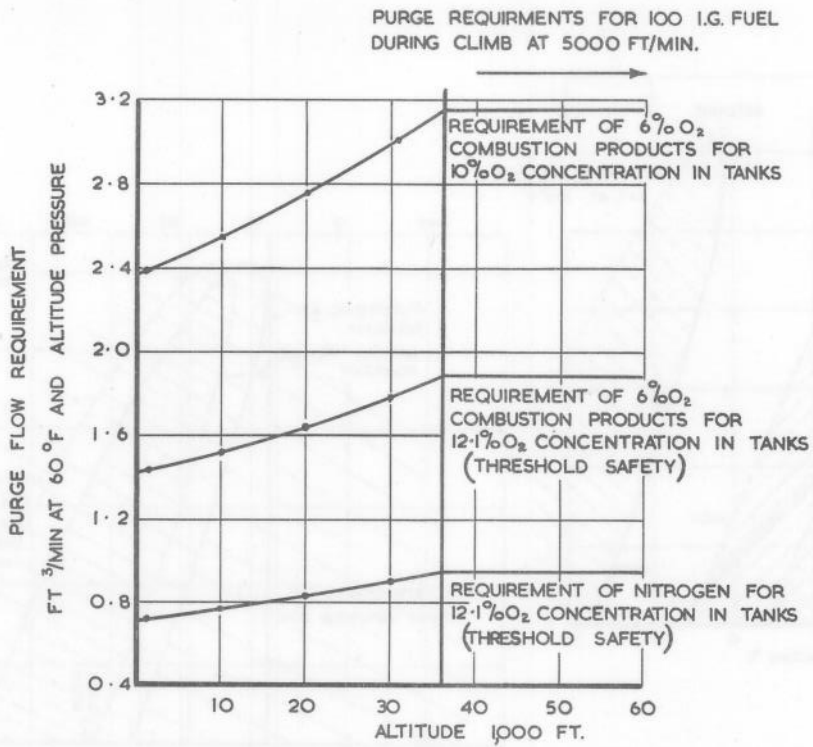
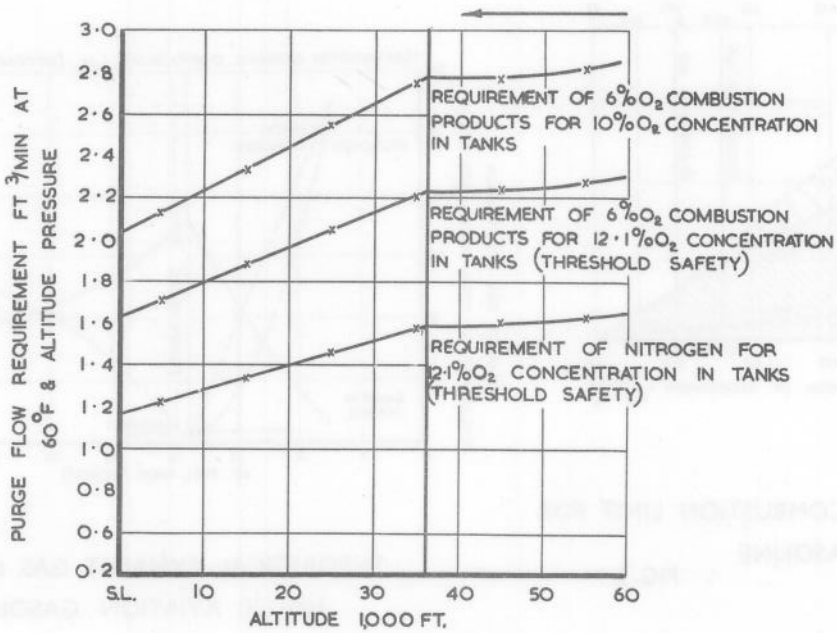


FIG 5a.

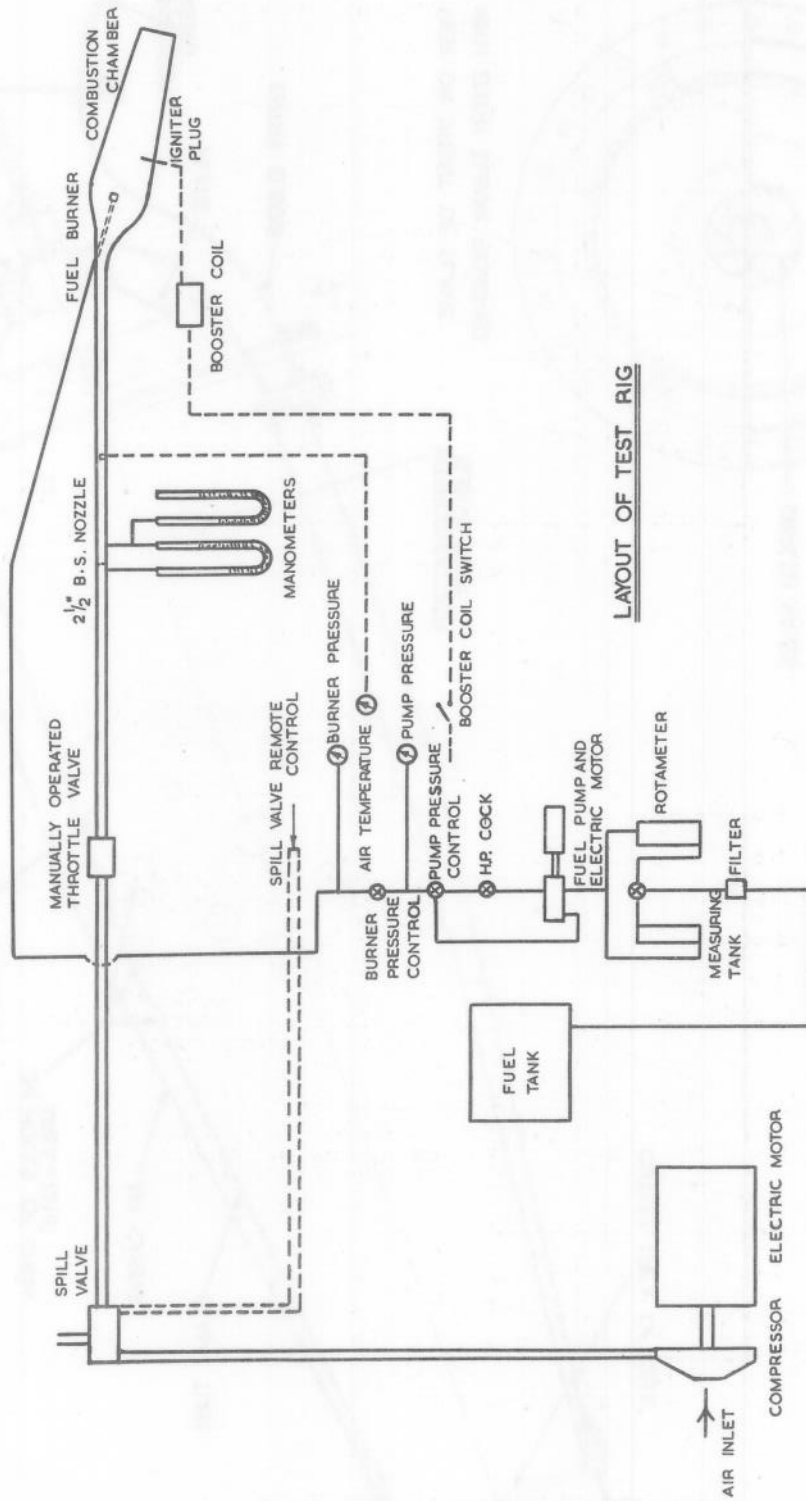
PURGE REQUIREMENTS FOR 100 IG FREE SPACE
DURING DESCENT AT 10,000 FT/MIN

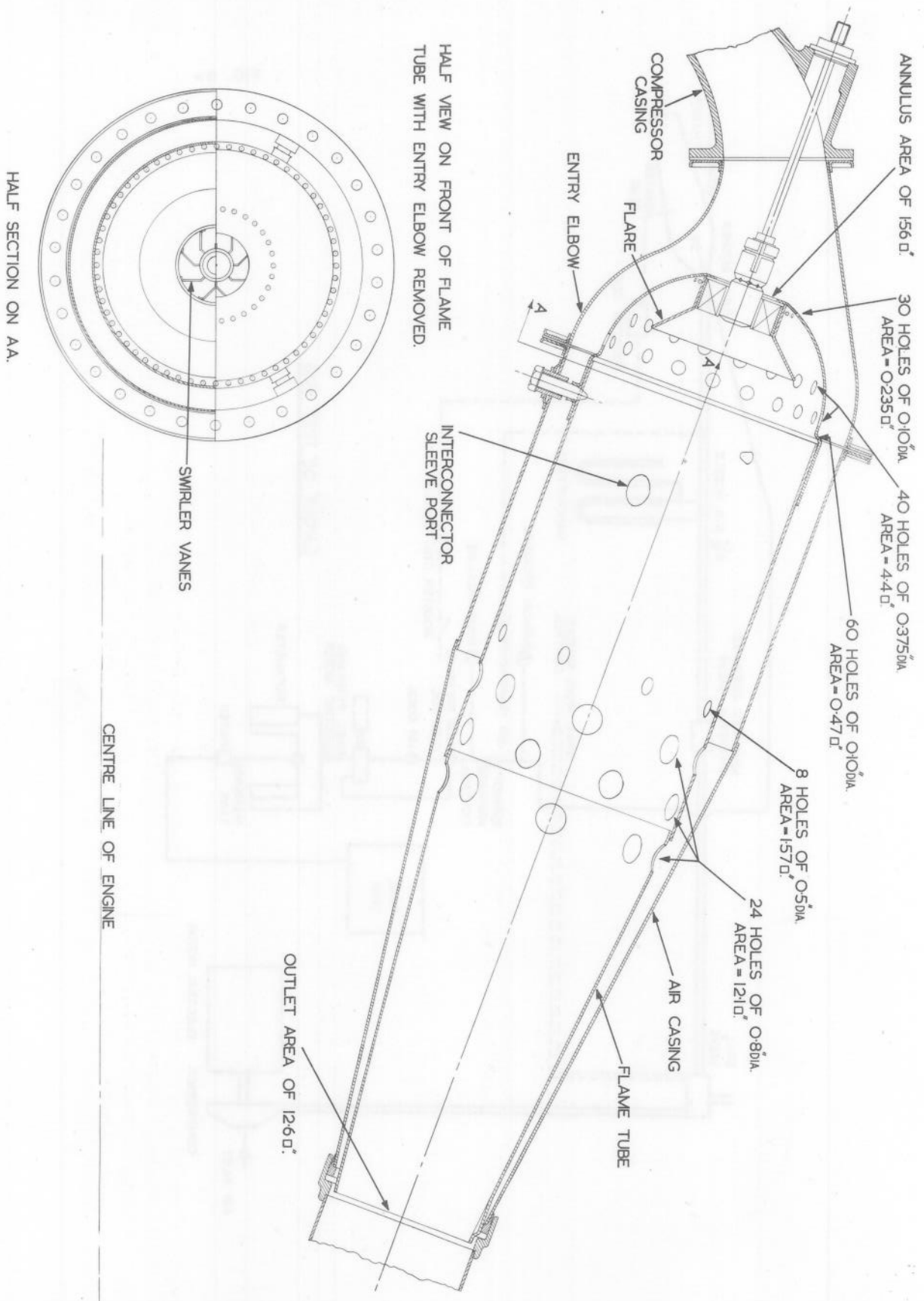


FLOW REQUIREMENTS OF PURGE GAS

FIG 5b.

FIG. 6a

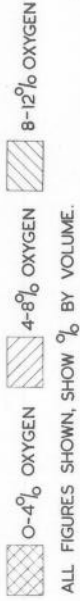




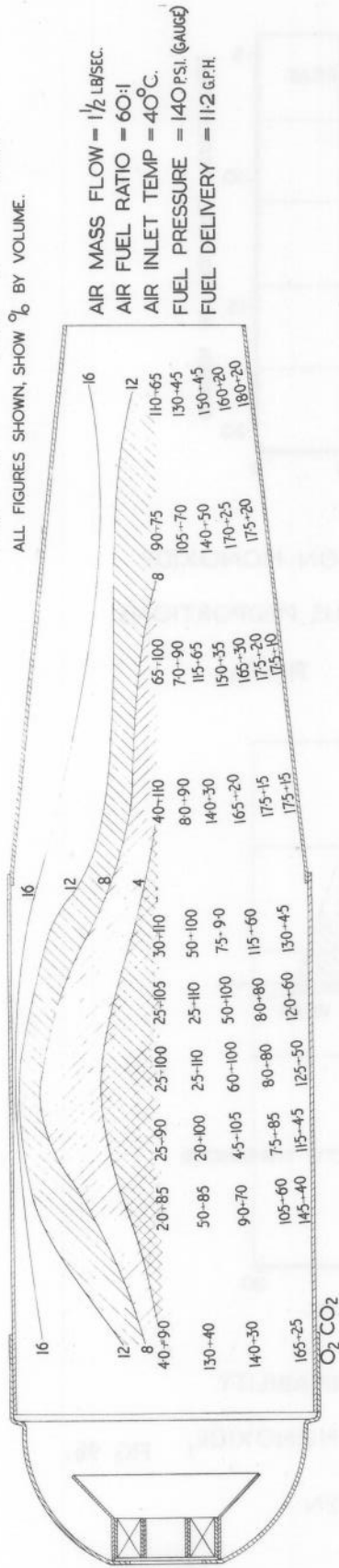
LAYOUT OF TEST RIG

FIG. 6.a

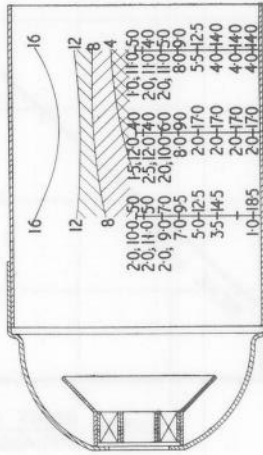
LEGEND



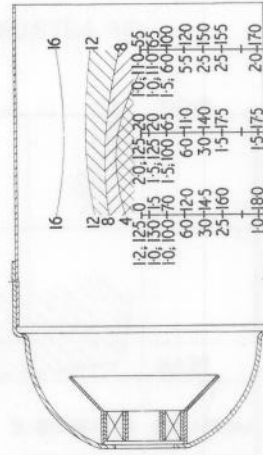
ALL FIGURES SHOWN, SHOW % BY VOLUME.



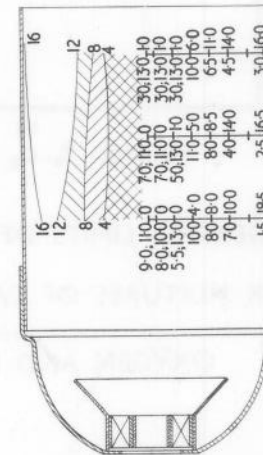
EXPLORATORY TEST RESULTS WITH WATER COOLED PROBE FIG. 7.



AIR MASS FLOW = 1 1/2 LB/SEC.
AIR FUEL RATIO = 60:1
AIR INLET TEMP = 40°C.
FUEL PRESSURE = 140 PSI. (GAUGE)
FUEL DELIVERY = 11:2 G.P.H.

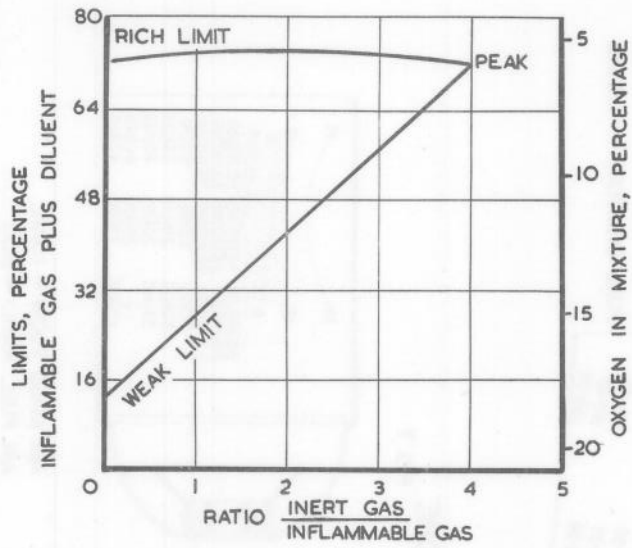


AIR MASS FLOW = 1 1/2 LB/SEC.
AIR FUEL RATIO = 90:1
AIR INLET TEMP = 40°C.
FUEL PRESSURE = 60 PSI. (GAUGE)
FUEL DELIVERY = 7.5 G.P.H.

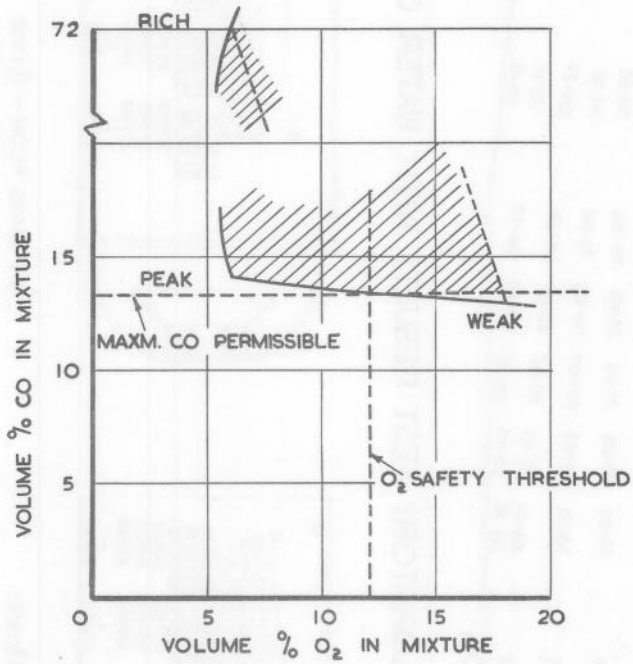


AIR MASS FLOW = 1 LB/SEC.
AIR FUEL RATIO = 60:1
AIR INLET TEMP = 40°C.
FUEL PRESSURE = 60 PSI. (GAUGE)
FUEL DELIVERY = 75 G.P.H.

TEST RESULTS WITH UNCOOLED PROBE FIG. 8.



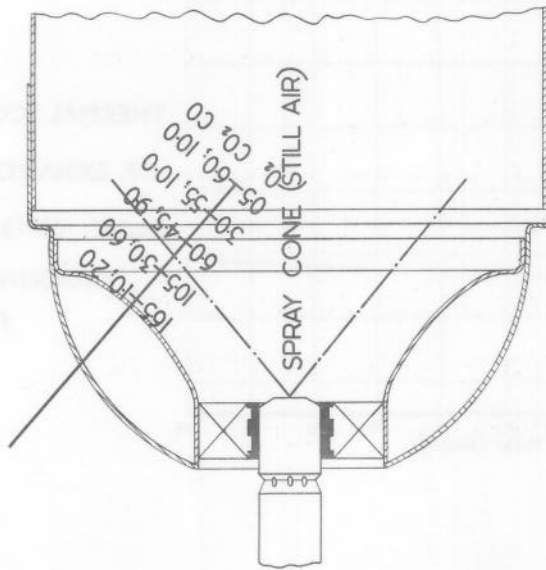
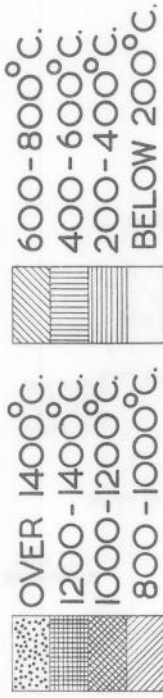
LIMITS OF INFLAMMABILITY OF CARBON MONOXIDE
WITH AIR WHEN MIXED WITH VARIOUS PROPORTIONS
OF NITROGEN FIG 9a.



DERIVED LIMITS OF INFLAMMABILITY
FOR MIXTURES OF CARBON MONOXIDE, FIG 9b.
OXYGEN AND NITROGEN

ALL FIGURES SHOWN, SHOW % BY VOLUME.

LEGEND



AIR MASS FLOW - 1 LB/SEC.
 AIR FUEL RATIO - 60:1.
 AIR INLET TEMP - 40°C.

DOME HEAD TEST RESULTS
 WITH UNCOOLED PROBE

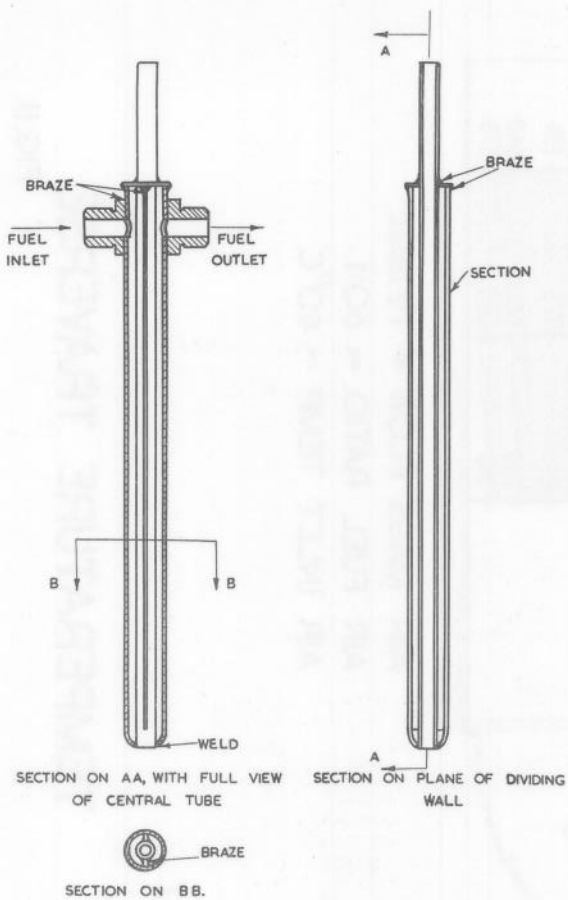
FIG. 10.



AIR MASS FLOW = 1/2 LB/SEC.
 AIR FUEL RATIO = 60:1.
 AIR INLET TEMP = 40°C.

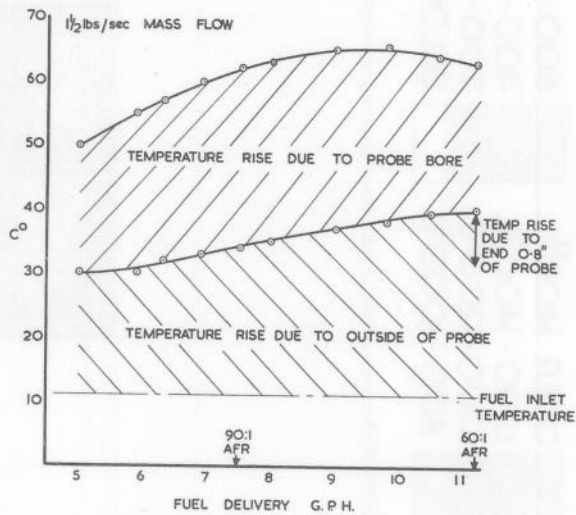
TEMPERATURE TRAVERSE

FIG. 11.



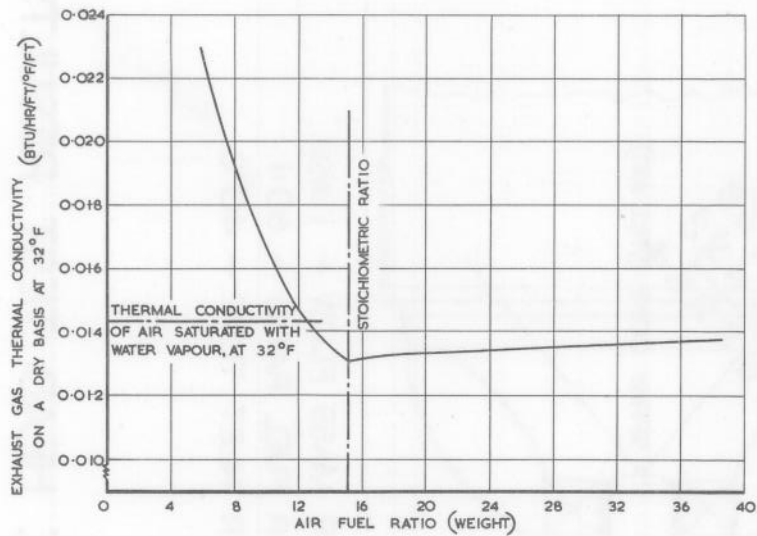
DESIGN OF FUEL-COOLED PROBE

FIG. 12



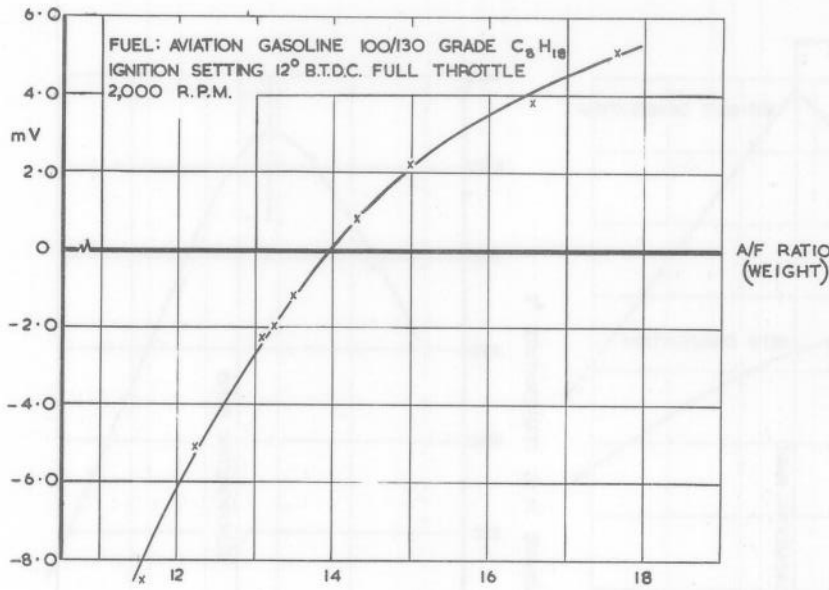
TEMPERATURE RISE OF COOLING FUEL

FIG. 13



THERMAL CONDUCTIVITY OF EXHAUST GASES FROM 100/130 AVIATION GASOLINE

FIG. 14

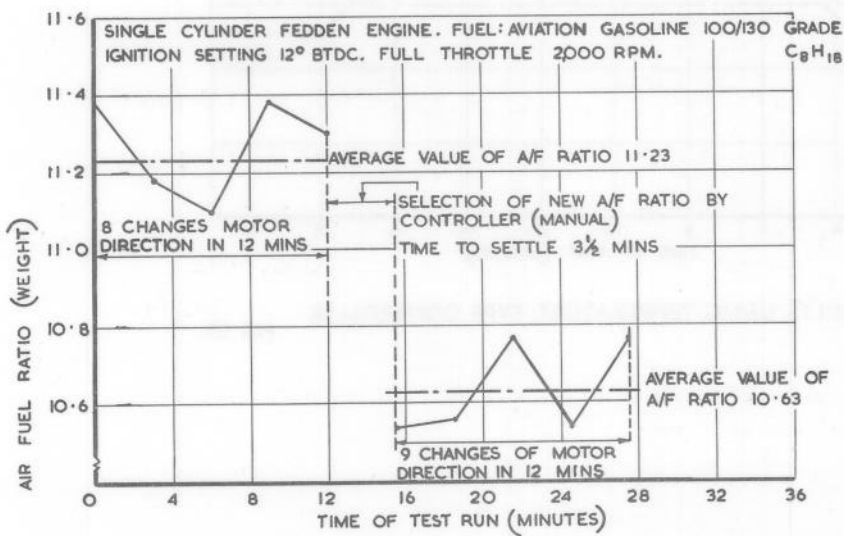
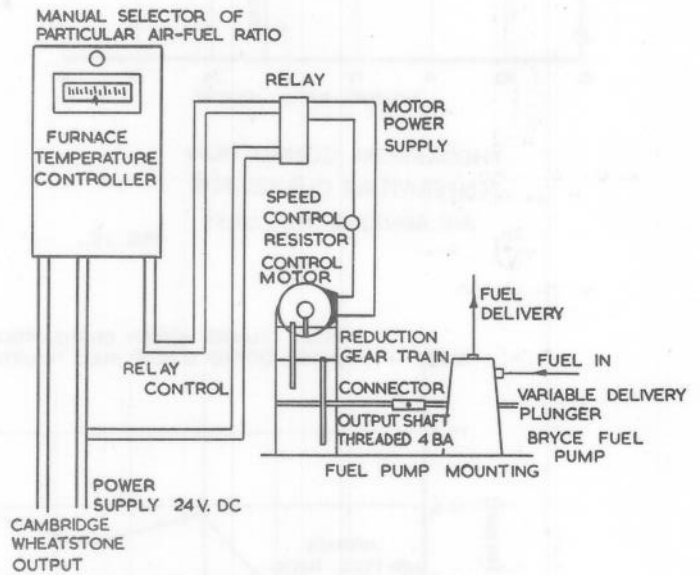


BRIDGE CHARACTERISTICS OF
CAMBRIDGE INSTRUMENT

FIG 15.

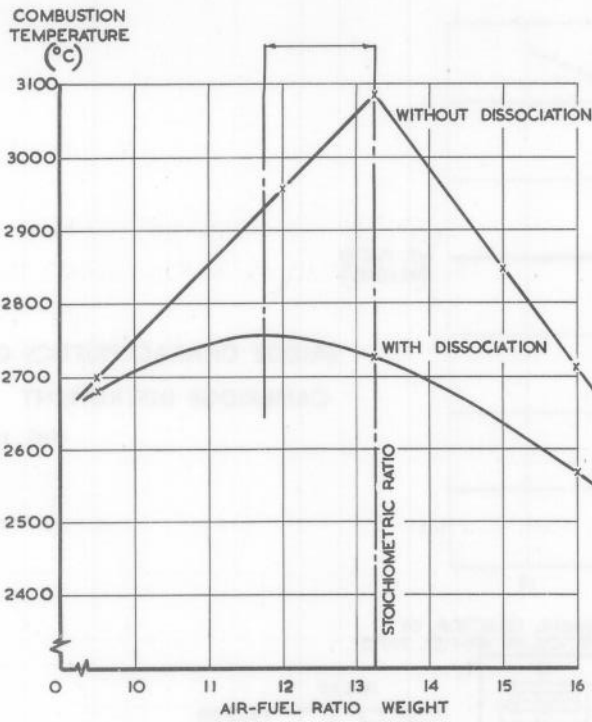
LAYOUT OF THERMAL CONDUCTIVITY
TYPE CONTROLLER

FIG 16.



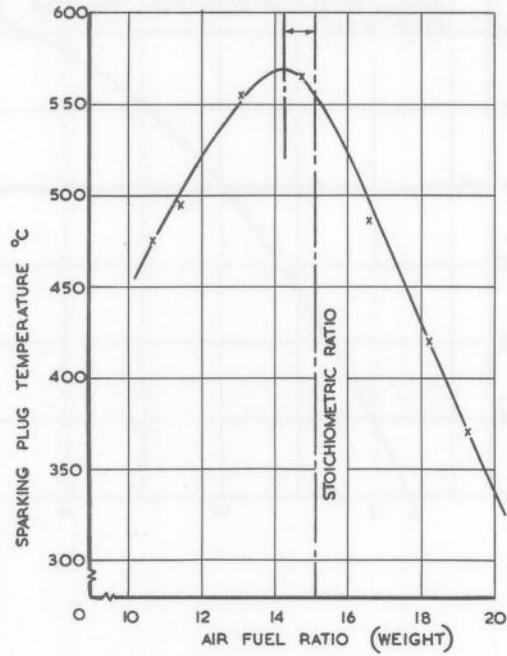
TEST RESULTS USING
THERMAL CONDUCTIVITY
TYPE CONTROLLER

FIG 17.



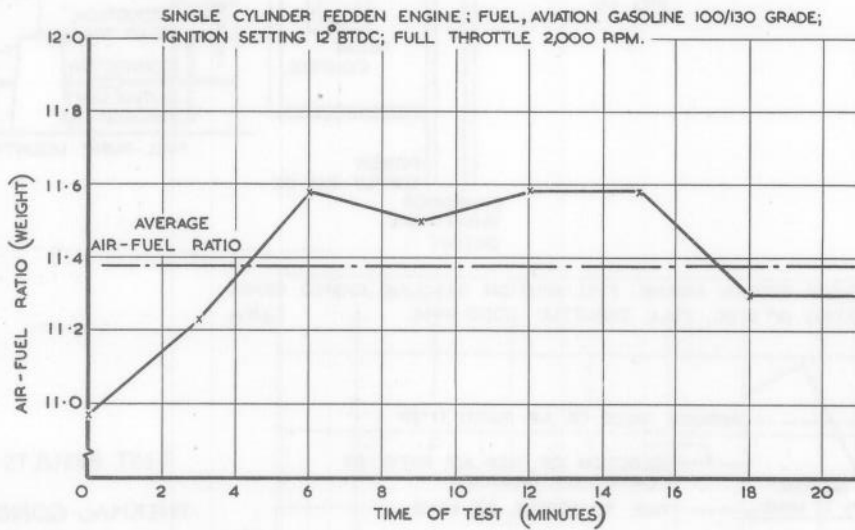
THEORETICAL COMBUSTION TEMPERATURE CURVES FOR AIR BENZENE MIXTURES

FIG 18.



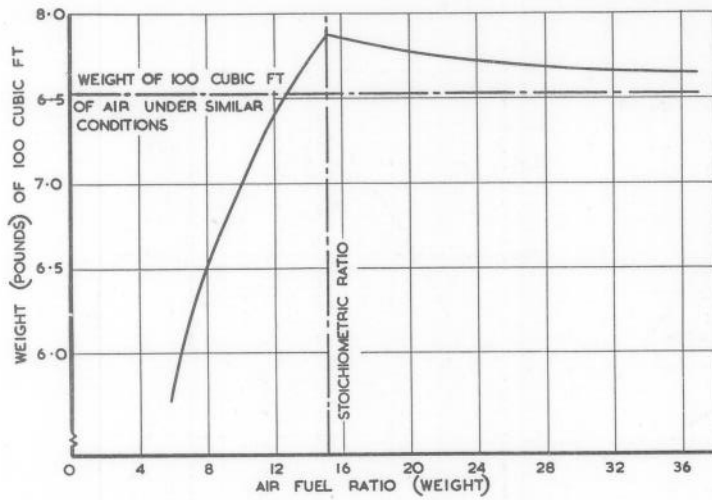
EXPERIMENTAL TEMPERATURE-MIXTURE CURVES FOR 100/130 GASOLINE IN FEDDEN ENGINE

FIG 19.



TEST RESULTS USING TEMPERATURE TYPE CONTROLLER

FIG 20.

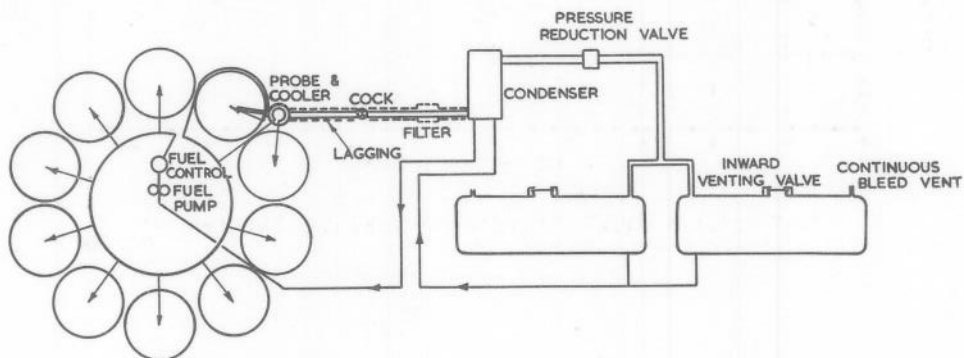
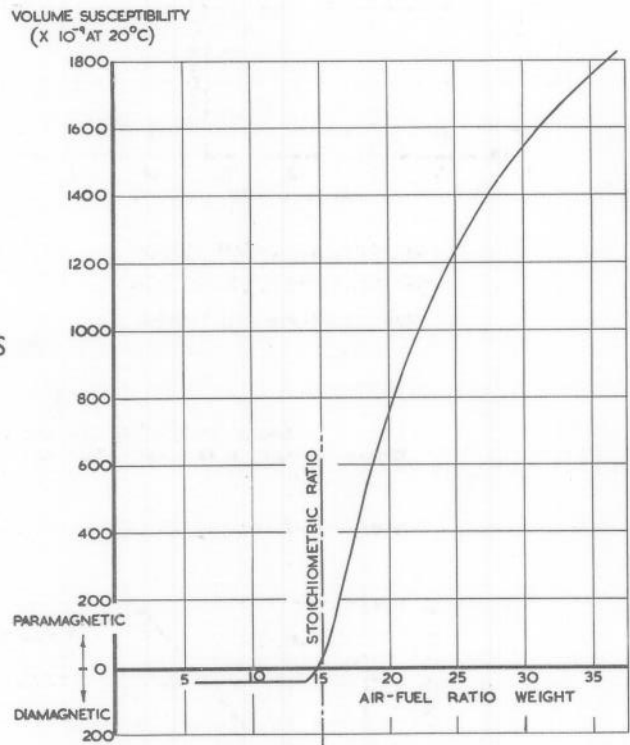


DENSITY OF EXHAUST GASES FROM 100/130 AVIATION GASOLINE

FIG. 21

MAGNETIC PROPERTIES OF EXHAUST GASES FROM 100/130 AVIATION GASOLINE

FIG. 22



SCHEMATIC LAYOUT OF CHAMBER PROBE PURGING SYSTEM

FIG. 23