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Objective:

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

CONTROL OF FIRES IN LARGE SPACES WITH INERT GAS
AND FOAM PRODUCED BY A TURBO-JET ENGINE

PART 1 - INTRODUCTION AND PROPERTIES OF INERT GAS AND FOAM

by

D. J. Rasbash

Summary

This note outlines the background of the development of the jet
engine inert gas and foam generator and describes some of the physical
properties of the inert gas and foam that may be produced in this way.

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Introduction

From time to time fires occur which are very difficult to fight because
of the presence of dense smoke. During the years 1944 - 1950 a special
study of such fires was made including an examination of the methods used at that
time for clearing smoke. This included the use of artificial ventilation [1],
the use of water sprays for washing down smoke [2], and devices for location of
objects and sources of heat through smoke [3] [4]. However, none of the
above methods offered a satisfactory solution to the problem, although each of
them could be a palliative under certain conditions [5]. The objection to
artificial ventilation was that, in conditions under which the smoke was
likely to be a major problem, a far greater capacity for moving air was
necessary than was available at that time. Thus, it was estimated that for
a fire, which occurred in Covent Garden in December, 1949, an air moving
capacity of the order of 1,000,000 cu. ft/min was required if artificial
ventilation were to have any useful effect [1]. The effect of air is to
increase the rate of burning, and although the burning might become more
efficient there is no decrease in the total amount of smoke produced.

The use of an inert gas would suppress the burning rate and diminish
the amount of material that entered the atmosphere as smoke. However, at
that time (1944-1950) there was no known method of producing inert gas
which would fill a building in a reasonably short time.

In 1954 [6] it was suggested that quantities of inert gas of the right
order of magnitude of 10,000 to 100,000 ft³/min could be obtained by the use
of a jet engine and with this flow rate of inert gas it should be possible
to use this medium to control difficult smoky fires. Inert gas may be
obtained by vaporising the appropriate amount of water into the exhaust of
the engine. This would give a transparent gas of a sufficiently low
oxygen content to prevent normal flaming combustion. It was not possible
to examine the proposal in detail at that time, but a detailed examination
of the proposal and an inquiry into the possible usefulness of the appliance
was made in 1957 with the helpful co-operation of the National Gas Turbine
Establishment [7]. This examination showed that certain practical problems,
which would accompany the building and operation of the appliance, were
likely to be surmountable. Moreover, the range of types of fire in which
such an appliance might find use was wider than just those fires which had
given difficulties in the past due to dense smoke, and which had prompted
the enquiry in the first place. Thus in reports of 100 fires occurring
in 1954 in which the loss was greater than £10,000, thirty-six contained
sufficient information to allow an assessment of the usefulness of the
appliance. It was estimated that in 26 of these the use of the inert gas
generator would have significantly reduced the fire losses. For these
reasons it was decided to request the National Gas Turbine Establishment
to build a prototype unit producing 50,000 cu. ft/min. of inert gas which
could be used for experimental purposes; and the appliance was delivered
to the Joint Fire Research Organization in April, 1960, and is shown in
Plate I. In the meantime (1956) a new method of controlling mine fires
was developed at the Safety in Mines Research Establishment. In this
method the ventilated air in the mine was converted into a high expansion
foam, by interaction with an appropriate amount of a detergent solution.
It was clear that the gas produced by a jet engine could also be made to
produce high expansion foam in a similar way. This could be used as an

alternative or supplementary method to inert gas in extinguishing fires. A re-examination of the incidents mentioned above indicated that in 32 of the 36 cases the use of combined inert gas-foam generator would have reduced the fire losses. A further examination of 22 fires occurring in 1959-60 in which more than five pumps were used, 14 contained sufficient information to allow an assessment of the appliance and in 13 of these an inert gas-foam generator would have been of assistance. A provisional patent was taken out in 1957[8] covering the use of a jet engine to help fight fires in a number of ways including the production of inert gas, of high expansion foam and a current of entrained air.

In this note some of the basic properties of the gas and foam that may be produced by an applaince of this nature are outlined. Experiments with the actual appliance produced by the National Gas Turbine Establishment will be described in later notes.

Inert gas

Rate of production and composition of the gas

The basis of the method by which the inert gas is produced is shown diagrammatically in Fig. 1. The jet engine is used to burn a substantial part of the oxygen present in the air used and the hot combustion gases are subsequently cooled by vaporising water introduced as a fine spray. The rate at which air passes through the engine is controlled by the speed of the turbine, which in itself is controlled by the fuel feed to the engine itself. As long as the speed of the turbine is above a certain limit a substantial quantity of additional fuel can be burned in the reheat or after burner section downstream of the turbine, and thus varying this quantity of fuel, the ratio of the total mass of fuel burnt in the appliance and the mass of air passing into the engine may be controlled. This allows a degree of control in the composition of the final gas obtained after cooling the hot combustion products with the appropriate amount of water. Figure 2 shows the composition of the inert gas produced as a function of the fuel-air ratio, and in Fig. 3 the density of the gas and the volume of inert gas produced per unit mass of air entering the engine is also shown as a function of this ratio. The data in Figs. 2 and 3 are based on the assumptions that the fuel is completely burned, that the cooling water is introduced initially at 15°C and that the water cools the exhaust gases of the engine to 120°C and is vaporised completely in this process. The appliance which was developed at the National Gas Turbine Establishment can burn up to a total of 0.83 lb of fuel/s with an air input of 25 lb/s. The fuel-air ratio is therefore 0.033. Theoretically according to Fig. 2 the composition of the most inert gas obtainable with this airinput would be 47.5 per cent water vapour, 42.5 per cent N_2, 6 per cent O_2, 4 per cent CO_2. Actually mainly because combustion is not complete, but also because of heat losses this inert gas approximates to the composition corresponding to a fuel/air ratio of 0.030. It is, of course, practicable to produce an appliance operating with a greater fuel/air ratio and giving a gas with less oxygen.

Extinguishing properties of the gas

The most important property of the inert gas that controls the extinction efficiency (of flaming and smouldering combustion) is the oxygen concentration. Figure 2 shows that as the ratio of fuel to air is increased from 0 to 0.067, the concentration of oxygen in the inert gas is reduced from 21 per cent to zero. In addition, the temperature of the gas, and the proportion of carbon dioxide and water vapour, will also have some effect on the inerting properties of the gas. The extinction of a hydrocarbon or similar flame would be expected to occur if the combustion zone were cooled to the temperature which it would have at the lower flammable limit. A temperature of 1,590°K may be taken as appropriate for this purpose, and has been used by Mullins to assess whether gases containing water vapour can allow propagation of a flame [9]. If the oxygen concentration is higher and the gas were mixed with the stoichimetric quantity of fuel vapour, then on ignition this would produce an adiabatic flame temperature in excess of 1,590 K, and on the above criterion, flame might be expected to propagate. On this basis it may

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be shown that an inert gas from the appliance containing $12\frac{1}{2}$ per cent of oxygen will be the limiting gas for suppressing flaming combustion. The adoption of this criterion for extinguishing flaming combustion is likely to give rise to a substantial margin of safety, since available information indicates that except under unfavourable conditions diffusion flames are extinguished at a higher oxygen concentration than pre-mixed flames and limiting flame temperatures are likely to be substantially higher than $1,590^{\circ}$K for most of the flammable vapours and gases likely to be encountered [10]. Using a limiting temperature of $1,590^{\circ}$K, it is possible to calculate the amount of air with which the inert gas may be mixed, yet still be capable of inerting flaming combustion. This is shown in Fig. 4 as a function of the fuel-air ratio used in the appliance to produce the inert gas. The curve rises from zero at a fuel-air ratio of 0.014 to 1.0 at a ratio of 0.046. In the appliance used at the Fire Research Station, the fuel air ratio may be varied up to 0.033. There is thus a substantial margin for dilution of the gas produced with air, when the appliance is running at its maximum fuel-air ratio.

The extinction of smouldering combustion depends to a marked degree on the thickness of the smouldering layer as well as on the nature of the smouldering material. Experiments carried out by Bowes [11] have shown that smouldering would be suppressed in a layer of cork of less than 8 cm thickness if the concentration of oxygen in an oxygen-nitrogen mixture is less than 9%. For mixed hardwood sawdust, the corresponding figure is about 12%. At greater depths smouldering might continue with lower concentration of oxygen. Extinction of a smouldering fire may also take a long time, even if the oxygen concentration is low enough, since the exothermic reaction may need to be suppressed throughout a large depth of material and time will be needed for the inert gas to diffuse into the material. Once extinction has been accomplished, the mass of material will then begin to cool to the temperature of the inert gas. Even if the smouldering has been extinguished it is possible for re-ignition to occur fairly rapidly after air is readmitted if the smouldering material has not been cooled sufficiently. Thus, if it is assumed that the temperature during smouldering is 500°C and that this temperature needs to be reduced to 250°C to avoid the risk of rapid re-ignition on re-admittance of air then a cooling time of about 10 to 20 hours would be required for a sphere of smouldering material 1 ft in diameter. If the exothermic reaction has not been completely suppressed, then this time would be longer. It follows that an appliance that produces a gas containing about 7% oxygen might be expected to produce extinction of smouldering in layers of depths of 10 to 15 cm. However, very little dilution with air could be allowed and continuous application for a day or so would be necessary to be reasonably sure that rapid re-ignition would not occur on re-admittance of air. For preference it would be more desirable to work with a gas containing less oxygen.

Transparency of the gas

The gas as it is produced by the inert gas generator is transparent, but because of its high water vapour content it can become opaque on being mixed with air or on being cooled. The conditions under which this can occur, is shown in Fig. 5. The curved line is the saturation curve for water vapour and the alteration of the condition of the gas from that on the right to that on the left of the curve e.g. by cooling the gas would result in condensation and mist formation. Point A represents the conditions of moisture content and temperature for the inert gas produced when the fuel air ratio is .03. The curve AB, joining this point to 0°C and 0% relative humidity represents the range of conditions obtained when the inert gas is mixed with air at 0°C and 0% relative humidity. The hatched area between AB and the saturation curve represents the conditions at which condensation and mist formation would occur if the inert gas is mixed with ambient air at a temperature greater than 0°C.

If the gas is mixed with air at 25°C and 0% relative humidity (line AC) no condensation would occur. Fig. 6 shows the volumes of air that could be added to one volume of inert gas before conditions of mist formation occur. This volume decreases as the fuel-air ratio increases. Fig. 6 also shows the temperature of the cooled inert gas when mist condensation begins to occur. It will be seen that it is possible to dilute the gas with at least an equal volume of air over a wide range of fuel air ratios and ambient temperatures without mist formation. If the appliance at the Fire Research Station is operated without reheat the fuel air ratio is 0.012. Fig. 6 indicates that about 13 volumes of cold air may be mixed with the gas produced under these conditions and the resulting mixture would remain transparent. However, if the outlet temperature of the gas from the appliance were only 90°C instead of 120°C, the mixture would become saturated when 2.2 volumes of air was mixed with the gas.

Condensation of water vapour might also occur when the inert gas flows over cool surfaces. The gas will be cooled according to the line AD (Fig. 5) parallel to the temperature axis as long as the surface is dry. If the temperature of the surface is well below the temperature D, then the gas might become misty in a layer some distance from the surface. This distance is unlikely to be greater than a few inches, unless the gas flowed for a long period, close to a large area of cold surface. Under these conditions the gas would become transparent after the surfaces had been heated by the gas.

High expansion foam

A number of authors have described the production and properties of high expansion foam based on the use of air at ambient temperature.[12] [13] The principle of extinction with this type of foam, is that after the water in the foam has been vaporised by a fire, the oxygen concentration of the resulting steam-air mixture would be sufficiently low to suppress combustion. Thus if air contained 1,000th of its volume of water then the vaporisation of all the water would produce a gas containing 9% of oxygen. This would be sufficiently low to suppress flaming combustion in all common liquid or solid fuels and also smouldering combustion under certain conditions. However, if the water drains out of the foam before the foam reaches the fire area, or if it is not completely vaporised insufficient steam may be formed and combustion might continue below the surface of the foam. If the foam is made by an inert gas generator, then the gas inside the bubbles can have in itself a reduced oxygen concentration, such that if the bulk of the water in the foam drains off then the gas in itself would be sufficiently inert to extinguish combustion in most instances. As long as the gas contains more than about 1/3,000th of its volume as water, the foam will be heavier than air and, therefore, will tend to fill buildings from the floor upwards, whereas inert gas tends to fill buildings from the ceiling downwards. For this reason the production of foam and inert gas using the jet engine are complementary, the main use of the foam being to keep the inert gas close to the lower part of a building for a sufficient time for combustion in that part of the building to be suppressed.

The volume of foam which can be produced by the appliance would be less than the volume of inert gas before mixing with the foaming solution, and the oxygen content of the gas inside the foam bubbles would be higher than that in the original inert gas. The reason is that during the foam-making process the gas is cooled to a temperature somewhat lower than its adiabatic saturation temperature and in this process a certain amount of the water vapour present in the gas will condense out. As an approximation the maximum volume of the foam which can be produced will be about two thirds of the volume of the inert gas, and about one third of the water vapour present will condense out leaving the oxygen concentration inside the bubbles about 1-2 per cent higher than in the original gas.

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Imperial College reports 69, 94, 104, 125, 127. 1944 - 1945.

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(11) J.F.R.O. Annual Report 1960. H.M.S.O.

(12) H. S. Eisner, P. B. Smith and E. T. Linacre. S.M.R.E. Research
Reports Nos. 130, 171, 179, 182. 1956 - 59.

(13) I. Hartmann, J. Nagy, R. W. Barnes and E. M. Murphy.
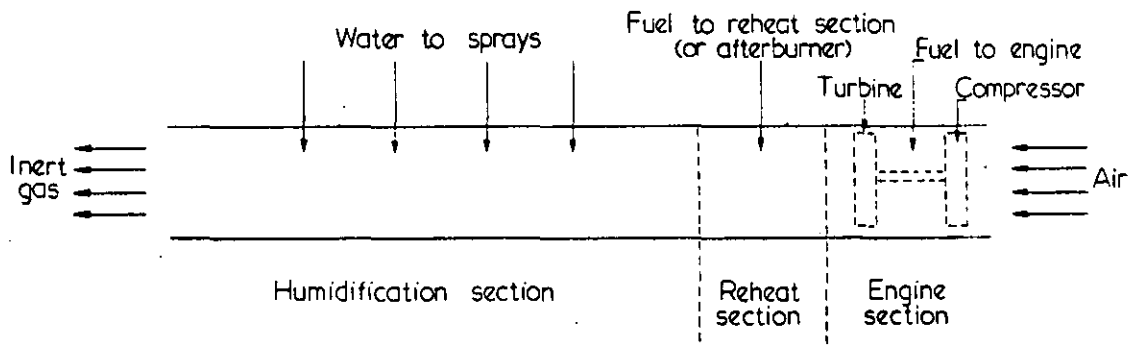U.S. Bureau of Mines R.I. 5419 1959.

Water to sprays

Fuel to reheat section
(or afterburner)

Fuel to engine

Turbine

Compressor

Inert
gas

Air

Humidification section

Reheat
section

Engine
section

FIG. I. DIAGRAM OF INERT GAS GENERATOR

PER CENT OF CONSTITUENTS IN INERT GAS

FUEL/AIR RATIO —wt/wt
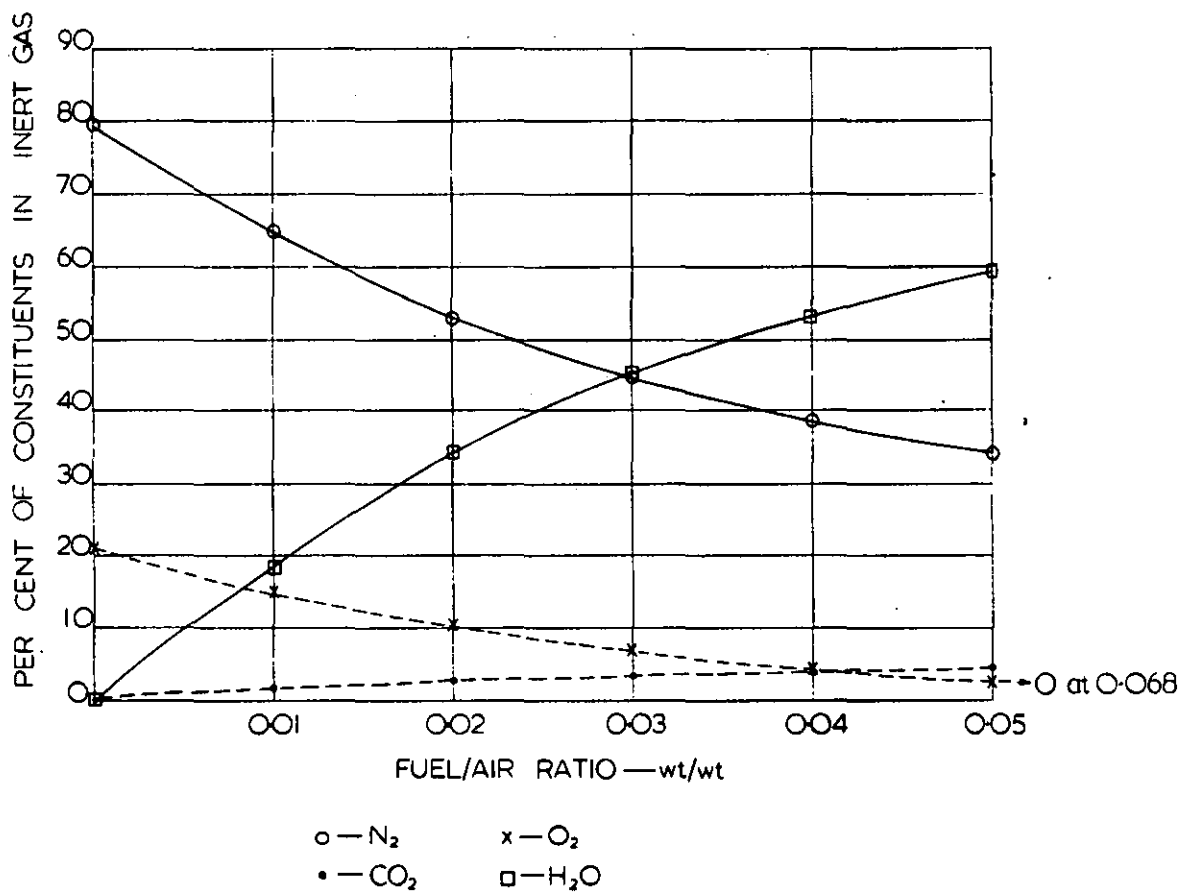
o — N_2 x — O_2

• — CO_2 □ — H_2O

O at 0·068

FIG. 2. COMPOSITION OF INERT GAS FROM JET ENGINE
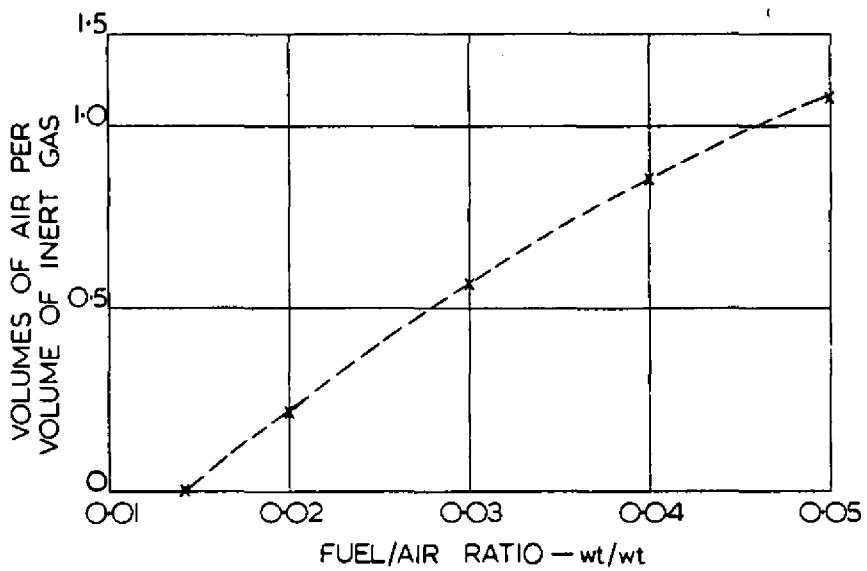## OUTLET TEMPERATURE 120°C
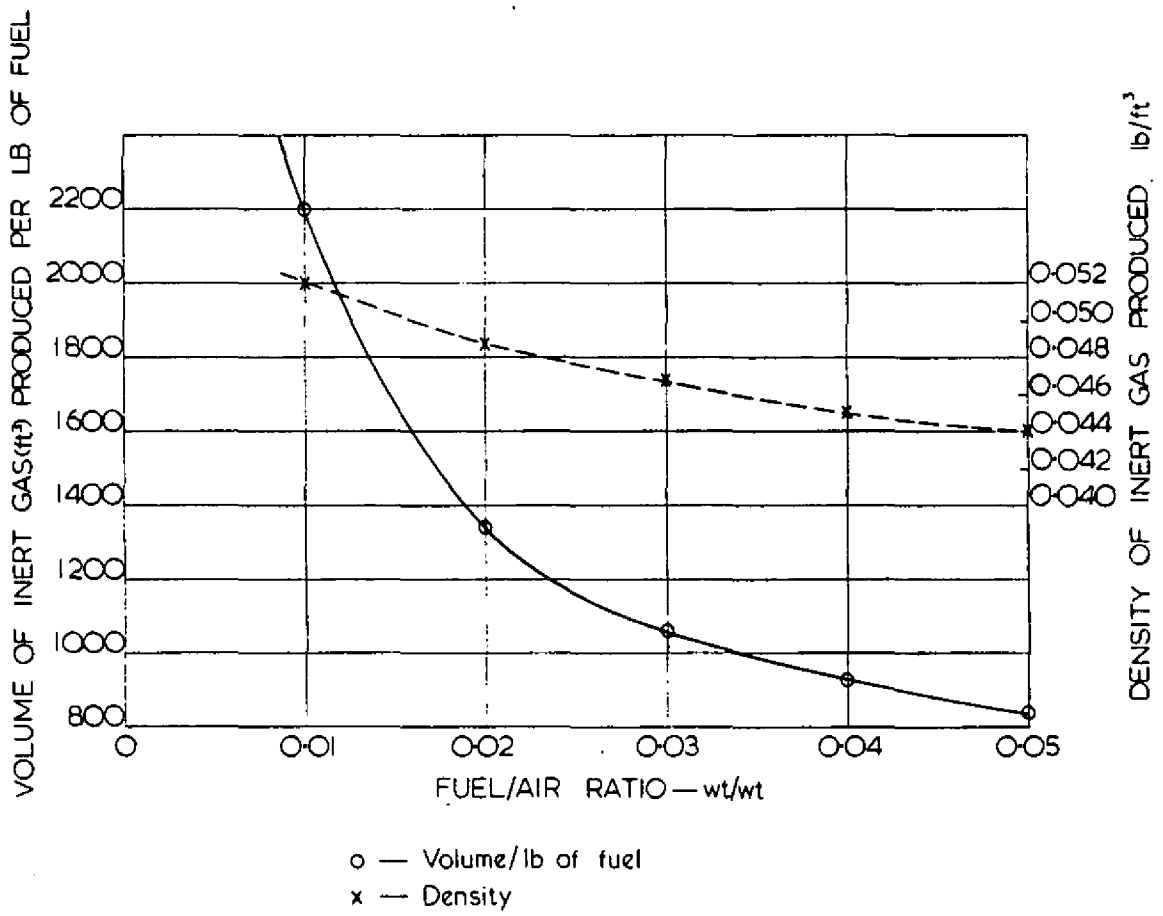
FIG. 3. VOLUME AND DENSITY OF INERT GASES

o — Volume/lb of fuel
x — Density

FIG. 4. VOLUMES OF AIR AT 20°C THAT CAN BE
MIXED WITH 1 VOLUME OF INERT GAS AT
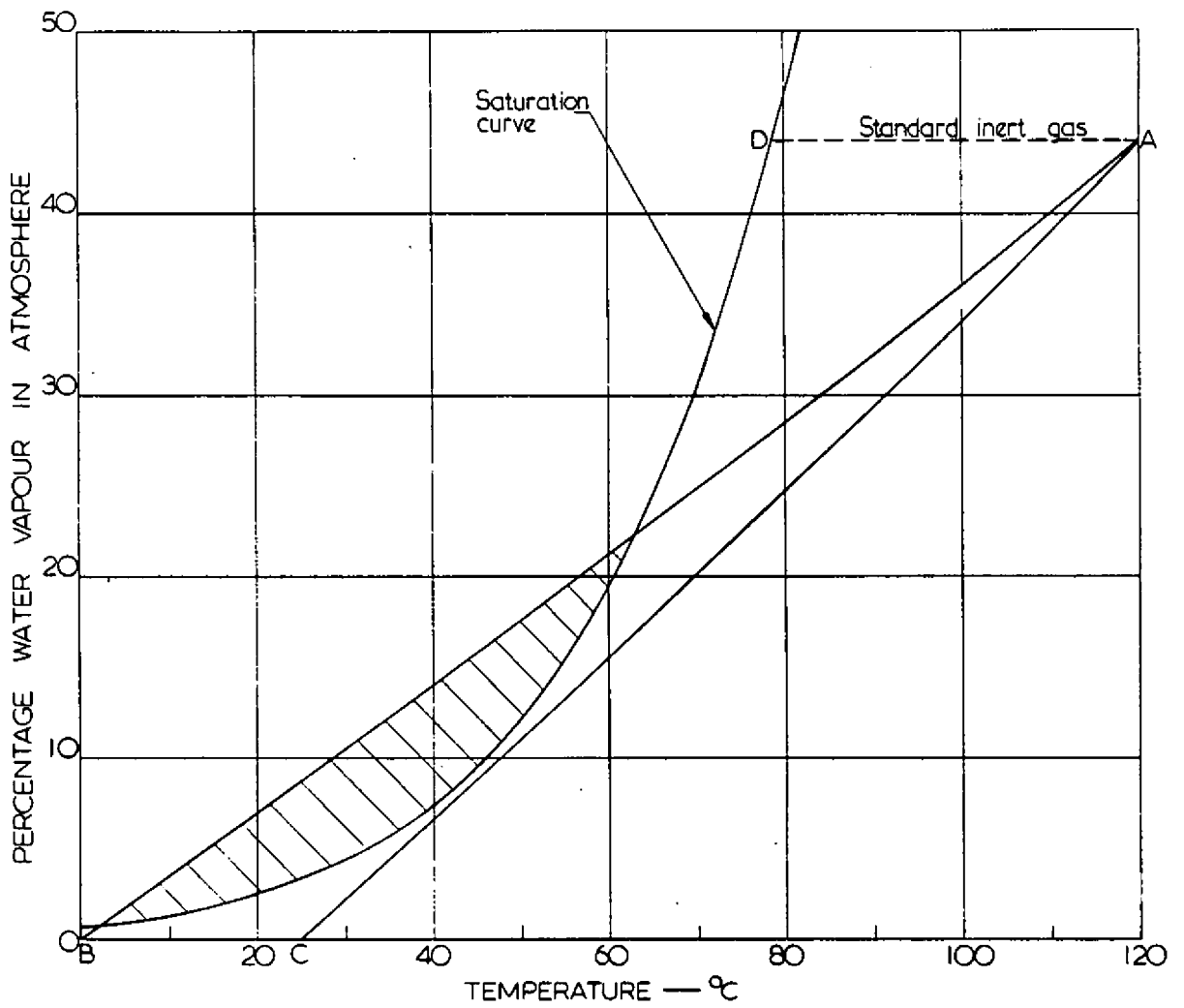120°C BEFORE THE GAS WILL ALLOW
FLAME PROPAGATION
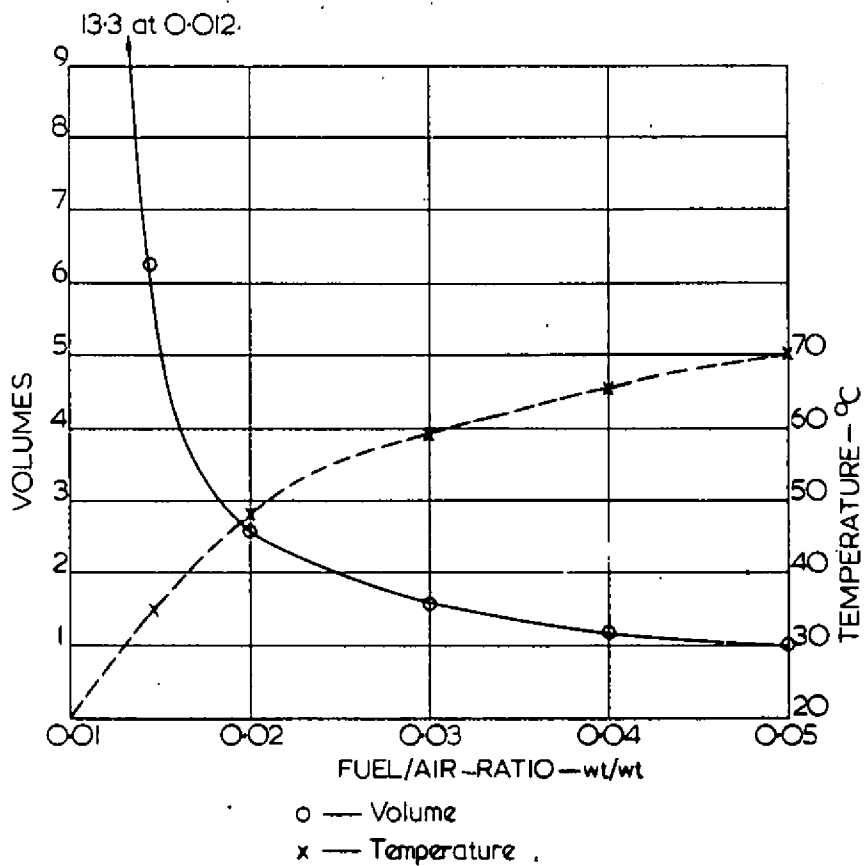
FIG. 5. TRANSPARENCY AND OPACITY OF INERT GAS

FIG. 6. VOLUMES OF AIR (20°C, 100% R.H) ADDED TO INERT
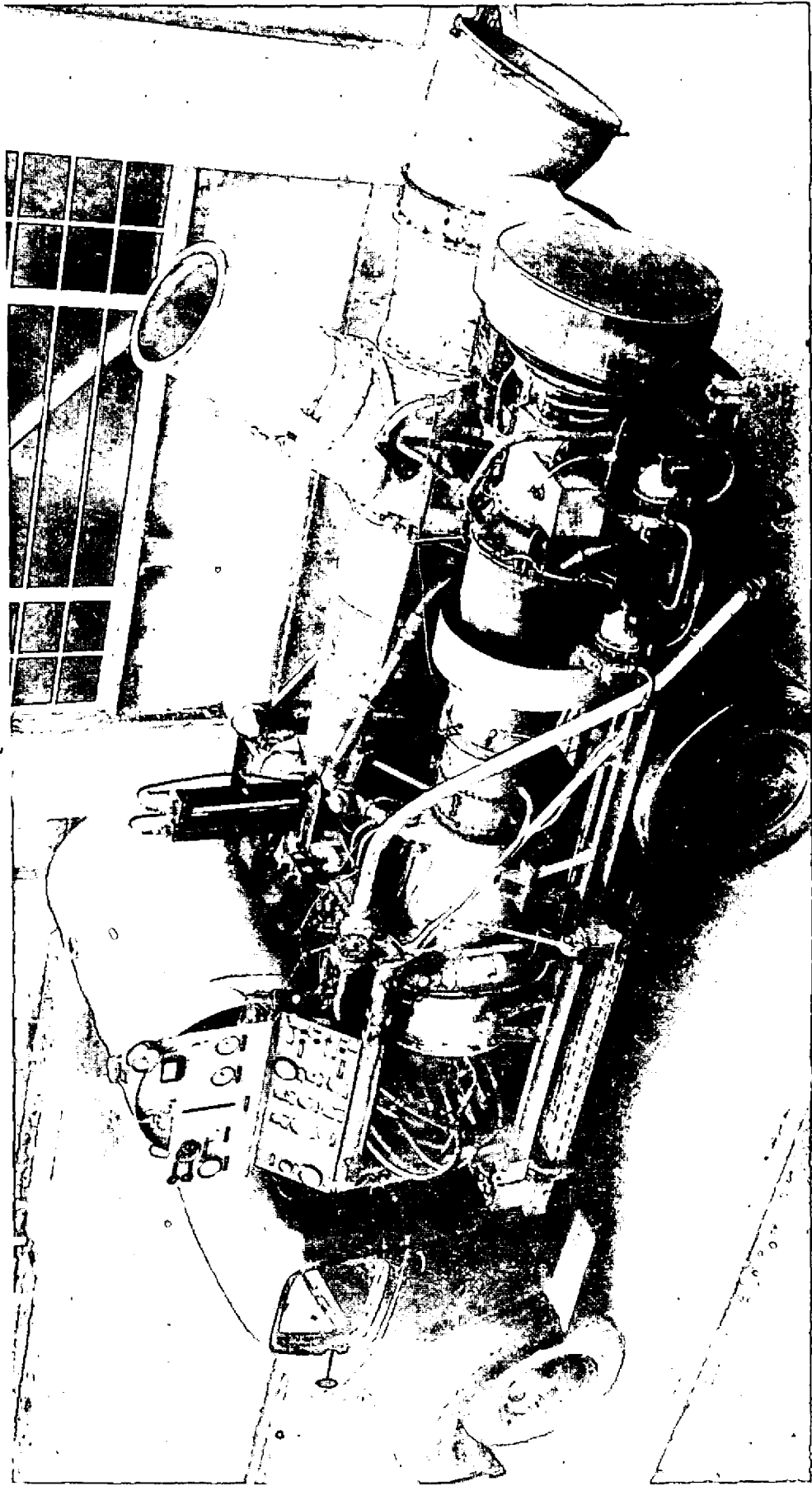GAS (AT 120°C) TO GIVE A SATURATED CONDITION
AND TEMPERATURE OF SATURATED AIR

PLATE 1. JET ENGINE INERT GAS GENERATOR