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SOME EXPERIMENTAL TECHNIQUES IN THE STUDY OF FLAME STABILIZATION

by

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List of Symbols

B - Fraction of fuel burned

C_o - Concentration of oxygen

C_f - Concentration of fuel

E - Activation energy cals

K - Ratio of nitrogen/propane by weight

K' - Local ratio of nitrogen/propane by weight

M - Mass flow rate lb/sec.

P - Pressure (atmospheres)

R - Universal Gas constant (1.987 cal/mol. ^{o}K)

T_R - Reaction temperature ^{o}K

V - Reaction volume ft^{3}.

e - Base of natural logarithms

f - fuel/air ratio by weight

k - 2nd order reaction velocity constant

ϕ_R - Equivalence ratio, reaction zone.

ϕ_p - Equivalence ratio preheating

Introduction and Summary

The purpose of this note is to describe one or two techniques which are currently being used at Cranfield in various investigations into the effects of flameholder geometry and flow parameters on the process of flame stabilization. Much of the report is concerned with a description of the nitrogen dilution technique as a means of simulating low combustion pressures, and a comparison is made between this and the now established water injection technique. It is shown that many aspects of flame stability can be effectively studied by local injection of nitrogen directly into the combustion zone, with appreciable economies in the amounts of nitrogen required. A further application of this local injection method is also described which has proved useful in an investigation of the factors governing the amount of air entrained in the recirculation zone.

1.0 Low pressure simulation by nitrogen dilution

A number of techniques for simulating low combustion pressure have appeared in the literature in recent years (1) (2) (3). One of these techniques in particular has proved to be cheap and effective. Basically, this method depends upon decreases in both temperature and partial pressure of the reactants involved in the combustion process, which are achieved by the addition of water to the combustible mixture. The theory and application of this method have been fully described in an earlier paper presented to the G.T.C.C. Combustion Sub-Committee (4).

The use of water as a diluent has the advantage of a cheap working fluid, but there are certain drawbacks mainly in terms of experimental complication and pressure loss. An essential item for the water dilution method is an air preheater to vaporise the injected water and cause it to remain in a vapour state during its passage through the combustion zone. Although the pressure loss of a preheat chamber is normally quite small it can be very significant if a fan is used as the source of air. In any case its associated fuel pump, fuel system and controls constitute an added complication. The problem of distributing the dilution water in such a way as to produce a uniform mixture also arises. In most installations it is necessary to introduce large numbers of individual injectors in order to spread the water evenly across the air stream. Moreover, mixing devices, which inevitably introduce pressure loss, must often also be used, particularly when the quantity of injected water is large.

Although not a serious limitation on the use of water, it should not be overlooked that water does not remain inert at the high temperatures produced by stoichiometric mixtures. Fortunately, the dissociation of the water into H_2 and O_2 , and the resulting production of radicals which affect the reaction rate of the process, does not occur to any great extent. This is due to the fact that the water itself reduces the reaction temperature to a level where dissociation is slight.

Because of these inherent limitations in the use of water, alternative diluents have from time to time been considered. One obvious alternative, which remains chemically inert to much higher temperatures than water, is nitrogen. The effects of nitrogen dilution have been reported (5) in the study of inflammability limits and flame velocity measurements and, more recently, a paper submitted to the G.T.C.C. Combustion Sub-Committee has shown the advantage of using nitrogen in observing the behaviour of hydrogen/oxygen reactions in a spherical reactor (6).

The use of nitrogen gas as a diluent for simulating low combustion pressures has a number of practical advantages over water. No preheating is required, and mixing of the nitrogen with the air is much easier. One useful method of ensuring homogeneous mixtures is to introduce the nitrogen at the inlet to the fan which provides the supply of air. The only real disadvantage of nitrogen is that of cost, which is approximately £2. 10. 0/1000 cu.ft. of gas. The cost is, however, relative to the scale of the work on which the technique is employed, and hence for small scale laboratory work the use of nitrogen can sometimes be more economical overall than water. It should be added that if very large quantities of nitrogen are contemplated, liquid installation is considerably cheaper than bulk storage of gas

2.0 Theoretical background

The principles of simulating low combustion pressure by the dilution technique are confined to the use of a reaction rate criterion. This criterion is the equality of the reaction rate at the simulated and true pressure condition. One may formulate this equality for second order homogeneous gaseous reactions by the use of well-known looading parameter, $\frac{M}{VP^2}$, in the following way:-

$$\left[\frac{M}{k\ VP^2}\right]_{SIM} = \left[\frac{M}{k\ VP^2}\right]_{TRUE} \qquad \text{\_\_\_\_\_\_\_\_} \tag{1}$$

where k is the unknown 2nd order reaction velocity constant.

The derivation of the loading parameter has been described many times and, therefore, only the bare essentials need be given here. It can be shown that for second order reactions the equation which relates the loading to other indepenednt variables is:-

$$\frac{M}{k\ VP^2} = C_o \cdot C_f \cdot \frac{p^2}{f_{BR}2} \cdot \frac{e^{-E/RT_R}}{T_R{}^{3/2}} \qquad \text{\_\_\_\_\_\_\_\_} \tag{2}$$

The effect of adding an inert gas on the reaction rate becomes apparent by considering equation (2). By the addition of a diluent gas the concentration of oxygen, C_o and of fuel, C_f, will decrease and the reaction rate will vary as the product of these decreased values. In addition, the presence of the inert gas will decrease the reaction temperature, T_R, due to its capacity for absorbing heat. Expressions can be developed from equation (2) which relate the loading parameter to the weight ratio of diluent to fuel, K, and the following expression is that for propane/air mixtures and nitrogen dilution with factors included for preheating with kerosine:-

$$\frac{M}{k\ VP^2} = \frac{e^{\frac{-21,000}{T_R}}}{T_R{}^{3/2}} \cdot \frac{(1 - B)}{B} \cdot \frac{\left(1/\phi_R + 3.6\phi_p\right)\left(1/\phi_R - B\right)}{\left(1 + B + \frac{23.8}{\phi_R} + 91.68\ \phi_p + 1.571K\right)^2}$$

Since calculations of reaction temperature rate at equivalence ratios near to stoichiometric become difficult, a Pegasus Autocode Programme was prepared and used for these calculations. Typical values of reaction temperature are shown in figure (1) for the case $\phi_R = 0.9$ and initial mixture temperature 298°K. Figures (2) and (3) show respectively, for the same conditions, the effect on reaction rate of reduction in pressure and the addition of nitrogen. These two graphs are combined in figure (4) to show the theoretical relationship between nitrogen dilution and the equivalent decrease in pressure.

3.0 Experimental techniques

The application of the nitrogen dilution technique has so far been confined to investigations into the factors influencing bluff body flame stabilization. A typical test rig is illustrated in figure (5). The stabiliser under test is mounted in a circular duct which is connected to the outlet of a fan via a preheat combustion chamber. Arrangements are made for the uniform injection of gaseous fuel and gaseous nitrogen at suitable mixing distances upstream of the stabiliser. The quantity of air supplied by the fan is measured by means of a venturi in the fan intake ducting, and the quantities of fuel and nitrogen injected into the air are measured directly on gas flow meters. Pressure and temperature measuring devices are installed immediately upstream of the flame stabiliser, and traverses are carried out to ensure that uniform mixture velocities and temperatures are maintained over the complete range of test conditions required of the rig.

The test procedure is first to adjust the velocity and temperature of the air to the desired values. The gaseous fuel is then turned on and supplied in sufficient quantity to establish a flame on the stabiliser. Nitrogen is then added in increasing amounts, whilst maintaining the supply of fuel and air constant, until extinction of the flame occurs. This procedure is repeated over a range of fuel flows until a complete stability loop is obtained. Typical stability loops obtained by this procedure are shown in figure (6) in which the effect of the velocity of the gas approaching the stabiliser is clearly shown. Similar stability loops in figure (7) show the marked effect of gas temperature. Figures (6) and (7) are typical of results obtained during investigations into the influence on flame stability of velocity and mixture temperature. These are only two of the factors affecting flame stability which can be easily separated and investigated by the nitrogen dilution technique. From the results of such investigations, it is hoped that a general parameter can be established incorporating all the thermodynamic and aerodynamic factors which are known to influence flame stability.

A complication which has arisen in the procedure described above is that of maintaining a constant velocity while varying the amount of nitrogen. Considerable adjustment and preselection of flow conditions are required if loops of constant velocity are to be obtained. A modification of the technique, initially introduced to overcome this complication, is injection of the nitrogen directly into the combustion zone. Since, with this method, only small quantities of nitrogen are required to produce extinction of the flame, there is little variation in the flow conditions. The quantities of nitrogen needed to produce extinction in this modified technique are so small that a further important advantage of this method is the great saving in nitrogen. An illustration of the rig requirements for this modified technique is given in figure (8), in which nitrogen is introduced into the combustion zone through a porous backplate located inside the stabiliser. This ensures even distribution of the diluent. Figure (9) shows typical stability loops obtained with this method for different velocities.

4.0 Experimental verification of relationship between quantity of added nitrogen and equivalent reduction in pressure

A programme of rig tests is now in hand to seek confirmation of the relationship between nitrogen dilution and the effective decrease in pressure as illustrated in figure 4. It will be several months before these tests are complete; in the meantime some supporting evidence for the nitrogen dilution technique is contained in figure 10. This figure shows two curves which have been constructed using data obtained on the effects of fuel/air ratio, nitrogen/oxygen ratio and pressure on minimum ignition energies in stagnant mixtures (7). It is apparent from this figure that minimum ignition energies are effected in a similar manner by either a reduction in pressure or an increase in nitrogen concentration.

5.0 An application of the local injection method in the investigation of air entrainment in stabilised flames

5.1 Introduction

One of the main drawbacks of afterburner systems in jet engines is the pressure loss associated with the stabilizer system. This pressure loss constitutes a penalty on engine performance at all flight conditions regardless of whether afterburning is in operation or not. Now afterburner systems normally consist of a number of concentric annular gutters, and thus a very convenient method of reducing this pressure loss would be by decreasing gutter widths. In practice, however, gutter widths have to be made large in order to be capable of stabilizing flames over a wide range of fuel/air ratios.

This situation would be improved considerably if data were available on the amount of air entrained in the recirculation zone formed behind a bluff-body stabilizer. It would then be comparatively straightforward to design an afterburner system in which just sufficient fuel was supplied locally to the gutters to maintain the stabilized flame at a constant stoichiometric fuel/air ratio. Under these conditions the gutter width could be made substantially less and the pressure loss of the system thereby appreciably reduced. The fuel not required for flame stabilization would be injected into the airstream flowing in between the gutters and subsequently burned in the flame propagation zone downstream. Any variations in afterburner fuel flow resulting from varying thrust requirements would affect the propagation zone only and not the stabilized flame.

It was in order to obtain these entrainment data that the present study was initiated. It comprises essentially an experimental and theoretical investigation into the effects of air velocity and temperature, and stabilizer size and blockage, on the amount of air entrained in the recirculation zone behind a stabilizer.

Experimental

The apparatus employed is shown schematically in the attached Fig. 11. Basically it consists of a fan which supplies air to the conical stabilizer under test via a preheat combustion chamber. Arrangements are made for the uniform injection of propane upstream of the stabilizer and also for local injection direct into the recirculation zone. The experimental method employed is first to adjust the temperature and velocity of the airstream to the required values, and then to establish a flame on the cone using locally injected propane gas as the fuel. This fuel is then gradually reduced until extinction occurs, when the fuel flow is noted. This process is carried out several times, first with all the fuel supplied locally to the gutter, and then with gradually increasing amounts of propane supplied uniformly upstream until, finally, a weak extinction is obtained with all the fuel injected upstream and none locally at the stabilizer. The amount of air entrained in the stabilized flame is then obtained as follows:-

Let q_u and q_l denote respectively the fuel/air ratios obtained by dividing the uniformly injected propane and the locally injected propane by the total airflow. Now it will be appreciated that provided that the air temperature and velocity remain constant, extinction of the stabilized flame will occur at a constant fuel/air ratio regardless of the source of supply of the propane i.e. at weak extinction,

$$q_u + \frac{q_l}{x} = \text{constant} \qquad \text{\_\_\_\_\_}(1)$$

where x = fraction of total air flow entrained in recirculation zone.

If suffices 1 and 2 are used to denote weak extinctions at two different values of uniformly injected fuel, from equation (1) it follows that

$$(q_u)_1 + \left(\frac{q_l}{x}\right)_1 = (q_u)_2 + \left(\frac{q_l}{x}\right)_2$$

$$\text{or } x = \frac{(q_l)_2 - (q_l)_1}{(q_u)_1 - (q_u)_2} \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_}(2)$$

If, for any given airflow conditions, weak extinctions are obtained for n values of uniformly injected propane, then n - 1 values of x may be obtained from equation (2).

Tests have been carried out at various values of air temperature and velocity, using three circular pipes of 4, 5 and 6 inches diameter respectively, in conjunction with fifteen conical stabilizers each of 30° included angle. Values of stabilizer blockage ranged from 11 to 44% , the actual stabilizer dimension being carefully chosen in order to permit stabilizer size and blockage to be investigated independently.

The experimental results obtained show that the amount of air entrained in the recirculation zone behind a bluff body stabilizer depends entirely on the velocity and temperature of the airstream and on the stabilizer blockage.

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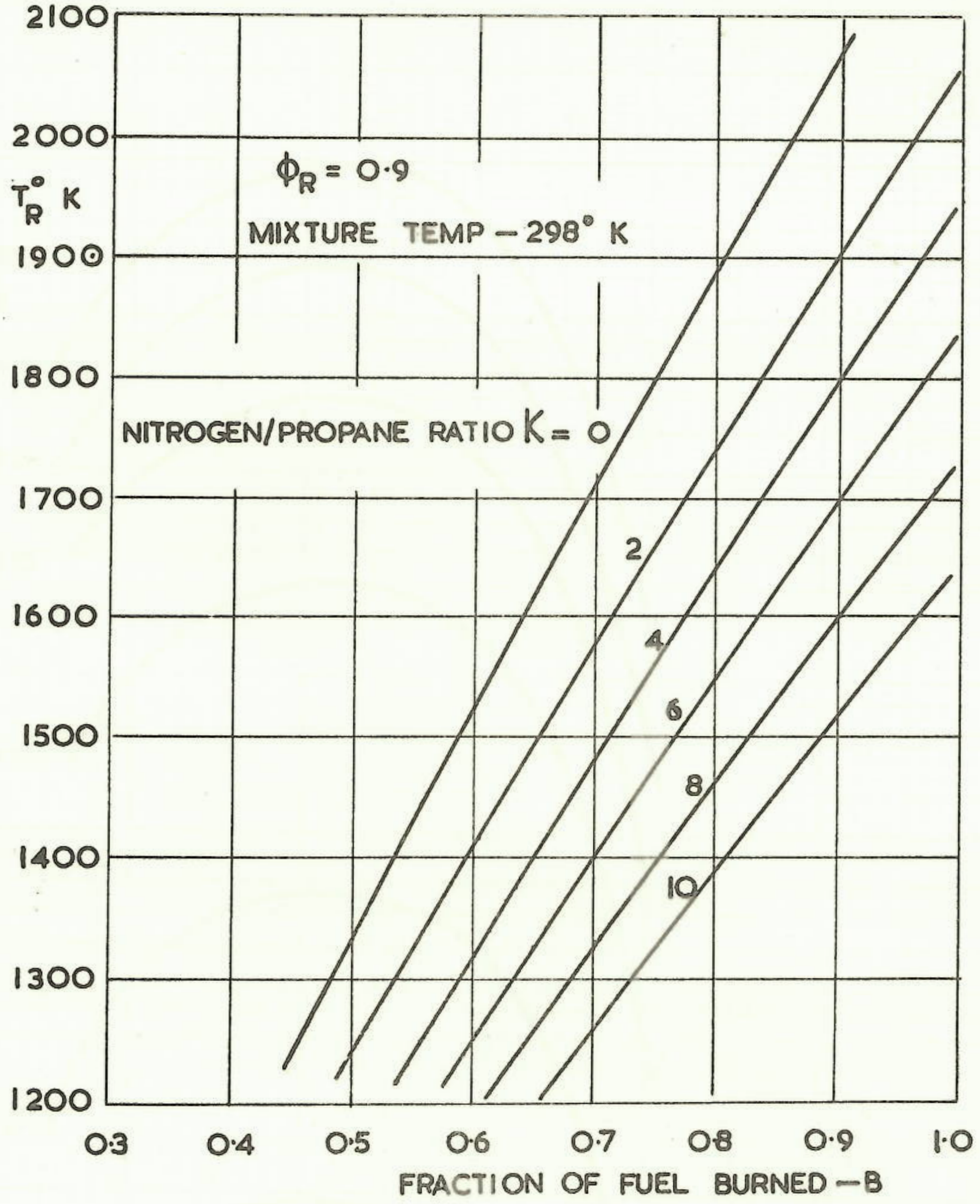
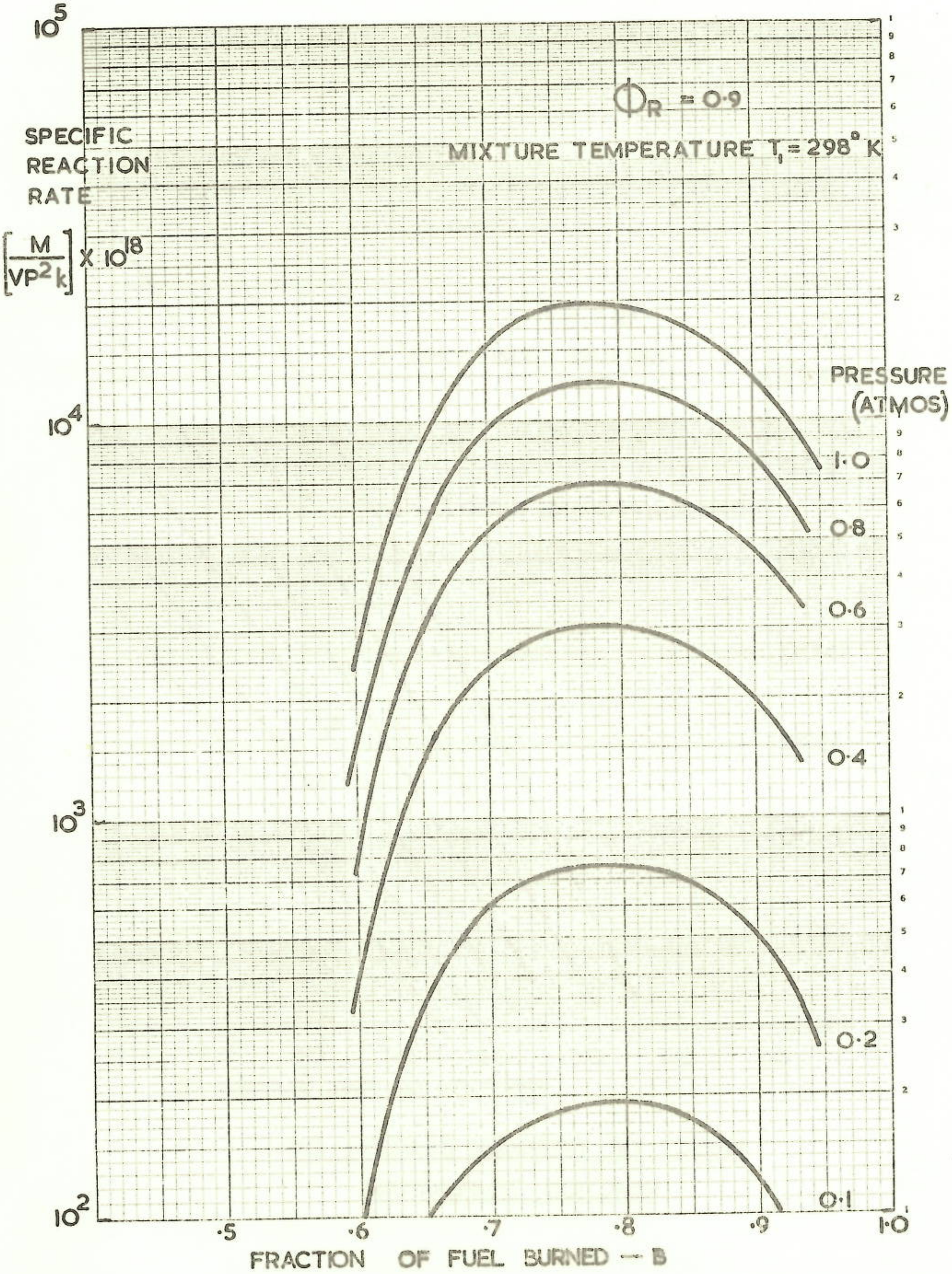
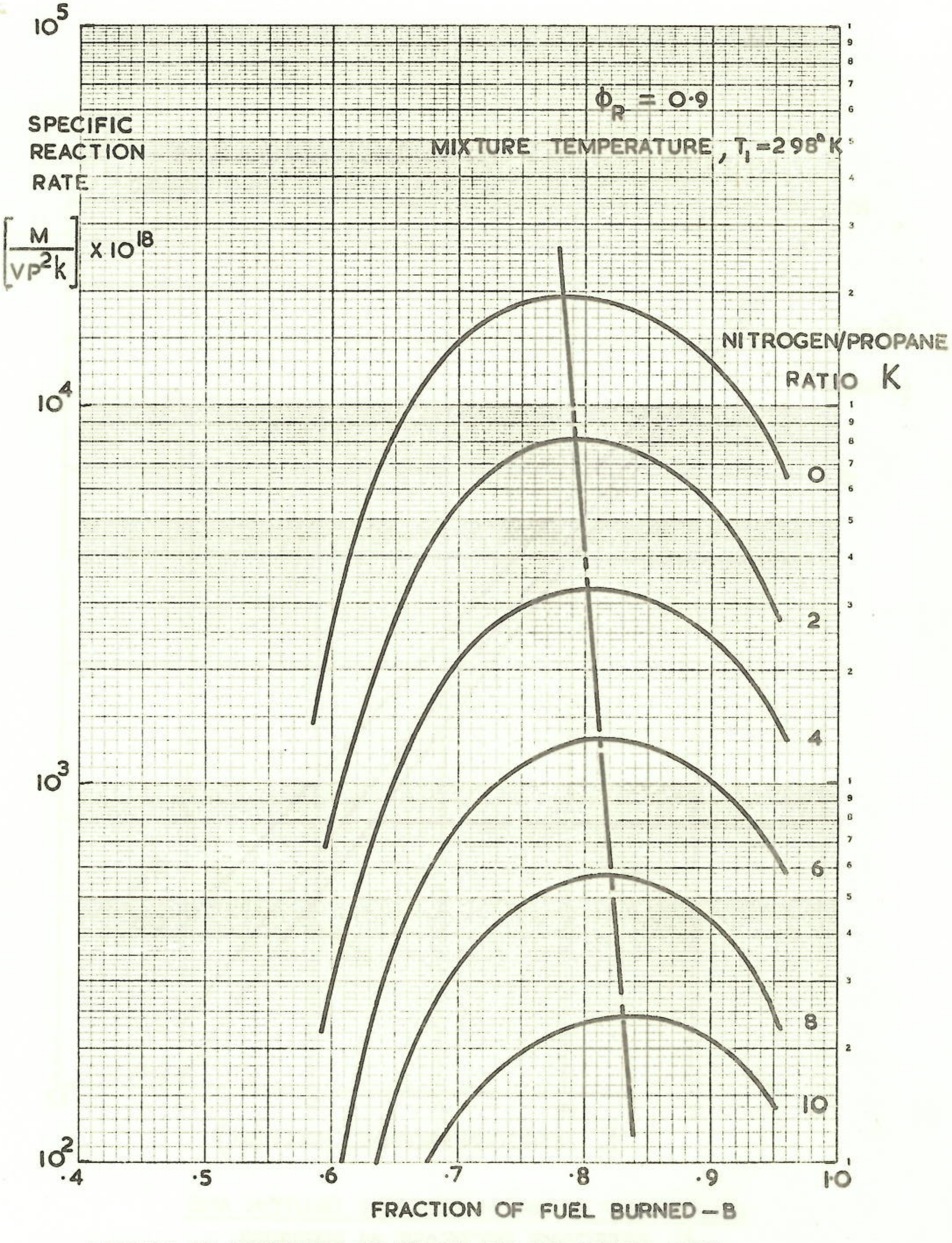


EFFECT OF NITROGEN DILUTION ON REACTION TEMPERATURE.



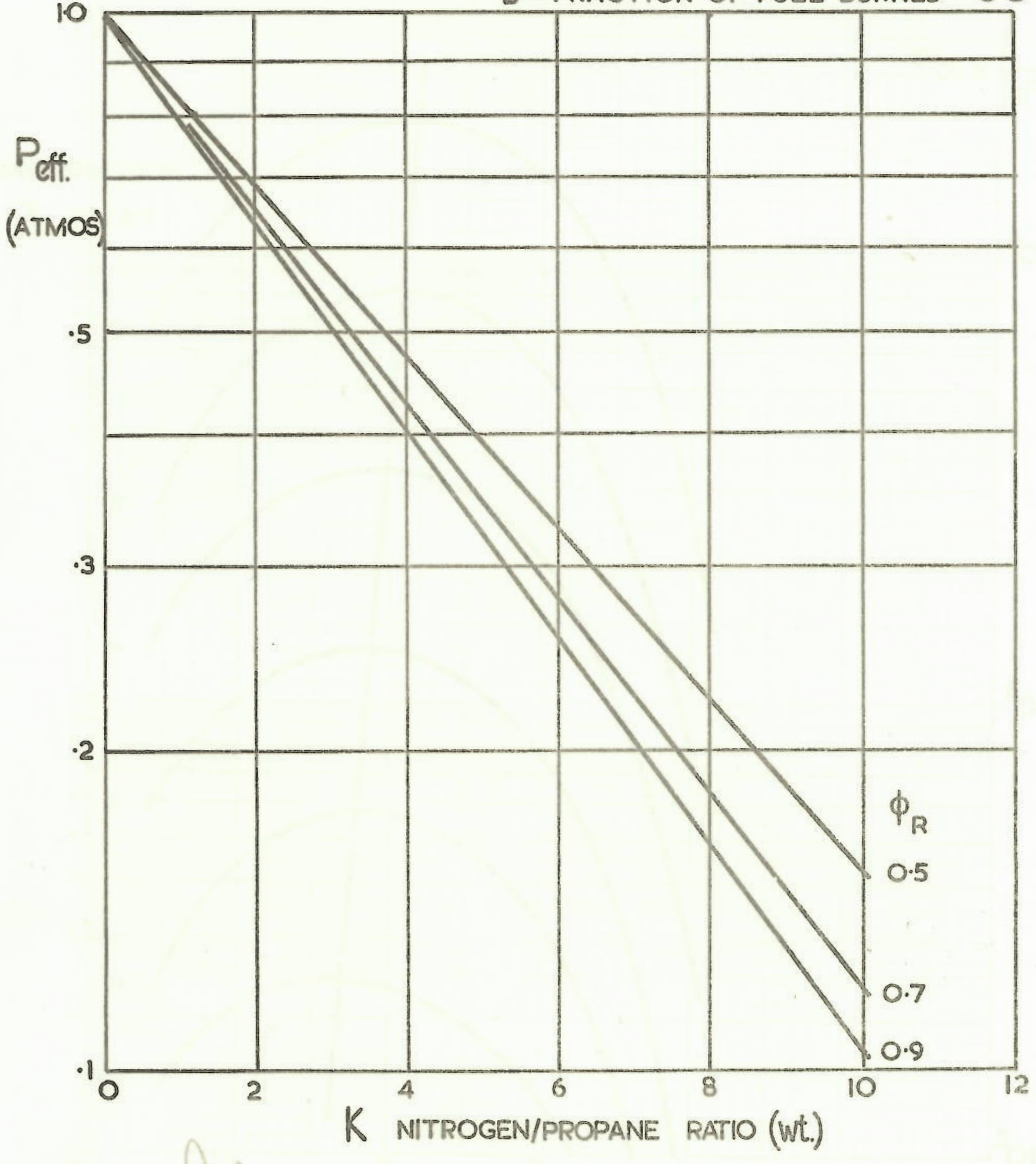
EFFECT OF PRESSURE ON REACTION RATE.

FIG. 3



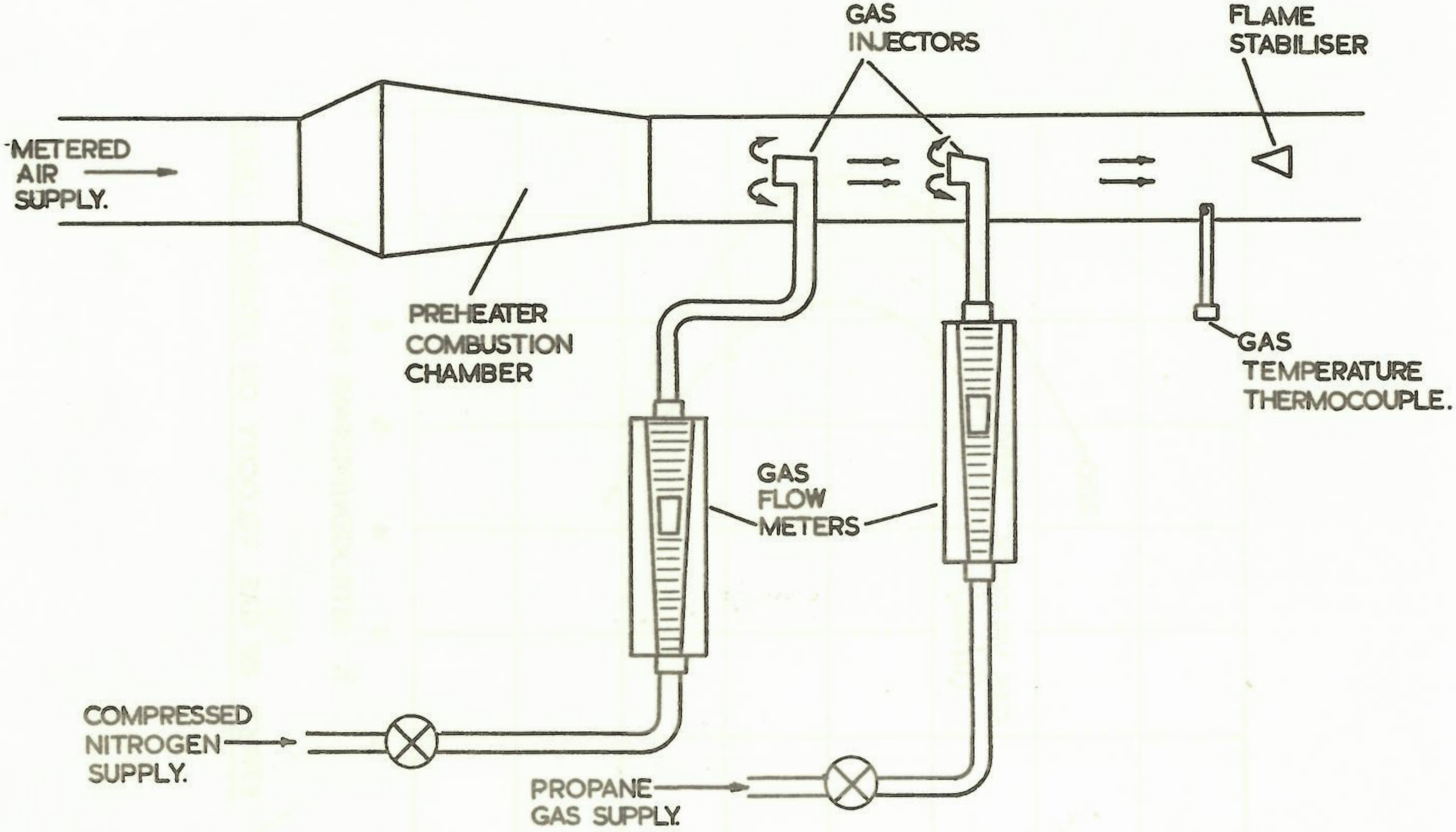
EFFECT OF NITROGEN DILUTION ON REACTION RATE.

FIG. 4



T_1 — MIXTURE TEMPERATURE — 298°K
B — FRACTION OF FUEL BURNED — 0·8

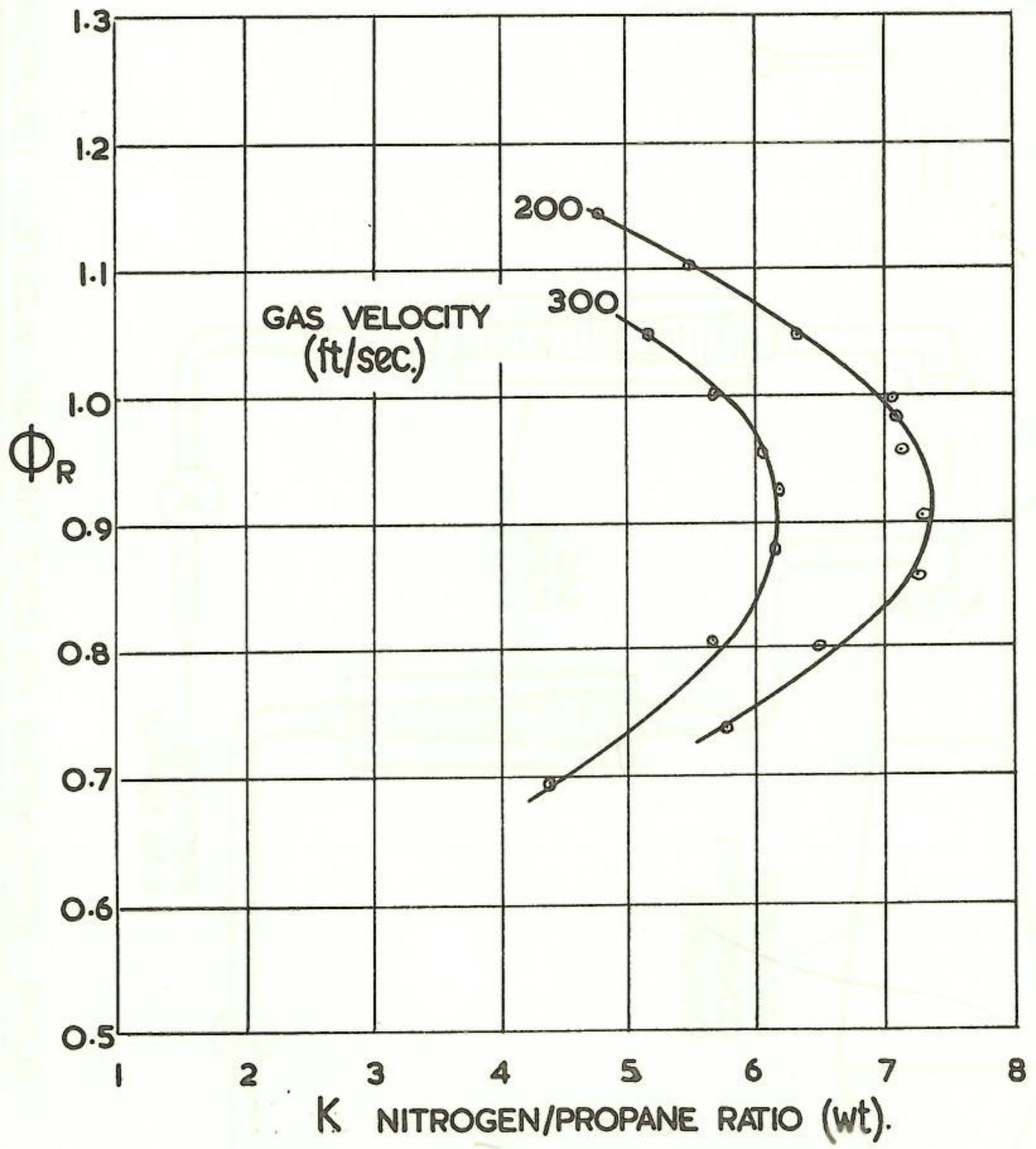
RELATIONSHIP BETWEEN NITROGEN DILUTION AND EFFECTIVE DECREASE IN PRESSURE.



FLAME STABILISATION RIG USING NITROGEN INJECTION TECHNIQUE.

FIG. 5

FIG. 6



Exptl. Result ✓

Approaching

EFFECT OF GAS VELOCITY ON STABILITY LIMITS.

Exptl Results

EFFECT OF MIXTURE TEMPERATURE ON STABILITY LIMITS.

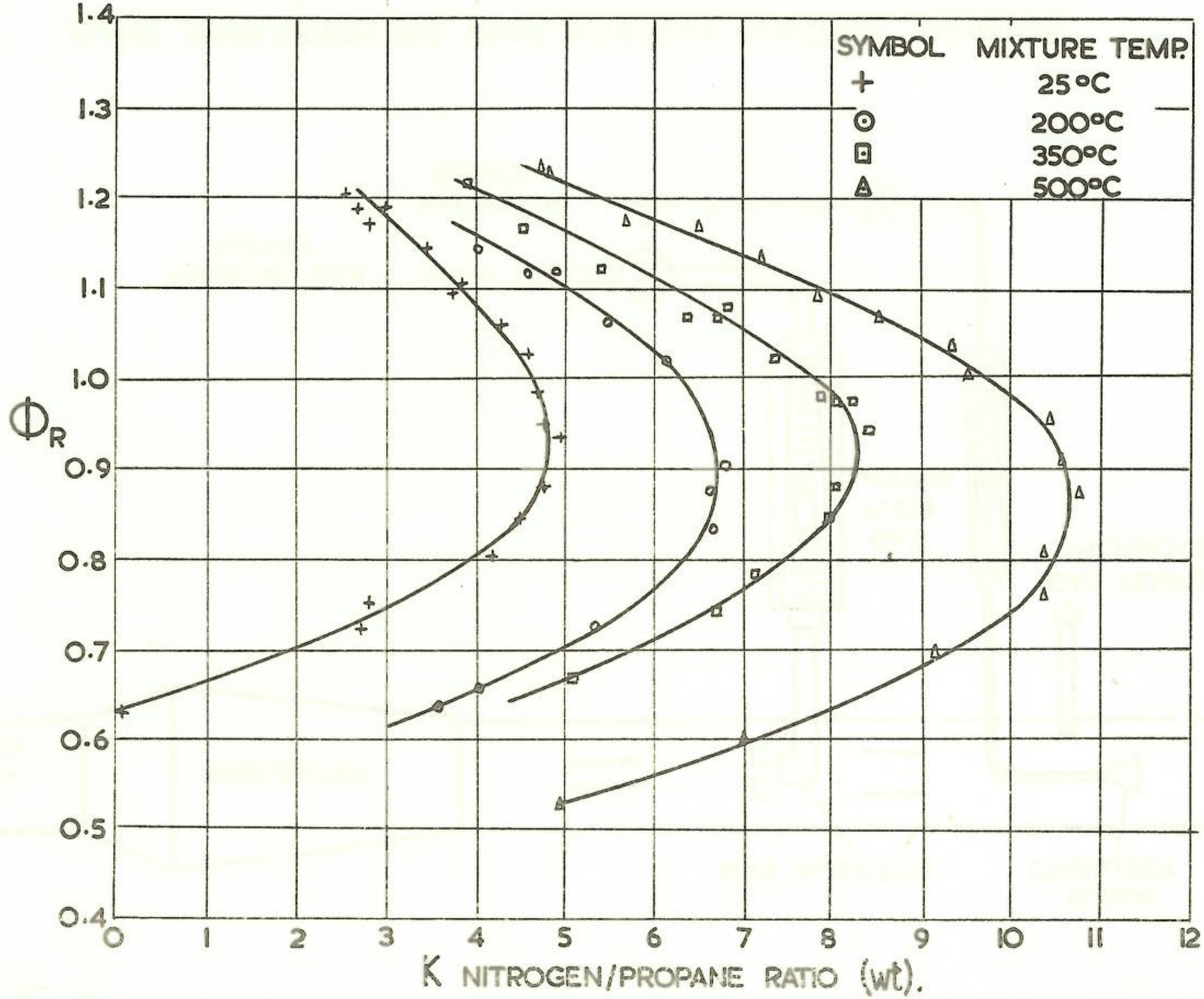
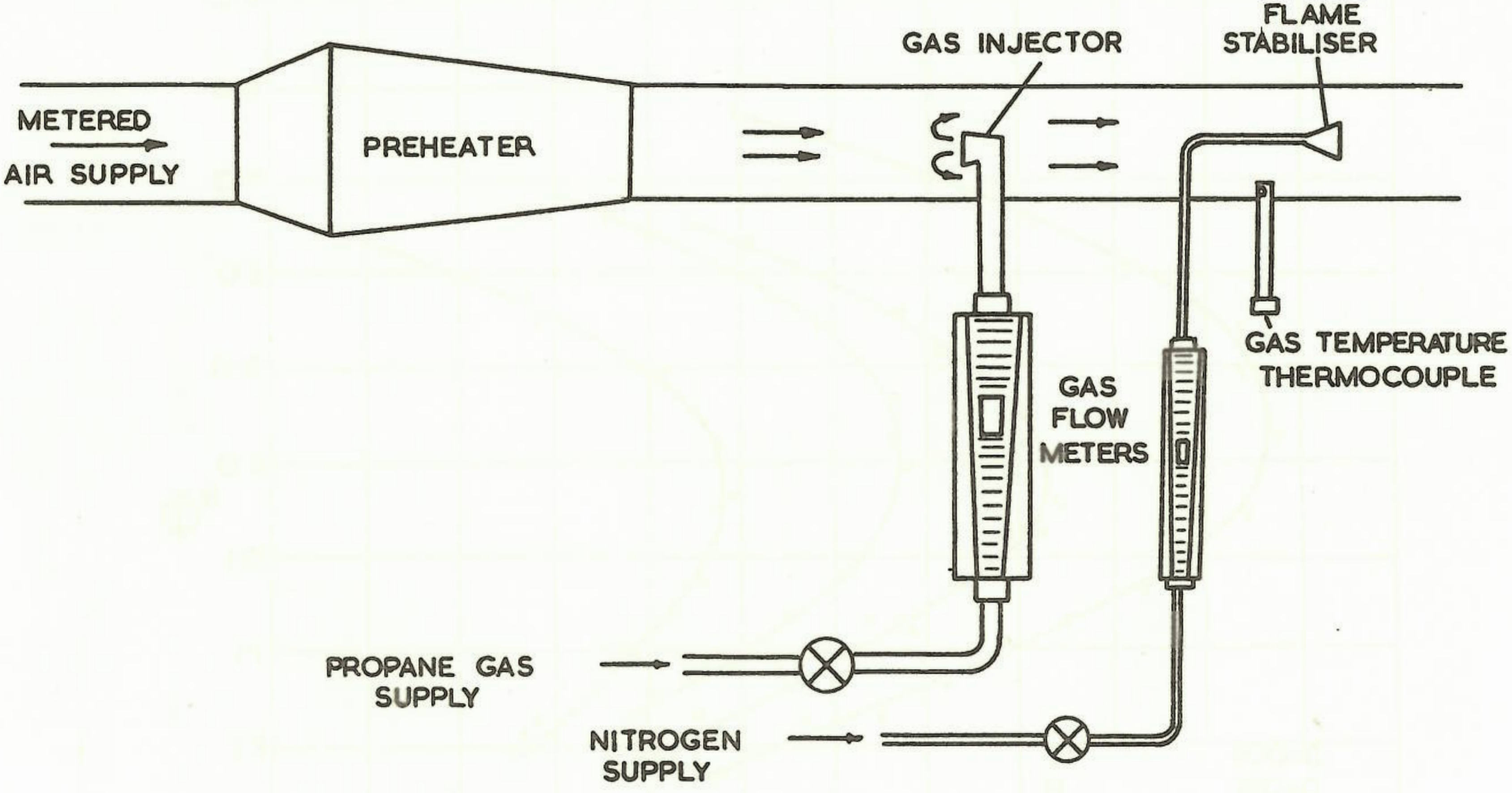


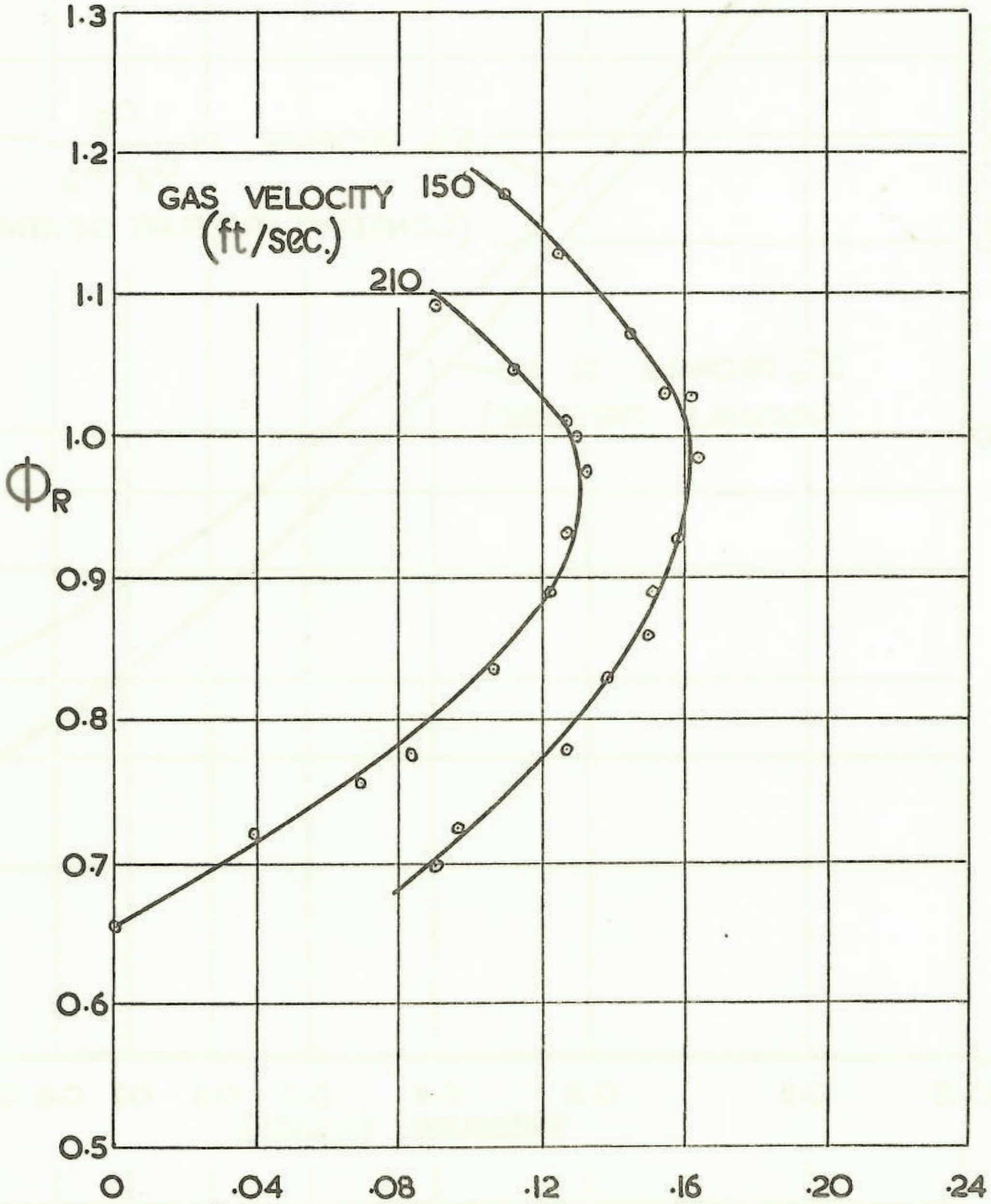
FIG. 7



FLAME STABILSATION RIG USING NITROGEN INJECTION TECHNIQUE.

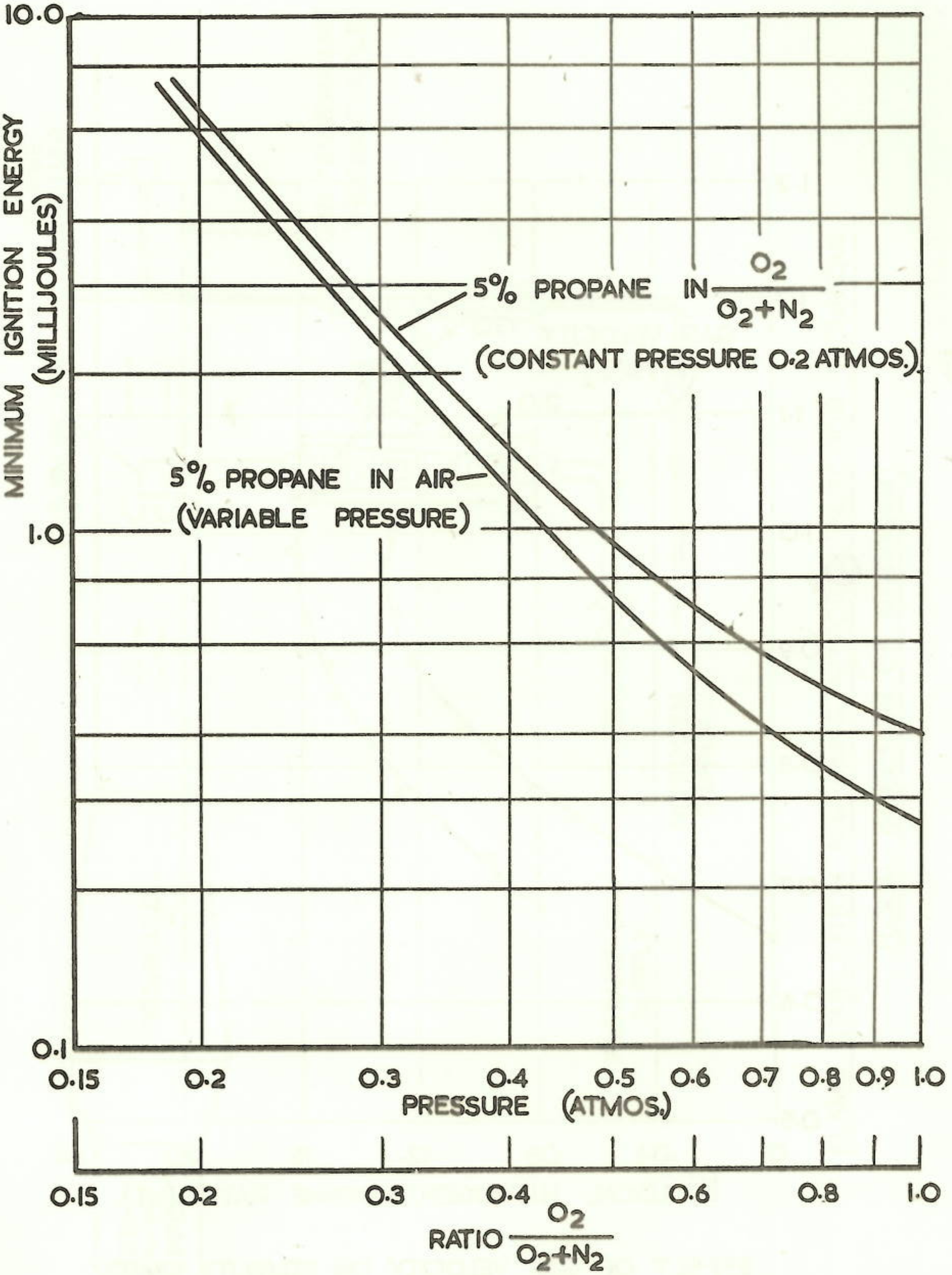
(LOCAL INJECTION OF NITROGEN)

FIG. 8



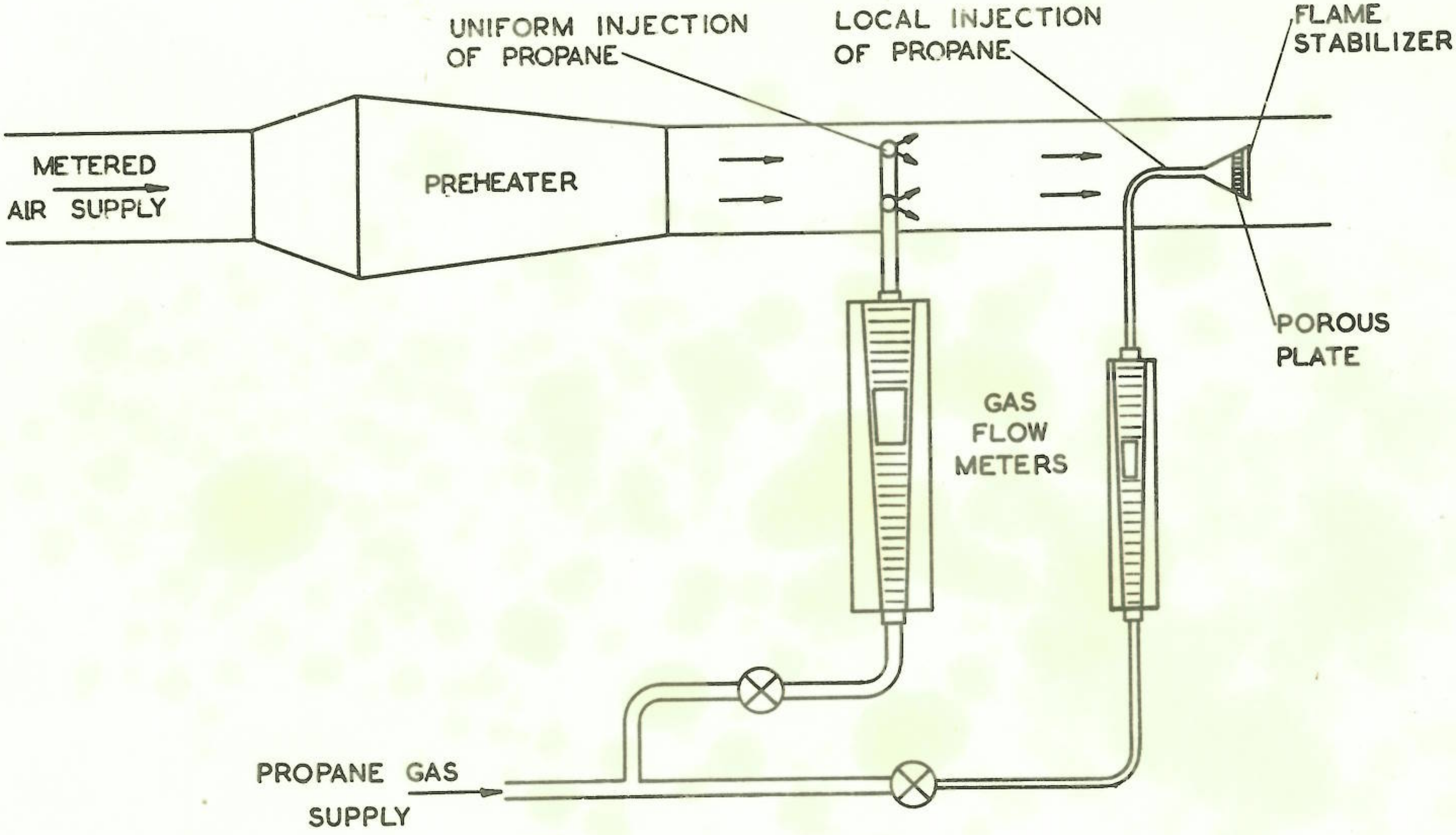
EFFECT OF GAS VELOCITY ON STABILITY LIMITS.

(LOCAL INJECTION OF NITROGEN.)



EFFECT OF PRESSURE AND NITROGEN CONCENTRATION ON MINIMUM IGNITION ENERGY.

FIG. II



SCHEMATIC DIAGRAM OF APPARATUS