

T H E S I S .

AUTHOR:-

D.T. RUSSELL.

SUPERVISOR:-

PROFESSOR A.H. LEFEBVRE.

DEPARTMENT:-

AIRCRAFT PROPULSION.

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A B S T R A C T.

The objective of this thesis was to investigate flame radiation and smoke emission phenomena in a combustor typical of those in use in aircraft gas turbine engines. One of the primary aspects of the investigation was to compare the performance of airblast atomisers with that of conventional swirl atomisers under as near identical conditions as possible.

A brief study of combustion chamber processes and carbon formation and thermal radiation mechanisms was made, with consideration of such experimental data as exists in the literature.

An airblast atomiser and combustion chamber was developed to a state whereby testing at rich mixtures at moderate combustion pressures could be performed for short periods. This enabled a preliminary comparison to be made monitoring the following parameters:-

- (i) Flame total radiation.
- (ii) Exhaust smoke level.
- (iii) Weak extinction.

Data was collected at three different combustion pressures for various air-fuel ratios and chamber velocities. The results showed that the airblast atomiser offers significant advantages over swirl atomisers with regard to total flame radiation and exhaust smoke emissions whilst suffering from a poor weak extinction.

A more detailed analysis was performed for swirl atomisers using the Schmidt Method to establish flame temperatures and emissivities. The object of this work was to assess the effects of droplet size and combustion pressure on flame radiation.

Owing to the poor atomisation quality and fuel distribution of the airblast atomiser used for the preliminary work, two new injectors were designed. It was hoped that a detailed analysis for these injectors could be performed via the Schmidt Method in order to provide a comparison with the swirl atomisers. Unfortunately, manufacturing was not completed with sufficient time left for this analysis to be completed.

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D.T. Russell.

D.T. Russell.
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LIST OF SYMBOLS.

A	=	Area.
AFR	=	Air-fuel ratio.
α	=	Beer Law absorption coefficient.
C_D	=	Drag coefficient.
c	=	Velocity of light.
$\bar{c}$	=	Mean soot concentration.
D	=	Drag force.
d	=	Droplet diameter.
E_1	=	Correction for instrument error.
E_2	=	Correction for emissivity.
F	=	Flow number.
h	=	Planck constant.
h_v	=	Latent heat of vapourisation.
K	=	Boltzmann constant.
ℓ	=	Optical path length.
$\dot{m}$	=	Mass flow rate.
m	=	Complex refractive of soot, $m = n(1-ik)$.
n	=	Real refractive index of soot.
k	=	Absorption index at wavelength
Nu	=	Nusselt number.
P	=	Total pressure.
p	=	Static pressure.
Δp	=	Pressure differential.
Q	=	Non-dimensional mass flow.
q	=	Primary zone fuel-air ratio.
$\dot{q}$	=	Radiant intensity.
R	=	Ratio of fuel momentum to air momentum.
Re	=	Reynolds Number.
r	=	Nozzle orifice radius.
S	=	Penetration distance.
T	=	Total temperature.
t	=	Static temperature.
U	=	Velocity.

V	=	Combustor volume.
We	=	Weber number.
α	=	Flame absorptivity.
β	=	Window total absorption.
σ	=	Surface tension.
a	=	Beer Law absorptivity.
ϵ	=	Flame emissivity.
μ	=	Viscosity.
η	=	Efficiency.
I	=	Luminosity factor.
σ	=	Stephan-Boltzmann constant.
λ	=	Wavelength.
ρ	=	Density.
ν	=	Kinematic viscosity.

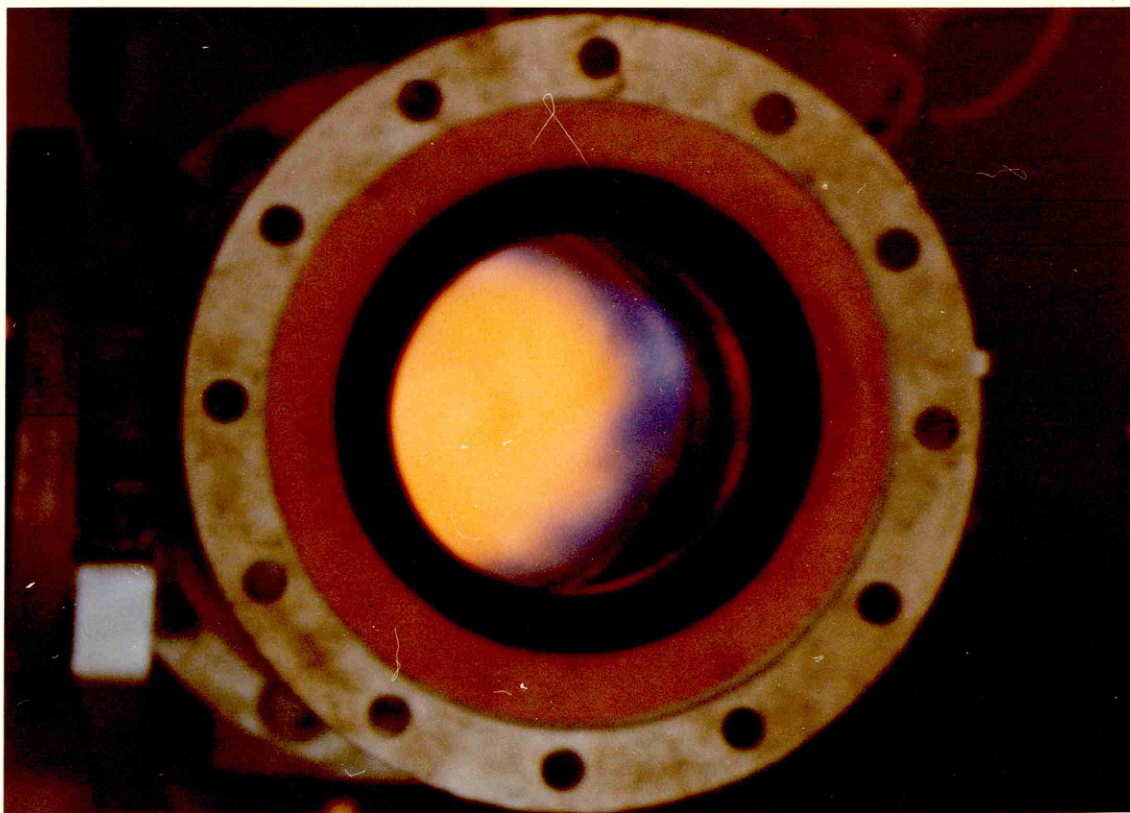
SUBSCRIPTS.

OC	=	Overall cycle.
TH	=	Thermal.
PROP	=	Propulsive.
T	=	Total.
λ	=	Spectral.
n	=	Non-luminous.
F	=	Fuel.
SMD	=	Sauter Mean Diameter.
L	=	Liquid.
A	=	Air.
M	=	Mass Median Diameter.
ft	=	Flame tube.
bb	=	Black body.

THE FRONTISPIECE.

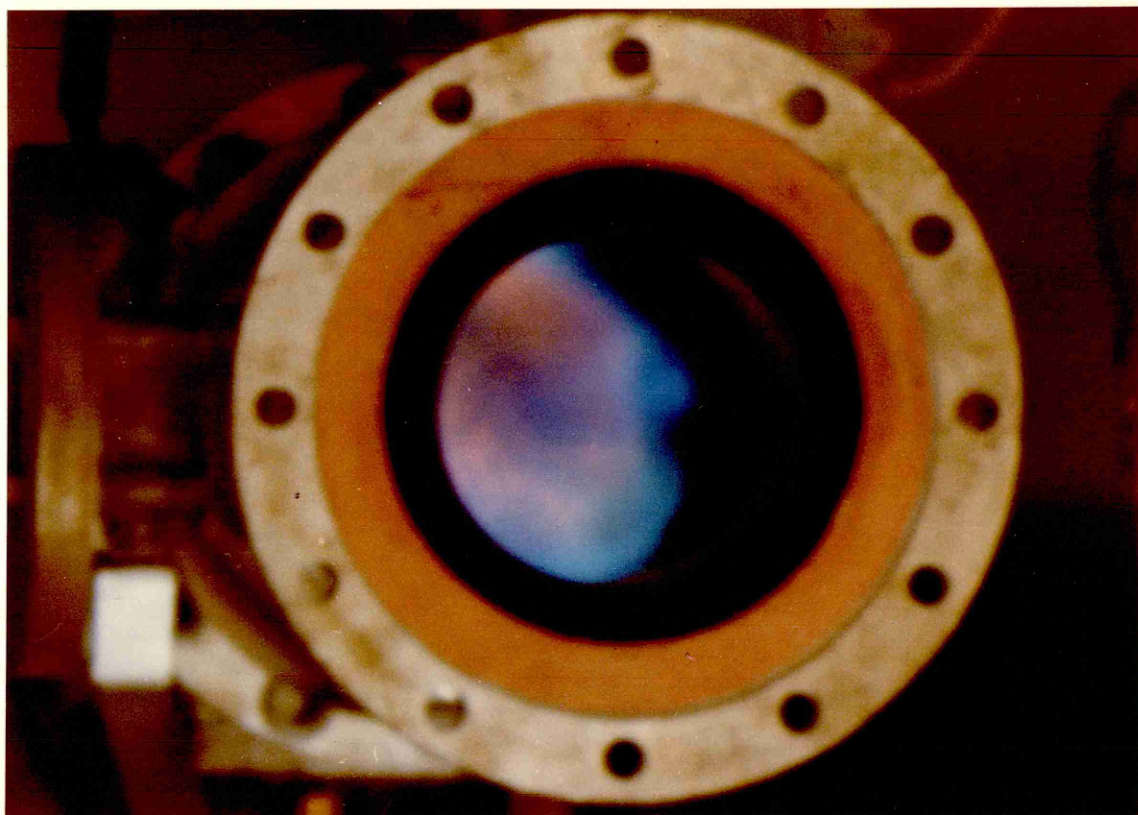
THE ATMOSPHERIC FLAME OF THE SWIRL ATOMISER
AT 50 AFR & 100% DESIGN REFERENCE VELOCITY.

FIG. 42



THE ATMOSPHERIC FLAME OF THE AIRBLAST ATOMISER
AT 50 AFR & 100% DESIGN REFERENCE VELOCITY.

FIG. 43



SECTION 1.

INTRODUCTION.

In the conventional gas turbine combustor, the flame tube is protected from the searing heat of the flame by film cooling. It is essential in the interests of exhaust traverse quality and combustion efficiency that the quantities of air used for cooling should be minimised, thus this problem, which is being aggravated by the continued increase in engine pressure ratios, could be alleviated by any process which reduced the heat transfer to the combustor walls. The specification of cooling air is a compromise between achieving adequate combustion chamber service life and obtaining satisfactory exhaust traverse and combustion efficiency.

In Reference 17, Schirmer & Quigg point out that combustor durability is a severe problem even in present generation engines. A recent unpublished report (40) by B.A. Fuller and D.T. Russell, presented as Appendix I, underlines the problem of combustor durability in engines in current airline operation.. In Rolls-Royce Conway engines, for example, combustor repairs represent 5% - 8% of total engine overhaul costs, and combustor defects are frequently the cause of unscheduled engine removal with an indirect cost of approximately \$4.5 for each hour of unexpired B.C.A.R. approved life. In addition to this, approximately 10% of the scrap to N.G.V.s and turbine blades is due to distorted thermal profiles and direct combustor debris damage.

It has long been established that thermal radiation from the hot gases and material in the combustor can constitute the major portion of the total heat transfer to the combustor walls. In circumstances where flame radiation is such as to be the predominant mode of heat transfer, the flame is invariably highly luminous with a high total emittance. Whilst one is almost obliged to accept the convective heat transfer and non-luminous radiation, unless combustor geometries and fuels are drastically altered, there seems to be a distinct possibility that the important luminous component can be significantly reduced, and thus the cooling problem eased considerably. One of the objectives of this thesis is to investigate the reductions in luminous radiation that can be achieved by the application of partially premixed fuel injection systems.

The luminous component of radiation is known to emanate from the carbon particles formed within the flame, which superimpose a continuum of radiation upon the banded spectral emissions of the heteropolar gases. Reduction of luminous radiation thus implies a reduction in the concentration and size of carbon particles within the combustor, if such a

reduction could be obtained, the added benefit of reduced exhaust smoke level would be achieved. There has been an increasing awareness and intolerance shown towards all forms of atmospheric pollution in recent years, and whilst negligible toxic pollutants are released, gas turbine exhaust smoke emissions have received much criticism. Since the times are not far away when suitable legislation will stipulate maximum smoke levels, it is most appropriate that methods to reduce smoke emissions should receive attention.

Unfortunately, the mechanisms and factors involved in the production of carbon in hydrocarbon combustion are not well understood, this situation being explicable in terms of complexity, not a small factor in this situation being the inability to predict and determine the prevailing conditions at the sites of carbon formation. This being the case, progress can only be made using the best of empiricism, and thus there is a requirement for much experimental data, in order to improve empirical methods and provide material for analytic attempts. Whilst there is a real need for data from specialised apparatus in which particular aspects or mechanisms can be studied to the exclusion of others, there is also a need for data from combustors typical of those used in gas turbines. The reason for this is that many of the processes and mechanisms oppose one another, thus the relative importance and dominance, which may alter with operating conditions, can only be established in real combustors. It is thus the aim of this thesis to perhaps contribute in a humble way to the data from real combustors.

SECTION 2.

FLAME RADIATION.

2.1 Future Engine Trends.

In the inevitable quest to improve upon engine design and performance, Pratt (17) predicts the following trends to increase overall efficiency at a lower specific weight. The overall cycle efficiency defined:-

$$\eta_{OL} = \eta_{TH} \times \eta_{PROP.}$$

where $\eta_{OL.}$ = overall cycle efficiency

$\eta_{TH.}$ = thermal efficiency

$\eta_{PROP.}$ = propulsive efficiency

Both $\eta_{TH.}$ and $\eta_{PROP.}$ will be improved, η_{TH} by increasing engine pressure ratio, and $\eta_{PROP.}$ by increasing by-pass ratio. In addition, lower specific weight will be achieved by increasing turbine inlet temperatures, and improved mechanical design to reduce weight directly.

These trends affect combustion parameters as follows:-

- (a) Combustor inlet temperature increased.
- (b) Combustion pressure increased.
- (c) Combustor mass flow increased.
- (d) Volumetric heat release rate increased.

Reduced weight will tend to shorten combustors and reduce their volume. This trend can only be realised if more effective control is gained over combustor heat transfer and carbon production. To aggravate the situation, the above mentioned combustion parameter trends are such as to worsen the heat transfer via flame radiation and, in addition, would necessitate the use of increased cooling air, since the heat sink capacity of the air is reduced by virtue of its increased initial temperature. Sterry (21) also predicts this increasing adversity which the combustor will be asked to endure, and also points out that the cooling problem will be critical, since cooling air must be minimised in the interests of traverse quality and pressure loss. Cooling air increases must also be minimised in the interests of combustion efficiency since fuel entrainment in the cooling air, and quenching, reduce combustion efficiency.

In anticipation of future problems, it is appropriate that much emphasis should be placed upon radiative heat transfer from the flame (8). This is so, because although the convective heat transfer will increase in future engines, the radiative heat transfer is increasing at a greater rate as combustion pressure is increasing. Schirmer & Quigg (17) point out that for highly luminous flames, radiative heat transfer can constitute 10% of the total heat release, and up to 80% of the total flux to the walls. Reeves (6) also suggests that radiation can be the predominant mode of heat transfer to the liner. As will be demonstrated later, it is also appropriate that much attention should be paid to flame radiation since it is far less clearly understood than convective heat transfer, and its accurate prediction at the design stage is impossible at present.

It is of interest to note that a knowledge of mechanisms involved in the control of flame radiation, is not only important for use in the gas turbine field for reduction of radiation. Foster (10) points out that such knowledge could equally well be used in furnace design where an increase in flame radiation would be desirable.

2.2 The Laws of Radiation.

Whilst a real combustor flame radiates in a manner which is usually far removed from that of a black or grey body, a knowledge of the laws of black body thermal radiation is necessary, since these provide the basis for any description of flame radiation.

The basis for the laws and concepts of black body radiation was laid down in 1860 when Kirchhoff postulated that the radiation issuing from a small hole into a large cavity was black in nature (1). He then formulated his law upon which the Schmidt Method, used in this work, hinges. The law may be stated as follows:- "At thermal equilibrium, the emissivity and absorptivity of a body are the same". (2)

From experimental data, Stephan in 1879 deduced that the total radiant energy from a body was proportional to the fourth power of its temperature. From theoretical considerations, Boltzmann, 1884, confirmed this fourth power law, which is now known as the Stephan-Boltzmann law for total hemispherical radiation:-

$$q_T = [\sigma T^4] \quad \text{--- (1)}$$

In 1891, Wien, again from theoretical considerations, derived his "Displacement Law", which stated that for a black

body, the product of the absolute temperature and the wavelength at which the maximum spectral radiant intensity occurs is a constant. This law, in fact, defines the shift of peak of the Planck curve towards the visible as temperature increases.

Perhaps the most important law of radiation was developed in 1901 by Max Planck. He developed his law during an attempt to reconcile the existing empirical laws by formulating a universal law from theoretical considerations. Planck's Radiation Law is:-

$$\dot{q}_\lambda = \frac{2\pi hc^2 \lambda^{-5}}{e^{ck/\lambda T} - 1} \quad \text{--- (2)}$$

The equation is usually stated in reduced form:-

$$\dot{q}_\lambda = \frac{c_1 \lambda^{-5}}{e^{c_2/\lambda T} - 1} \quad \text{--- (3)}$$

N.B.

$$\dot{q}_T = \sigma T^4 = \int_0^\infty \dot{q}_\lambda d\lambda = \int_0^\infty \frac{c_1 \lambda^{-5} d\lambda}{e^{c_2/\lambda T} - 1} \quad \text{--- (4)}$$

During the derivation of his equation, Planck was led to a postulation which was to be the basis of the quantum theory (1). Fig.1 shows the Planck Law for two different black body temperatures, and it also illustrates the need for radiation studies to be carried out well outside the visible range of the spectrum into the infra-red, since this is area of the major portion of radiant heat transfer. This is illustrated by considering a black body at 2000°K, for example, where the percentage of the total radiation from all wavelengths, which is passed between 0 and 1 micron, is approximately 7%, whereas between 0 - 10 microns, approximately 96.5% is passed.

The final important concept is that of the grey body. A grey body emits less radiation than a black body at the same temperature, and at any wavelength λ , the grey body emits a fixed proportion of that emitted by the black body, such that:-

$$\frac{q_{\lambda \text{ grey}}}{q_{\lambda \text{ black}}} = \text{Constant}, \epsilon_{\lambda} \quad \text{--- (5)}$$

and

$$\epsilon_{\lambda} = \epsilon_T \quad \text{--- (6)}$$

For real flames, ϵ_{λ} is very rarely a constant for all wavelengths, as illustrated in Fig.1, although one must assume that the flame is grey for all techniques of estimating flame temperatures and emissivity that use total radiation rather than spectral or monochromatic radiation. This is discussed more fully in Section 7.

As pointed out in ref. (4), the ending "-ivity" should strictly only be used to describe a property that is independent of size or shape, i.e. a specific property. Where a property is dependent on size or shape, the ending used should be "-ance". Throughout this thesis, however, the terminology used conventionally in the literature has been adopted and, for instance, the term "flame emissivity" is used, whereas "emittance" is the correct term, since flame emittance is definitely a size and shape dependent property.

2.3 The Nature of Flame Radiation.

All materials radiate energy, the amount depending on the material properties and the temperature. In combustor flames, the important materials are unburnt fuel, air and combustion products. From temperature considerations, only the combustion products and heated excess air need be considered important radiators.

As previously hinted, the most important radiators in gas turbine combustor flames are the carbon particles formed during combustion. These particles may be very small in size compared with the important wavelengths, and thus contribute very little to the total radiation from the flame, when this situation exists the flame is called a "non-luminous" flame. This term has little to do with the visible properties of the flame, since non-thermal radiation of an electronic nature such as chemi-luminescence, can often make a flame very bright and yellow to the eye, whilst radiating little thermal radiation in the important infra-red.

Where, however, the carbon particles have sufficient size and concentration to emit substantial radiation in the infra-red, the flame is then termed "Luminous".

(i) Non-luminous Flames.

Gases are selective emitters in that they emit a large proportion of their total radiant energy in discrete wavelength bands. (6) (2) (1) (3). In each band, high resolution spectroscopy has shown that many spectral lines exist (3) (4) which are caused by well defined quantum number changes within the molecule. Hodgson (3) points out that there are three types of quantised energy transitions:-

- (1) rotational transitions
- (2) vibrational transitions
- (3) electronic transitions

In a general transition, one particular type of transition dominates the energy change and the bands are correspondingly named:-

- (1) rotational changes, $[10^2 - 10^4 \mu]$ (far infra-red)
- (2) vibrational changes, $[1 - 30 \mu]$ (infra-red)
- (3) electronic changes, $[10^{-2} - 1 \mu]$ (visible)

Due to the energy distribution defined by the Planck equation (see equation (2) Section 2.2 and Fig.1), the bands of most interest are the vibrational bands from 1 to 30μ . Whilst the change in vibrational quantum number defines the spectral position of the band, the actual lines within the band are defined by simultaneous vibrational and rotational transitions, thus the vibrational bands are often referred to as the "vibrational-rotational" bands (3).

At the temperatures encountered in furnaces and gas turbine combustors, the only species that emit significant quantities of radiation are heterapolar molecules of unsymmetrical structure such as carbon monoxide, carbon dioxide, water vapour and hydrocarbons. In the gas turbine combustor, the molecules of main interest are the carbon dioxide and water vapour in the combustion products. Both carbon dioxide and water vapour emit in two important spectral bands at about 2.8μ and 4.5μ , this is illustrated in Fig.1, and shows that the spectral emissivity in these bands can be quite high. This fact may well be of importance in the measurement of gas temperatures by narrow band

pass pyrometry, since, if as appears to be the case, the spectral emissivity in the 4.5μ band were nearly constant over a wide range of conditions, a pyrometer with filters such that only this band is viewed, could be used to give gas temperatures with a single reading. This is currently being considered for use in gas turbine control systems such that combustor exit temperature could be monitored as a control system input rather than jet pipe temperature as currently used in the interests of thermo-couple durability. Such a system would enable one to sail closer to the wind during engine transients, since the control system programme would not need to have built-in estimates of factors such as turbine thermal capacity and turbine acceleration work in order that turbine inlet temperature can be controlled from jet pipe temperature. Since maximum turbine inlet temperature is one of the most important engine operating limits and also is an important cycle parameter, one would like to directly monitor this anyway.

Whilst the spectral emissivities in the 2.8μ and 4.5μ bands may be approaching unity, the effective total emissivity as defined by the Stephan Boltzmann law, postulating an equivalent grey body, is usually very low, typically in the region of 0.05 to 0.10:-

$$\dot{q}_T = [\epsilon_T \sigma T^4] \quad \text{--- (7)}$$

(ii) Luminous Flames.

Whilst pre-mixed flames tend to be of a non-luminous nature, emitting radiation in discrete spectral bands, diffusion flames with many fuels generate carbon particles which can emit radiation that is essentially black-body in character. Thus, superimposed on the banded molecular radiations is a continuum in the infra-red which can raise the effective flame total emissivity to a high level, and thus drastically raise the total radiant flux issuing from the flame.

The radiation from a cloud of carbon particles depends both on the particle size and the total mass concentration. The carbon particles can only radiate appreciably when their size is large enough to emit at the important wavelengths in the infra-red, thus very

small carbon particles could well be present in some non-luminous flames, some workers (7) have postulated that carbon particles are present in all hydrocarbon flames so long as fuel is burning. Unfortunately, far less is known about the factors that affect the formation and size of carbon particles and the radiative properties of such particles, than is known about gas vibrational-rotational emissions; more thought is given to this subject in Section 3.

2.4 Prediction of Flame Radiation.

(i) Non-luminous Radiation.

Penner (4) presents the theoretical methods that are available for the calculation of vibrational-rotational gas emissions. The various theories and models illustrated generally require extensive use of the principles of wave mechanics, and exact numerical solutions require the knowledge of a considerable number of spectroscopic gas constants. Penner points out that whilst it is now possible to perform exact calculations for some diatomic gases, for which extensive spectroscopic studies have revealed the various constants, for polyatomic gases, this is not yet possible. He suggests that in principle there is nothing to prevent calculations for polyatomic gases such as carbon dioxide and water vapour, but such processes are prevented due to a lack of knowledge of the spectroscopic constants. Apparently, however, some success has been obtained with semi-theoretical correlations utilising such spectroscopic data as exists, although, for engineering purposes, a continued reliance upon empirical methods is necessary for the moment.

Whilst such theoretical methods are comparatively recent developments, empirical methods were formulated by R. Von Helmholtz in 1900. He proposed a very simple model which fitted in with the then popular view of chemiluminescence being the nature of flame radiation. Hottel (5) points out that such attitudes lingered for many years and flame radiation was frequently quoted as a percentage of heat of combustion.

In 1924, Schack published his work with furnace flames, which laid the foundations for flame radiation calculations based on a thermal radiation concept. It is rather illuminating to consider that Planck had already developed his radiation law nearly a quarter of a century beforehand, his law clearly indicated the nature of radiation and the importance of emissions in the infra-red.

The classical method of estimating the emissivities of carbon dioxide and water vapour is due to the work of Hottel and others. They performed extensive experimental work with both gases, and also correlated the results of other workers to present the famous emissivity charts. These charts present the emissivity of a hemispherical volume of gas radiating to the centre of its base, as a function of the product of the gas partial pressure and the hemisphere radius, and the absolute temperature of the gas at a total pressure of one atmosphere. For other pressure levels, they defined an overall emissivity correction factor for the total pressure range 0.05 to 5.0 atmospheres. Penner (4) points out the dangers of extrapolating empirical data beyond the range for which the data is valid, and Durrant (8) emphasises that as a result of this, the work of Hottel is no longer applicable to present and future generation gas turbine heat transfer calculations where pressure ratios of 25:1 or 30:1 place such calculations far beyond Hottel's work. Hottel's work does, however, provide for gas temperatures up to 5000°R, and provides a further correction factor for mixtures of the two gases where the coincidence of spectral emission bands makes the one gas slightly opaque to the other, and thus the total emissivity of the mixture is slightly less than the sum of the two in isolation at the appropriate partial pressures.

The actual use of the charts is laborious and Reeves (6) successfully reduced them to an empirical formula which is valid over the same range of conditions:

$$\varepsilon_T = 1 - \exp \left\{ \frac{-P(qL)^{0.5} 1.6 \times 10^4}{T^{1.5}} \right\} \quad (8)$$

(non-lum.)

For distillate fuels where:-

P = pressure (atmospheres)

q = fuel air ratio

L = optical path (feet).

T = temperature (° K)

Reeves (6) noted that by suitable choice of variables, supposedly non-luminous flame emissivities approaching unity could be obtained, suggesting that some of the flames examined by Hottel were in fact luminous.

In conclusion, one can say that the emissivities of non-luminous flames can be estimated with fair accuracy up to pressures of 5 atmospheres, but beyond this into the range of current interest, very little useful data exists that could be of use to the designer.

(ii) Luminous Radiation.

McAdams (2) states that the theoretical prediction of luminous emissivities is not well advanced from an engineering point of view. To emphasise the importance of this fact, and that of the problem in general, the International Committee on Flame Radiation has been set up at IJmuiden, Holland, with the broad objective of developing a recommended procedure to predict flame radiation.

The nature of carbon particles formed in a combustor is discussed in Section 3. In order to perform heat transfer calculations for radiation from carbon particles, a knowledge of the temperature of the particles is necessary. Schirmer & Miller (9) state that there is evidence to suggest that such particles are at the same temperature as the hot gases, which, considering their size and formation mechanisms, would seem quite reasonable.

Most attempts to predict the radiation from clouds of carbon particles have hinged on the solution of Maxwell's equations for the interaction of electromagnetic waves with a homogenous sphere of unit permeability as formulated by Mie. (10) (11). The Mie equations express the fractions of incident radiation upon a cloud of uniform particles, scattered and absorbed by the cloud, and take the form of Bessel Function series. In Ref. 10, these Bessel functions are expanded in power series, which prove so convergent that, it is stated, only the first term need be considered. With the assumption that scattering of radiation is unimportant, the following equation defines the spectral emissivity:-

$$\epsilon_{\lambda} = 1 - \exp \left\{ - \left[\frac{72}{\lambda} \frac{n^2 k}{(n^2 + n^2 k^2)^2 + 4(n^2 - n^2 k^2 - 1)} \right] \bar{c} L \right\} \quad (9)$$

where n = real relative refractive index of soot

k = absorption index at wavelength λ

$\bar{c}$ = mean soot concentration $[\text{mg/litre}]_{\text{ref}}$

L = optical path length $[\text{cm}]$

N.B. The complex refractive index of soot, m , is defined

$$m = n[1 - ik] \quad \text{--- (10)}$$

Equation (9) may be directly compared with an empirical equation used by Hottel & Broughton (2) for the correlation of luminous flame data of the form:-

$$\Sigma_{\lambda} = 1 - \exp \{ -f(\lambda) \varepsilon L \} \quad \text{--- (11)}$$

where $f(\lambda)$ is frequently used in the form:-

$$f(\lambda) = [B\lambda^{-\alpha}] \quad \text{--- (12)}$$

where B and α are constants.

The form of the equations (9) and (11) is, in fact, very similar to Beer's Law for a uniform absorbing medium which may be written:-

$$a_{\lambda} = 1 - \exp \{ aL \} \quad \text{--- (13)}$$

where a_{λ} = spectral absorptivity
 a = absorption coefficient
 L = medium thickness

In Ref.11, a similar technique to that used by Foster (10) was employed, but here account was taken of the non-luminous background radiation which led to the following equation:-

$$\Sigma_T = 1 - \exp [-B\lambda^{-\alpha} \varepsilon] [1 - \Sigma_n] \quad \text{--- (14)}$$

Whilst these theoretical equations have provided good correlations with experimental results under certain circumstances, their general application to gas turbine combustors would seem to be hindered

by an inadequate knowledge of the optical properties of combustor carbon particles, and the inability to predict carbon concentrations.

Various empirical methods have been suggested to account for luminosity in flame radiation calculations, Reeves (6) presents a modified version of equation (8) of the form:-

$$\Sigma_T = 1 - \exp \left[- \left\{ \frac{P(qL)^{0.5} \times 1.6 \times 10^4}{T^{1.5}} + AL \right\} \right] \quad (15)$$

where A is a function of combustion pressure, P and fuel air ratio, q , typically for gas oil fuel:-

$$A = [1.65 P^{1.5} (q - 0.022) - 0.015] \quad (16)$$

Another approach used by Lefebvre & Herbert involved the definition of a luminosity factor $\mathcal{L}$ such that:-

$$\mathcal{L} = \left[\frac{\log_e (1 - \Sigma_T)}{\log_e (1 - \Sigma_{\text{nonlum}})} \right] \quad (17)$$

At one atmosphere for a kerosene flame in one chamber, $\mathcal{L} = 1.7$, and in another chamber also at one atmosphere, $\mathcal{L}$ was calculated from wall and gas temperatures to be 1.97. (8)

Whilst these empirical correlations may well give good agreement for one chamber size and geometry, reservations must be placed on their application to geometrically different chambers operating at different conditions.

In conclusion, one can only assume that the prediction of luminous radiation in real combustors at realistic conditions is equally ill-advanced as the prediction of non-luminous radiation, and a great deal more experimental work is required if the situation is to be improved.

2.5 The Geometry of Combustor Radiation.

Due to a combination of Lambert's Cosine Law, the Inverse Square Law and the effects of optical path length, the radiation of a general gas volume to some surface is very complex geometrically. There have, however, been

exact analytic solutions for certain uniform gas volume shapes radiating to certain surfaces. The usual way in which such geometry is allowed for is in the evaluation of a factor applied to the geometrical path length, to define an effective path length to be used in radiation calculations.

For application to combustor flames, the situation is complicated by the definition of the relevant gas volume, since the flame geometry and temperature fields are extremely complex. In the literature, however, most workers have adopted a factor of 0.6 to the flame tube diameter to define an effective optical path length. This is, in fact, the factor for a right-circular cylinder with height equal to diameter, radiating to the whole curved surface, and this factor will be adopted where necessary in this work.

SECTION 3.

SMOKE EMISSIONS AND COKE DEPOSITS.

3.1 Importance and extent of the problem.

It is interesting to note that the problem of atmospheric pollution in the form of smoke is not a new one. In 1288 A.D., Edward I banned the use of soft coal in place of wood in the lime kilns near London, due to the unsightly smoke which was seen to issue forth. Today, there is increasing attention drawn towards all forms of atmospheric pollution, and it is understandable that gas turbine smoke emissions should be at the forefront of discussions, since they are amongst the most clearly visible of all forms of smoke sources. In the literature (14) (22) it is pointed out that toxic pollutants such as carbon monoxide, the oxides of nitrogen and sulphur and hexane are present in only insignificant quantities, however, the large volumes of smoke generated by large airliners at take-off represent a considerable nuisance factor in the vicinity of airfields. Toone (7) quoted some military engines as producing up to 36 lb. of smoke per hour, which, although this represents a negligible loss in efficiency through unburnt carbon, could be of great importance in the detection of the aircraft at a distance. Ref.22 points out that smoke has also been a considerable nuisance in carrier launch and recovery activities.

The importance of the problem is underlined by the fact that both Rolls-Royce (22) and Pratt & Whitney (14) are expending considerable efforts in an attempt to reduce smoke at the design stage by an understanding of the mechanisms and design features which affect smoke production. Considerable effort is also being put into attempts to improve the smoke level of existing engines. Typically, the smoke production of the Spey Mk.512 was reduced from 33 to 15 parts per million via better primary zone oxygen distribution using flanged chutes to improve air penetration.

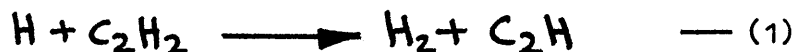
Coke, the carbon deposits within the flame tube, is less of a problem today than it used to be. This is the result of both improved design and the fact that the increased combustor temperatures tend to burn deposits away. Carbon deposits are, however, still a problem (23) on colder components such as the fuel injector, where excessive deposits can indirectly cause liner damage by altering patternation and cone angle to cause hot spots. Liner distortion and cracking can be a problem where uneven deposition occurs, causing severe temperature gradients and differential expansion. Coke deposits have been of importance in smoke

research, since the soft coke deposits, which originate as smoke, have provided valuable information concerning the nature of smoke before being subjected to exhaust burn-out.

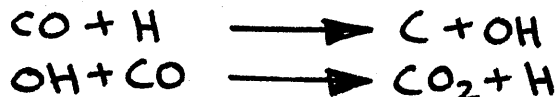
3.2 Carbon Formation Mechanisms.

Carbon is formed in fuel rich regions at high temperature. Gas and smoke sampling in the primary zone of Dart combustor (7) showed good correlation between lack of oxygen and carbon quantities to confirm this generalisation. The actual mechanisms involved in the production of smoke are exceedingly complex with a fuel such as kerosene, since the chemical composition is equally complex. Whelan (24) states that 159 different compounds with boiling points below 300°C. have been isolated, varying from methane CH_4 to n-tetracosane $\text{C}_{24}\text{H}_{50}$. Thus the variations in structure and oxidation sub-reactions of all these compounds makes the isolation of carbon releasing reactions impractical.

An excellent review by Schalla and Hibbard (12) discussed the results of many workers mainly using single compound fuel, and compares the many different mechanisms which are proposed for carbon formation. It would appear that both liquid and vapour phase reactions are of importance, probably very early in a droplet's lifetime thermal dehydrogenation occurs before coming into contact with oxygen, then in the vapour phase further dehydrogenation occurs due to active radicals. This dehydrogenation process receives further weight from energy considerations, since the activation energy is low for many hydrocarbon dehydrogenation reactions. For acetylene:-



the activation energy is only 5 kilocalories per mole. This is in contrast to reactions of the Boudouard type as proposed by Behrens (24):-



For this type of reaction there is a formidable energy barrier.

The active radical dehydrogenation processes have been partially confirmed by combustion with the concentration of these active species suppressed, and reduced smoke level was detected. (12)

Whelan (24) and Schalla and Hibbard (12) point out that acetylene is probably involved in many of the smoke forming reactions. Acetylene is willing to pyrolyse to carbon and hydrogen most readily at flame temperatures, and would thus be an excellent carbon generator, and in addition acetylene

is present as a product at the pyrolysis of nearly all hydrocarbons. In Spectroscopic studies, Cole & Minkoff (24) found acetylene very often present at hydrocarbon pyrolysis, but addition of extra acetylene to flames produced no extra carbon, which may be an important argument against the theory. However, many other workers consider acetylene to be very important in smoke formation.

Schalla & Hibbard (12) conclude from their review of smoke forming mechanism investigations, that the final mechanism to convert the small molecules and radicals to free carbon is as yet unknown for certain. It seems unlikely that polymerisation of C_2 radicals following acetylene pyrolysis is the final answer. Much evidence points to simultaneous polymerisation and dehydrogenation, which makes the chemistry of smoke formation exceedingly complicated. (Schalla & McDonald (24) point out that whatever the smoke mechanisms may be, under nearly all circumstances, the smoke forming tendency increases with increasing combustion pressure, which is of utmost importance in that the consequent luminous radiation component likewise increases.)

Combustor coke is generally seen to be of two forms, a hard and a soft variety, both existing in varying proportions. The hard variety is thought to be the result of liquid pyrolysis of fuel droplets impinging on the hot liner wall with the deposition of the heavy non-volatile residues which yield hard deposits upon final pyrolysis. The soft variety of coke is thought to be smoke particles which reach the wall and become trapped in the hard coke matrix as it is undergoing final dehydrogenation, or under certain circumstances may form deposits independently.

3.3 The Nature of Smoke.

Whelan (24) states that X-ray and electron diffraction techniques have shown that smoke particles are not amorphous, as was originally thought, but consist of an agglomeration of chrySTALLITES with a lattice structure similar to graphite. A typical analysis of smoke shows about 96% carbon, 1% hydrogen, with the remainder thought to be oxygen. The chrySTALLITES are typically about 20 angstrom with the smoke particles being almost spherical of diameter 0.01 to 1.0 micron (12). Toone (7) states that sampling in the predilution zone of a given chamber showed more smoke than in the dilution zone, therefore smoke particle burn-out must occur. This is confirmed by the eroded nature of exhaust smoke particles under the electron microscope.

The burn-out phenomenon could allow one to postulate the presence of smoke at all times in, say, the primary zone.

At low pressures, the size could be such as to be easily consumed before leaving the chamber. This need not imply that luminous radiation must be present at all times in the primary zone, since, as pointed out by Schirmer (25), their small size could be such as to only absorb and scatter at short wavelengths in the visible, and thus contribute nothing in the important infra-red, being transparent.

It has been shown in Section 2 that for the purposes of estimating flame radiation, both carbon particle size and mass volumetric concentration would need to be known at the radiation site. The experimental techniques available for the measurement of these quantities with accuracy have only been developed comparatively recently for application in the primary zone. Toone (7) has shown that sampling should be isokinetic, and a more recent classified report shows the sophisticated techniques that are required to overcome the problem of carbon deposition in the sampling line and meter, due to condensation of the water of combustion.

In conclusion, one may perceive that it is impossible at present to make accurate quantitative predictions of the size and mass concentration of carbon particles in any sort of flame from a theoretical point of view. This situation exists because the carbon formation mechanisms are not fully understood, so that no theory can exist. There is also very little empirical data available from which reliable estimates can be made of carbon concentrations in combustor flames.

SECTION 4.

COMBUSTION PROCESSES.

4.1 Effect on Flame Radiation and Smoke Emissions.

It may be possible in the future to calculate radiant heat fluxes to the wall of a gas turbine combustor in some detail using a machine solution to an elemental model. This would imply that both luminous and non-luminous radiant fluxes could be accurately calculated for an element from a knowledge of the composition and thermodynamic state existing within an element, this proposal is discussed in Section 2. A further, and more difficult, implication is that one could predict the composition and thermodynamic state that exists at all points within the combustor. This prediction could only be performed with a quantitative knowledge of the following combustion processes and parameters and their mutual inter-action:-

- (a) Combustor aerodynamics.
- (b) Fuel injection and distribution processes.
- (c) Flame mechanisms.
- (d) Fuel type and chemistry.
- (e) Operating conditions.

With such knowledge, one could predict local carbon concentrations, and thus resultant smoke emissions, with a knowledge of the carbon formation mechanisms, this is discussed in Section 3. Some of the effects of the above processes are fairly well understood in isolation, but the effects of interaction and dependency make their combined action extremely complex. The situation is so complex that such solutions will probably not be obtained in the near future. It is nevertheless important that these processes should be understood, even if only qualitatively, in order to provide a basis for the design of combustion experiments and subsequent analysis, so as to make progress by empirical methods. Thus it is appropriate that combustion processes should be briefly discussed here with emphasis on those aspects that particularly affect flame radiation and smoke emissions.

4.2 Combustor Aerodynamics.

(i) Entry Velocity Profile.

Scull & Mickelsen (12) point out that entry velocity profile is most important for good diffuser performance. If the profile is unfavourable, high pressure losses can occur in diffusion which affects overall cycle performance if flame tube pressure

drop is maintained. Combustor inlet diffusers are, of course, designed as far as possible to cope with such maldistributions as exist. Bad profiles can also lead to maldistributions of secondary and cooling air, with the attendant adverse effects on flame tube durability.

(ii) Air Distribution.

Perhaps the most important air distribution factor is the split of air to the primary zone. Lefebvre (13) points out that primary air split has an important effect on every aspect of combustion performance. British primary zones tend to be stoichiometric, whereas American engines have featured over-rich primary zones in many engines. In stoichiometric primary zones, burning velocities and chemical dissociation are at a maximum (13), although stability limits are wider in an over-rich primary zone. This wider stability is important in the altitude relight criterion, and is probably a major factor in the use of over-rich primary zones. Lefebvre (13) points out that an over-rich primary extends the stability limits by both creating longer residence times for mixing and evaporation and reducing local air-fuel ratios in the last strongholds of combustion as the mixture is weakened off. An over-rich primary zone, however, has the important disadvantage that smoke production is always higher (8) (13). Durrant (8) reports a three-fold increase in engine smoke at nearly all engine speeds for an over-rich primary, although he does not state the equivalence ratio in operation to achieve this. He also points out that a stoichiometric primary zone does not appear to be as sensitive to variations in fuel type as far as smoke level is concerned.

Whilst the smoke level and therefore combustor carbon concentration is higher when over-rich, this need not necessarily imply that total radiation is increased. The emissivity of the flame will increase, but the local flame temperatures may well be lower to compensate (8).

In view of the increasing effort to reduce smoke levels, it may well be that the over-rich primary zone will fall from favour, and acceptable stability limits maintained by other design features. Beckwith (14) reports that Pratt & Whitney have successfully demonstrated a variable geometry combustion chamber such that the primary zone runs stoichiometrically under normal flight and take-off conditions, but for ignition at altitude, a proportion of the primary air holes are

blanked-off to create the over-rich conditions favourable to good ignition. He says that it is hoped that improved design of atomisers particularly will make such complication unnecessary. Some success has been obtained with presumably over-rich primary zones (14) by feeding extra air to the centre of the fuel cone, which is known to be a favourite centre for carbon formations (8).

Having decided the amount of primary air, the proportions of air to the intermediate and dilution zones are perhaps less important here than consideration of cooling air. The cooling air quantities are decided by the cooling design features used and the estimated total heat fluxes. It is essential that cooling air flows should be minimised from the viewpoint of traverse quality and loss of combustion efficiency via entrainment of unburnt fuel and quenching (13).

(iii) Combustor Pressure Loss.

Because of the low flame speeds available and the limits to which overall air velocity can be reduced in a sensible volume, flame stabilisation is achieved by a recirculatory system. It is inevitable that some pressure loss will be incurred. Scull & Mickelsen (12) point out that the pressure loss used in real combustors is a compromise between achieving a sensible combustor volume and minimising the loss of cycle efficiency through pressure drop across the combustor. Combustor pressure drop is typically 4% to 7% of inlet total pressure.

Pressure drop is an important factor in creating the turbulence levels required from mixing and evaporation considerations, and is also important in the dilution zone in respect of traverse quality (12). Since increased pressure drop will influence penetration and thus primary zone oxygen distribution, it may well be an important factor in the control of smoke production and flame radiation. Toone (7) showed this to be the case in three different combustors where the following smoke reductions were noted:-

(a)	In one combustor,	3% increase,	reduced smoke	70%
(b)	In another "	1½%	" "	37%
(c)	" " "	1%	" "	30%

From a cycle efficiency point of view, there is obviously a limit to the extent to which this mechanism could be used to reduce smoke, and it may well be that the actual air distribution, particularly in the primary zone, at

a given pressure loss factor will prove to be of more use via suitable design.

Pressure loss factor is also of importance in the use of unassisted airblast atomisers, since this dictates the velocity available at the atomiser. This is particularly important at engine cranking speeds (15), where the low driving force is critical in obtaining suitable atomisation for ignition. Miller (16) estimated that for typical combustors with a clean burner design, velocities in the region of 240 ft./sec. could be obtained at the site of atomisation.

4.3 Fuel Injection and Distribution Processes.

The method and quality of fuel injection is proving one of the most important factors in the control of flame radiation and smoke levels. For many years, pressure swirl atomisers of the simplex, duplex, duple and spill types have operated entirely satisfactorily at the pressure levels of previous generation engines, but with the continued increase of engine pressure ratio, increasing attention is being focussed on other methods of injection in an effort to reduce flame radiation and smoke. Schirmer & Quigg (17) point out that modern design trends must increase flame radiation unless some radical change in fuel presentation, such as premixing, is employed.

Graves & Bahr (12) point out that the experimental and theoretical work into the atomisation process is not sufficiently complete to permit direct application. There is no general theory in existence based on the mechanisms involved. Atomisation may be regarded as occurring in 6 steps:-

- (1) Stretching of the fuel into streams or sheets.
- (2) Small local ripples or protuberances are formed as a result of liquid or air turbulence.
- (3) The sheets and streams break down to form ligaments under the influence of aerodynamic and surface tension forces.
- (4) The ligaments collapse to droplets.
- (5) Further droplet breakdown can occur due to aerodynamic forces.
- (6) Droplets may re-combine or agglomerate to form larger droplets.

All, or combinations, of these mechanisms are present in atomisation by any injector system.

Three main types of fuel injector warrant consideration, for application to high pressure ratio engines, namely

vapourisers, pressure swirl atomisers, and airblast or airspray systems, which may be considered to approximate to a premixed system.

(i) Vapourising Systems.

Vapourisers of the classical "Walking-stick" type have proved effective in comparatively low pressure ratio engines, but there appears to be considerably doubt as to their suitability for high pressure operations. The reasons for this statement are twofold, firstly, their mechanical durability when immersed in the luminous flames at high pressures must be suspect, and secondly, it appears that above about 2 atmospheres combustion pressure the vapouriser acts more as a crude airblast atomiser than a vapouriser. Further disadvantages of vapourising systems are that a pilot atomiser is required for starting; since the vapourising tube is mechanically part of the combustor, design and development is difficult; fairly narrow stability limits prevail and a slow response to fuel flow changes is often evident. Advantages claimed for the system include moderately high heat release rates, as illustrated in Fig.2. the outlet temperature traverse is fairly insensitive to fuel flow, since the fuel is air borne, and only a relatively low pressure fuel system is necessary. Perhaps the most important advantage possessed over pressure swirl atomisers is that the partial premixing of fuel and air tends to produce less carbon and thus smoke levels and luminous flame radiation are lower.

The vapouriser thus does not warrant further consideration, since it will be shown that all the advantages, but only some of the disadvantages are shared with the airblast atomiser. There has been very little theory developed to account for vapouriser performance, and thus the systematic design of a vapourising chamber is not possible, which is a serious disadvantage in "new technology" engines.

(ii) Pressure Swirl Atomisers.

These types of atomisers have been the most widely adopted fuel injection system for many years. They are mechanically robust and easy to develop. Swirl atomisers do need high fuel pump pressures to be able to cover the flow range required (18), even with duplex or duple systems. The exhaust temperature traverse is dependent on fuel flow, since the fuel distribution is largely governed by fuel momentum rather than chamber aerodynamics.

Swirl atomisers are known to create fuel rich zones within the primary zone, the main zone being in the centre of the fuel cone near the nozzle. Toone (7) clearly illustrates this with a map of oxygen contours in the primary zone of a Dart combustor. These fuel rich zones are the source of probably the main advantage and disadvantage that has been claimed for the system. The main advantage being the very wide stability limits created, and the main disadvantage being the production of large quantities of carbon within these zones, thus offering considerable flame radiation and smoke production at high pressure.

Although no theory based on the mechanisms of atomisation has been developed for these atomisers (12), several workers have developed empirical equations to correlate their performance. To define the flow performance, dimensional analysis of the relevant variables yields the following relationship:-

$$\frac{\dot{m}_f^2}{\Delta p} = L^4 \rho_f \times f\left(\frac{\dot{m}_f}{\mu_f L}\right) \quad \text{--- (1)}$$

As shown in reference (19), Reynolds Number effects are generally neglected, and thus equation (1) reduces to:-

$$\frac{\dot{m}_f}{\sqrt{\Delta p}} = \text{Constant}, (\text{F.N.}) \quad \text{--- (2)}$$

where $\dot{m}_f$ = fuel mass flow rate
 ρ_f = fuel density
 μ_f = fuel viscosity
 Δp = differential pressure across the fuel nozzle
 L = a characteristic dimension
 F.N. = atomiser constant, Flow Number.

Over wide pressure ranges, the Flow Number is not, in fact, constant, but allowance can be made for this, and the concept is extremely useful.

An excellent review by Graves and Bahr (12) discussed some of the empirical dropsize equations that have been developed. Longwell obtained the following equation by a drop freezing technique:-

$$d_m = \frac{0.72 \times 10^4 r e^{0.070 \nu}}{\sin \beta/2 \Delta p^{0.37}} \quad (3)$$

where d_m = mass-median drop diameter [μ]
 r = Nozzle orifice radius [cm]
 ν = kinematic viscosity [cm^2/sec]
 β = spray cone angle

Watson proposed an equation of the form:-

$$d_{SMD} = \frac{C_1 (F.N.)^{0.209} \nu^{0.215}}{(\Delta p)^{0.348}} \quad (4)$$

where d_{SMD} = Sauter mean diameter
 C_1 = constant.

Consideration of equation (1) assuming a constant Reynolds Number shows that in equation (4):

$$(F.N.)^{0.209} = C_2 (L^4)^{0.209} = C_2 (L)^{0.836} \quad (5)$$

Thus comparison of the equations of Longwell and Watson show a fair similarity with regard to the general form of the equation and the indices on the nozzle fuel pressure differential and nozzle characteristic dimension, although the effects of fuel viscosity are accounted for in a different manner.

Bowen and Joyce (20), correlating data from molten wax sprays, proposed an expression of a somewhat different form:-

$$\log_e(d_{smo}) = (k_2 FN. - k_3)(\log_e \Delta p) + (\log_e k_1) - (6)$$

where k_1, k_2 & k_3 = constants.

The constant k_3 was seen to be much larger than k_2 and thus again the nozzle differential pressure is the dominant factor in determining droplet size. In comparison with the work of Longwell and Watson, it is again interesting to note the similarity of the exponent on differential pressure. The constant k_3 was found to be 0.3712, which inspection of equation (6) shows this to be the effective exponent on differential pressure, this compares with 0.37 proposed by Longwell and 0.348 proposed by Watson.

Empirical equations such as outlined here are, of course, only relevant for the environment used during data collection, in other words, when spraying into quiescent air at ambient temperatures and pressures. When spraying into a real combustor, the environment is a highly turbulent gas stream at elevated temperature and pressure. The information available for these sorts of conditions is strictly limited at the present time, and only qualitative trends have been established. Increasing ambient pressure appears to decrease droplet size, as does an increase in the relative velocity between the spray and working fluid. Increasing the ambient temperature appears to increase droplet size. These trends can well be determined from intuitive reasoning, remembering the importance of aerodynamic forces in the break up of liquid sheets into droplets.

(iii) Airblast and Airspray Atomisers.

In the airblast atomiser system, atomisation is achieved by subjecting a sheet of fuel to the aerodynamic forces generated by a high velocity air stream. Since air is used to break up the liquid sheet, a good degree of premixing of fuel and air is achieved, this fact leads to high volumetric heat release rates, as shown in Fig. 2, very little carbon formation and, unfortunately, very narrow stability limits. The traverse quality for an airblast chamber is insensitive to changes in fuel flow, since the fuel is airborne and fuel pressure probably plays a very small part in

the fuel distribution. This enables one to specify low pressure fuel systems and injectors of large flow number.

The mechanical design of an airblast atomiser may be very simple and, since it is constantly bathed in comparatively cool air, the durability in service should be very good. One of the main disadvantages of the system is that the low air mass flows prevailing at sensible cranking speeds drastically reduces the atomisation quality, which will generally mean that to obtain ignition, large fuel flows must be used to create atomisation via fuel pressure. Once light-up has been achieved, of course, the fuel flow must be rapidly reduced if turbine inlet temperature limits are not to be exceeded (23). As described in Section 9, this could be easily achieved on the test rig, but it is debateable if such a procedure would be acceptable on an engine. There are two possible solutions to the problem for engine application. A pilot swirl type atomiser could be specified with a duplex type fuel system such that ignition and run up to idling conditions could be achieved on the pilot jet (see Section 10), and maintaining an uncompromised airblast atomiser for cruise and take-off conditions. Alternatively, it may prove possible to specify an airblast atomiser with a lower flow number and suitable design such that atomisation via fuel pressure alone would be acceptable at ignition fuel flows. The latter solution, however, will probably imply that traverse quality will be dependent on fuel flow since fuel pressures at take-off and cruise may approach that for conventional swirl atomisers.

The problem of altitude relight is a difficult one, since by definition one cannot have wide stability limits without carbon forming fuel rich zones. For the application of airblast atomisers to engines which are to have acceptable relight performance, again, two possible solutions exist. A duplex fuel system with a pilot swirl atomiser for ignition and run up to idle could be specified with an uncompromised airblast atomiser for cruise and take-off. Alternatively, a compromised simplex airblast atomiser could be specified such that sufficient fuel rich zones could be created to achieve a satisfactory altitude performance, and accept the increased smoke output and flame radiation.

The possible solutions to the ground ignition and altitude relight problems, bearing in mind the operating qualities of a good exhaust traverse, low smoke and flame radiation levels and mechanical complexity, are discussed in Section 10, where design proposals are made.

The process of airblast atomisation is by no means a new proposal, and much experimental and theoretical work has been carried out. In the past, swirl atomisers have been chosen in preference because consideration of all aspects of combustion performance on past generation engines has shown them to be a better overall compromise. For future generation engines, however, airblast atomisers, in one form or another, are receiving increased attention for possible engine application, owing to the increasing emphasis on smoke emissions and flame radiation (22).

The optimum design geometry for airblast atomisers has not yet been established, and a wide range of geometries have been used in the past. The geometry of Nukiyama and Tanasawa (26) led to the belief that an airblast on one side of the fuel sheet was adequate to obtain good atomisation, but Miller (16) (18) found that air blasts on both sides of the fuel sheet prevented the generation of large droplets in stagnation zones, presumably due to agglomeration. The fuel sheet has been injected parallel to the air stream, both with and against it, and also normal to the air stream.

Various models have been proposed for the aerodynamic breakdown of a liquid fuel sheet into droplets. Eisenklam, Dombrowski and Hasson (27) propose that under partial vacuum conditions, the liquid sheet is disintegrated by expanding perforations which coalesce to form unstable ligaments, which then break down into droplets. At higher pressures, however, where aerodynamic forces become more important, the model that has achieved much attention is that of an unstable wave motion whose amplitude increases until breakup into ribbons, ligaments and finally droplets occurs (12)(27). In reference (27), the waves are assumed to propagate at the same velocity as the sheet, and in Fig. 3 the forces acting upon such a wave at the liquid-gas interface are shown. For the liquid sheet, two wave models have been proposed, Fig. 4 shows the symmetrical wave form, and Fig. 5 the unsymmetrical mode, at high relative velocities between the fluids the unsymmetrical mode appears to predominate (12).

The unsymmetrical model was used by Eisenklam (27) and the postulated break up process is illustrated in Fig. 6. A theoretical analysis revealed an optimum wavelength for a given set of conditions, and at this wavelength the infinite sheet was first assumed to collapse into a ribbon of half cycle width. The ribbon was then condensed into a uniform ligament of radius r_{lig} by conservation of mass, and then Rayleigh's criterion for jet break up was applied to define ligament collapse into droplets. Rayleigh's analysis showed that at the

optimum wavelength:-

$$d = 3.78 [r_{1g}] \quad \text{--- (7)}$$

where d = droplet diameter.

Their analysis showed the following equation for droplet size:-

$$d = \text{Constant} \times \left[\frac{k_0 \gamma}{\Delta p} \right]^{1/3} \left[\frac{\rho_L}{\rho_A} \right]^{1/6} \quad \text{--- (8)}$$

where k_0 = nozzle/film parameter = hr

h = film thickness

r = radial distance from nozzle

γ = surface tension

Δp = liquid sheet dynamic head

ρ_L = sheet liquid density

ρ_A = gas density

The pressure effect indicated by this equation is as follows:-

$$d = f \left[\frac{1}{\rho_A} \right]^{1/6} \quad \text{--- (9)}$$

where f is some function.

At high relative velocities, further breakdown of original droplets has been considered (12). The criterion for drop break up under these circumstances appears to be the appropriate Weber Number:-

$$W = \frac{\rho_A u_{rel}^2 d}{2\sigma} \quad \text{--- (10)}$$

where W = Weber Number

u_{rel} = liquid air relative velocity

σ = surface tension

It should be noted that this type of analysis has also been applied to swirl type atomisers under moderate fuel pressure differentials, but it was considered that discussion of these models and analyses was more appropriate in this section.

The classical empirical analysis of air blast atomisation was performed by Nukiyama & Tanasawa (26). They found that droplet size was well correlated by following equation (19), which stated for kerosene fuel is:-

$$d_{SMD} = \left[\frac{11930}{u_{rel}} \right] + 58.5 \left[\frac{\dot{m}_f}{\dot{m}_A} \right]^{1.5} \quad (11)$$

Wigg (28) tested three geometrically similar injectors, and found that the following equation gave good correlation although it is dimensionally incorrect:-

$$d_{SMD} = 2300 \left[\frac{\eta^{20.5} \dot{m}_f^{0.05} \left(1 + \frac{\dot{m}_f}{\dot{m}_A} \right)^{0.5}}{u_{rel}} \right] \quad (12)$$

where η = viscosity [centipoise]
 $\dot{m}_f$ & $\dot{m}_A$ = fuel and air mass flow rates [gm/s]
 u_{rel} = relative velocity [m/s]

It is interesting to note that Wigg found that recombination of droplets was important beyond a certain distance from the nozzle in increasing droplet size. He proposed a factor to account for this, so that droplet size some distance from the atomiser is given by:-

$$d_{SMD} = 2300 \left[\frac{2^{0.5} \dot{m}_f^{0.05} (1 + \frac{\dot{m}_f}{\dot{m}_A})^{0.5}}{u_{rel}} \right] \left[1 + 2 \left(\frac{\dot{m}_f}{\dot{m}_A} \right)^{0.7} \dot{m}_f^{0.25} \right]$$

— (13)

Inspection of equations (11), (12) and (13) show that above a certain value of injector air-fuel ratio, the dominant factor in deciding atomisation quality is the relative velocity, this is in agreement with the theoretical equation (8) of Eisenklam, Dombrowski & Hasson. Under these circumstances, equations (11), (12) and (13) may be written:-

$$d_{SMD} \propto \left[\frac{1}{u_{rel}} \right]^1 \quad \text{— (14)}$$

whereas equation (8) may be written:-

$$d_{SMD} \propto \left[\frac{1}{u_{rel}} \right]^{2/3} \quad \text{— (15)}$$

Equations (14) and (15) underline the importance of the air velocity at the atomisation site, and thus the importance of combustor pressure loss and high coefficient of discharge injectors which directly decide the air velocity. It is interesting to note that these empirical drop size equations seem to indicate that if fuel flow is increased for fixed air mass flow conditions, drop size increases, this is, of course, opposite to the trend shown by swirl atomisers where drop size decreases with increasing fuel flow due to increasing fuel pressure. This could well lead one to postulate that the concept of flow number has far less importance for airblast atomisers than swirl atomisers, except at very low air fuel ratios and fuel mass flows.

Wigg (28) correlated the data of three other workers using very different geometries and scales, by using his empirical equation (12): Re-writing equation (12):-

$$d_{SMD} = 2300X \quad \text{--- (16)}$$

where X = viscosity parameter $\left[\frac{2^{0.5} \cdot 0.05 \cdot \frac{\dot{m}_F}{\dot{m}_A} (1 + \frac{\dot{m}_F}{\dot{m}_A})^{0.5}}{u_{rel.}} \right]$

Wigg found that the following equations gave good correlation for the following workers' data:-

Clare:- $d_{SMD} = 2300X$ (N.G.T.E.)

Wood:- $d_{SMD} = 3000X$ (Rolls-Royce wax airspray).

Bigg:- $d_{SMD} = 2400X$ (Napier).

Under these circumstances, the good correlations obtained led Wigg to suggest that injector design has little effect on the initial atomisation process. This, of course, may be true for designs that work well.

In a further paper (29), Wigg presents an improved empirical drop size equation which is dimensionally correct and takes account of gas properties over a limited range of conditions:-

$$d_{SMD} = 190 \left[\frac{V_E^{0.5} \cdot \frac{\dot{m}_F}{\dot{m}_A} (1 + \frac{\dot{m}_F}{\dot{m}_A})^{0.5}}{\rho_A^{0.3} u_{rel.}} \right] \left[1 + 2.6 \left(\frac{\dot{m}_F}{\dot{m}_A} \right)^{0.6} W^{0.1} \right] \quad \text{--- (17)}$$

This equation correlated very well the results of nine different injectors of various shapes and sizes.

The previous work of Wigg and that of Nukiyama and Tanasawa took no account of gas properties and turbulence, thus the resulting equations probably would not be applicable to combustor conditions.

The airblast atomiser would seem to offer important advantages for application in high pressure ratio engines. Since a high degree of premixing is obtained, the lower carbon production presents a considerable advantage in terms of smoke production and luminous radiation. Lefebvre (30) also points out that the onset of soot formation in premixed flames tends to be more a function of air-fuel ratio and velocity than pressure.

Whilst radiant heat fluxes tend to be reduced with premixed flames via a reduction in flame emissivity, the higher volumetric heat release rates will partly counteract this trend because of higher gas temperatures. This situation may well imply that although total cooling air flow could be reduced, the proportion of cooling air to the region of the reaction zone could well be increased.

The amount of data available on the performance of airblast atomisers under typical combustion conditions is strictly limited. Deacon & Bamford (31) carried out a comparative study in a highly loaded annular combustor using a Rolls-Royce centre pintle airspray atomiser with an internal contracting fuel film. This atomiser showed considerably better combustion efficiency at altitude cruise conditions, but would not idle below a simulated 40,000 ft. and required auxiliary air for starting. It should be remembered, however, that this atomiser did not represent the ultimate in airblast injector design by latest standards, which may partly explain the bad aspects of its performance.

Bater and Poulton (32) performed comparative tests between swirl atomisers and an airspray atomiser in a Rolls-Royce Dart R.Da.3 primary zone at pressure levels between 0.5 and 1.0 atmospheres. They found that the airspray atomiser gave better combustion efficiency particularly at weak mixture strengths, and also gave wider stability limits than the simplex atomiser. This seems to suggest that the airspray atomiser was an exceedingly poor one, in that a high degree of premixing was not obtained, and thus the stability limits were wider due to richer or larger fuel rich zones. None of these pieces of work included any radiation measurements.

(iv) Effects of Droplet Size and Size Distributions.

Brokaw & Gerstein (12) point out that in most gas turbine engines the flame reactions are limited more importantly by mixing and evaporation processes than reaction kinetics. Thus since mixing and evaporation processes are affected by droplet size, it is important that droplet size and size distributions within the combustor should be known if progress towards the application of theory is to be made. In most studies to date, it has not been possible to completely separate the effects of actual size and the size distribution within the spray (8).

Joyce (33) illustrates the importance of size by

the following data for 1cc of fluid in the form of different drop sizes:-

For a single sphere:- surface area = $4.83 \text{ [cm}^2\text{]}$

For 10^6 drops $d = 124 \mu$:- surface area = $483 \text{ [cm}^2\text{]}$

For a spray $d_{SMD} = 124 \mu$:- surface area = $1200 \text{ [cm}^2\text{]}$
with a typical distribution. (approx.)

Thus, since evaporation rates are directly related to surface area, clearly a small droplet size is very important when remembering the low residence times available for evaporation and burning.

The presence of the size distribution certainly increases the total surface area as seen above, and increases the initial evaporation rate considerably by providing a population of very small droplets. Joyce (33) stresses the importance of this for ignition purposes, but the large droplets which do not reside long enough to complete evaporation and burning constitute a potential loss of combustion efficiency. Investigating the times to evaporate, 85% of a spray, Probert (12) found that evaporation times were affected significantly by the size distribution prevailing, but the times were affected more importantly by the SMD of the spray. This fact is underlined by work by Hall & Deiderichsen (23), who showed that an increase in Sauter Mean Diameter by a factor of three increased evaporation times by a factor of thirteen.

Due to the large variation in size found in real sprays, it seems likely that the evaporation rates of the extremes in size of the spray, imply that both homogeneous and diffusion flame regimes will exist in a combustor (12). This situation, of course, complicates the application of flame theory to gas turbine combustors.

Droplet size and size distributions are important factors in determining flame radiation and smoke emission. Whilst one must accept vapour phase cracking, the liquid phase cracking, to produce the luminous carbon, must be dependent on the population of large droplets in a spray. Thus the extent of carbon formation in the liquid phase can be minimised by obtaining as small a Sauter Mean Diameter as possible, accepting that one has no significant direct control over the size distribution. In addition to this, it may well be that the size of the carbon particles bears some relation to size of the initial

droplet(s) that were dehydrogenated, and thus to prevent significant radiation in the infra-red, the carbon particle size, hence droplet size, must be minimised. The literature is bare of work correlating flame radiation to droplet size directly, such work as exists with injection parameters as primary variables, generally correlates the results using the flow Number concept. This is acceptable providing injector pressure differentials are taken into account also. This situation is explicable, since there is no reliable information available which one can use to predict the performance of an injector at combustor conditions from, say, its performance in cold, quiescent air at atmospheric pressure.

Many distributions have been used and postulated for liquid fuel sprays; Nukiyama & Tanasawa's distribution, the Rosin-Rammler, the logarithmic normal, etc., but none of these is based upon a physical model of atomisation. It is of interest to note that the Rosin-Rammler distribution was proposed following studies of the size distributions within pulverised coal. In the literature, it seems that the distribution law assumed in any analysis is chosen because it best suits the particular purpose or such facts that are available.

One might infer from the previous arguments that it is always better to obtain as small a droplet size as possible. Jonash & Burnett (23), however, found that from the point of view of combustion efficiency, there was, in fact, a minimum size below which efficiency was seen to reduce, this is seen in Fig. 7. They used an annular combustor burning aviation gasoline at 7.7 lb/ft^2 with an inlet air temperature of 530° R. with reference velocity 64 ft./sec. This situation is probably due to the use of an over-rich primary zone in which the atomisation, and hence evaporation, was such as to create a mixture too rich to burn, thus moving the site of combustion downstream. If the atomisation quality was reduced, incomplete evaporation reduced mixture strength, thus making burning possible in the major portion of the primary zone. This phenomenon would certainly place no restriction on an airblast atomiser, since the fuel is well aerated at entry.

Finally, there are very many empirical formulae defining droplet size for various injector types, and these are discussed more relevantly elsewhere. A general expression was, however, obtained by dimensional analysis by Graves and Bahr (12):-

$$\frac{d_{av.}}{d_{noz.}} = \Phi \left\{ R_e, W_e, \frac{\rho_A}{\rho_L}, \frac{u_A}{u_L}, \frac{\mu_A}{\mu_L}, R_1, R_2, \dots, R_n \right\}$$

— (18)

where:-

 $d_{av.}$ = average droplet size $d_{noz.}$ = the nozzle diameter R_e = Reynolds Number W_e = Weber Number ρ_A, ρ_L = air and liquid densities u_A, u_L = air and liquid velocities μ_A, μ_L = air and liquid viscosities $R_1, \dots, R_n$ = dimensionless geometrical relationships defining the atomiser shape.

This type of expression has not yet proved to be of great practical importance, but such analysis can lead the way towards more uniform empirical correlations by indicating the initial correlation approach.

(v) Fuel Distribution.

The distribution of fuel within the primary zone of a combustor is governed, primarily, by four factors:-

- (a) Primary zone aerodynamics.
- (b) Fuel spray cone angle.
- (c) Droplet size.
- (d) The initial ratio of fuel momentum to air momentum, $\left[\frac{\dot{m}_f u_f}{\dot{m}_a u_a} \right]$

The primary zone aerodynamics are important in that they decide the forces that are exerted on the fuel droplet after leaving the injector. Flow directions normal relative to the fuel spray are perhaps the most important aspect, since this decides the deviation of

the fuel droplet trajectories away from the initial path defined by cone angle. Two major flows are the swirler air and the portion of the recirculation in the region of the fuel cone, both these flows have large components in the direction of droplet flow, which thus tend to reduce the relative velocity between droplets and air. The normal components of velocity depend on the chamber and swirler geometries and the cone angle, and are of importance in the aeration of the spray and thus smoke production. The air temperature and pressure affects distribution considerably by virtue of alteration in droplet drag and evaporation rate, higher air pressures increase the air density and hence the drag forces:-

$$D = C_D \left(\frac{1}{2} \rho V^2 \right) \quad \text{--- (19)}$$

Increased air temperature increases mass transfer rates, and thus decreases droplet size more quickly. This issue is somewhat complicated by the considerable variations found in droplet drag coefficients where mass transfer is occurring. The effects of turbulence scale and intensity within complicated flow regimes, such as are found in a combustor, is not yet fully understood. Increasing the intensity of turbulence undoubtedly increases mixing and evaporation rates by disturbing the buffer and laminar sub-layers around evaporating droplets, and thus reducing these important barriers to mass transfer (12). Increasing the scale of turbulence only appears to alter the eddy diffusivity in the fully turbulent region, which has little effect on mass transfer since this is the area of least resistance.

Turbulence can only be increased by either increasing the chamber pressure loss factor or increasing the chamber velocity, and thus other performance considerations limit the variations allowable via these means. The increase of chamber velocity to increase turbulence and thus mixing, may well be of little effect anyway, since residence times may well be reduced proportionately. One could argue that increasing chamber velocity and hence Reynolds Number, would alter flow patterns and thus effect residence times accordingly, but so little is known about these phenomena that extensive argument to any conclusion would seem to be misleading at this time.

Cone angle is the parameter by which the fuel spray can be best matched to the chamber aerodynamics to obtain required performance. Unfortunately, there are conflicting requirements, a small cone angle is

better for ignition and stability in that fuel rich zones are made more rich, but by virtue of this more smoke is produced. Toone (7), with a fixed combustor, noted that as cone angle increased smoke level decreased to a minimum at a cone angle of $100^\circ - 105^\circ$ and then began to increase again. Since the reversal FAR decreased continually with increasing cone angle, this led him to postulate that there could be some minimum level of carbon in a combustor flame whilst ever fuel burns. This could well be the case, although one could equally argue that as the cone angle increased the site of carbon production moved from the reversal, and that for cone angles of greater than 105° , the FAR in some other region began to increase and produce more carbon. Durrant (8) reported a continual decrease in smoke level with increasing cone angle, unfortunately, only up to a cone angle of 105° . Lefebvre (34), Toone (7) and Durrant (8) all point out that as pressure increases, for a constant pressure loss factor, cone angle is reduced due to the effective increase in the differential pressure across the fuel cone, this trend could well be of importance in very high pressure ratio engines since again the tendency is towards more smoke. Toone (7) also points out that cone angle is affected by shroud air proportions although as nozzle flow number is increased there is an increase in fuel momentum and the effect becomes less important.

Graves & Bahr (12) found that for a given nozzle size, fuel, and fuel pressure, there is an optimum cone angle for minimum droplet size. This phenomenon may well be connected with the minimum smoke level reported by Toone (7), where the minimum droplet size for his atomisers occurred at cone angle $100^\circ - 105^\circ$.

The ratio of fuel momentum to air momentum at the injector governs the penetration of the fuel droplets via momentum transfer from the fuel to the air, with swirl type atomisers. This ratio may well be a more relevant injection correlating parameter than flow number, since flow number does not define the spray velocity without a statement of fuel pressure differential in addition. As shown in Appendix 2, the ratio of the momenta is directly related to the differential between fuel pressure and combustor pressure thus:-

$$\left[\frac{\dot{m}_f u_f}{\dot{m}_a u_a} \right] \propto \sqrt{\Delta p_f} \quad \text{--- (20)}$$

In Section 4.3 (i), the empirical equation of Bowen & Joyce (20) for swirl atomisers is:-

$$\log_e(d_{smd}) = (k_2 FN - k_3)(\log_e \Delta p) - (\log_e k_1)$$

since $k_3 \gg k_2$ the effect of FN is small but that of Δp is large.

$$\therefore \log_e(d_{smd}) \approx \left[\frac{c_1}{\log_e \Delta p} - c_2 \right]$$

$$\therefore \log_e(d_{smd}) \approx \left[\frac{c_3}{\log_e R} - c_2 \right] \quad \text{--- (21)}$$

$$\text{where:- } R = \left[\frac{\dot{m}_t u_t}{\dot{m}_A u_A} \right] \quad \text{--- (22)}$$

Thus R is clearly a useful injection correlating parameter for flame radiation and smoke emission work where droplet size is very important. However, Flow Number is still used in the literature, and Durrant (8) shows a relation between flow number and exhaust smoke level which illustrates that smoke level is very dependent on Flow Number, and hence droplet size.

(vi) Mixing and Evaporation.

In most combustion chambers, mixing is achieved, directly or indirectly, by gas jets. Much work, both theoretical and experimental, has been done on the investigation of gas jets, although usually in simple models and test geometries. Attempts to apply the theory to gas turbine combustors have usually been unsuccessful due to the effect of distortion and interaction of the jets, the extremely complicated

flow patterns and temperature fields that exist, making flow prediction extremely complicated. Accordingly, only general design rules exist by which the mixing of a combustor can be pre-planned at the design stage. This situation is also a hindrance to theoretical combustion work, such as the investigation of carbon formation mechanisms, since the prevailing conditions are unknown.

Scull & Michelsen (12) point out that the aerodynamic mixing of mass, heat and momentum to obtain the desired distribution of momentum in the hot gases is achieved by the same mechanisms on two different scales. Large scale mixing can occur via the turbulent transfer of large groups of molecules, whilst small scale mixing is occurring locally by molecular action. They show that the equations for turbulent and molecular heat and mass transfer follow the same general laws from which soluble differential equations can be formed. However, the solution of the equations for turbulent diffusion is extremely complicated, and the equations have only proved soluble in very simple situations with certain assumptions. Thus again the theoretical application to real combustors is extremely difficult, and general application of the theories of mass, heat and momentum transfer will probably not be practicable for some time.

The application of single droplet evaporation models to spray evaporation has shown evaporation rates up to 100% larger than measured rates (19). This is presumably due to the interaction of concentration gradients thus reducing the driving force for mass transfer, hence bringing the evaporation rates well below single droplet rates. Ingebo, however, made allowance for this in his theory and obtained good agreement with Bahr's (see later) empirical correlation over a narrow range of conditions. Graves & Scull (19) discuss the problems of predicting mixing and penetration in a combustor, and consider the problem to divisible into three main issues. Firstly, the estimation of droplet drag coefficient is necessary for evaluation of penetration. Ingebo solved the equations for droplet acceleration, instantaneous drag and rate of change of droplet mass, to obtain his well-known equation:-

$$C_D = 444 \left[\frac{\rho_d}{\rho_o} \frac{d}{(u_o - u_d)} \right] + \left[\frac{8k_o(\Delta T)(N_u)}{gh_v d \rho_o (u_o - u_d)} \right] \quad (23)$$

where:-

C_D = droplet drag coefficient

ρ = density

d = droplet diameter

u = velocity

ΔT = gas temperature - droplet wet bulb temperature

h_v = latent heat of evaporation

suffix o = gas quantities

d = fuel quantities

The form of this equation is shown in Fig.8, and demonstrates the large difference between fuel droplet drag and the drag of solid spheres of the same diameter.

Secondly, in order to use the Ingebo equation, a knowledge of the relative velocity between droplets and gas is required. Nearly all investigations into the velocity and size distribution within liquid sprays has been for sprays spraying into quiescent air at atmospheric pressure, and there seems to be insufficient information available that could be used to make a reasonable estimate of relative velocity under the conditions that prevail in a primary zone.

The third obstacle to theoretical mixing calculations is the complexity of equations defining the droplet diffusion in a turbulent field, which, as has already been pointed, cannot yet be solved for the conditions that exist in a combustor. Whilst rigorous application of the theory is impossible at present, it does, however, provide valuable guidance for empiricism, and can be used to estimate trends qualitatively.

Durrant (8) points out that evaporation rates for

droplets are pressure dependent. Bahr (14) found this when he correlated the evaporation of iso-octane spray to yield the following equation:-

$$\frac{N}{100 - N} = 9.35 \left[\frac{T_0}{1000} \right]^{4.4} \left[\frac{u_0}{100} \right]^{0.8} p_0^{-1.2} p_e^{0.42} L^{0.85}$$

— (24)

where:-

N = % of spray evaporated at L

L = axial distance from injector

T_0 = air temperature

u_0 = air velocity

p_0 = ambient pressure

p_e = fuel nozzle pressure differential.

Clearly, the most important factor in his equation is the temperature differential between fuel and air which will govern the heat transfer to a droplet, although no allowance is made for turbulence which is known to affect evaporation rates considerably. Also indicated is the fact that increase in fuel pressure will increase evaporation rates via reduced droplet size, again pointing to the importance of injection quality.

It is interesting to note that Schirmer & Miller (9) point out that evaporation rates for non-luminous flames will be less than for luminous flames, due to the non-coincidence of fuel absorption spectra and carbon dioxide and water vapour emission spectra. This would not appear to be an important phenomenon for airblast atomisers, since the partial premixing obtained should more than compensate, to ensure better overall mixing and evaporation than for swirl atomisers.

4.4 Flame Mechanisms.

A great deal of work, both experimental and theoretical, has been done on homogeneous and diffusion flames for gaseous fuels under both laminar and turbulent flow conditions, usually in very simple situations and models. Whilst combustor flames are definitely turbulent in character, laminar

flame studies have proved very useful in the investigation of chemical kinetics and the factors upon which reaction rates depend. Laminar flame speed studies are also of importance in the definitions of turbulent flame speed, since laminar flame speeds are virtually a function of only the mixture properties, whereas turbulent flame speed is dependent on experiment geometry and experimental technique (12) as well. Thus it is useful to state turbulent flame speed in terms of the more fundamental laminar flame speed. The concept of flame speed has proved extremely useful in the derivation of empirical formulae to correlate combustor performance. In particular, a burning velocity model was used by Lefebvre in conjunction with others to derive the well known parameter to correlate combustion efficiency data (36):-

$$\zeta_c = f \left[\frac{P_2^{1.75} A_{rct} D_{rct}^{0.75} \exp \left(\frac{T_2}{300} \right)}{\dot{m}_A} \right] \quad \text{--- (25)}$$

where:- f = some function
 P_2 = combustor inlet pressure
 $A_{rct.}$ = combustor reference area
 $D_{rct.}$ = combustor reference diameter
 T_2 = combustor inlet temperature

A high laminar flame speed is important in obtaining high heat release rates, which enable a combustor to operate at high through put rates for a given volume. Laminar flame speed is dependent on mixture inlet temperature and air fuel ratio, with maximum velocity occurring for mixture strengths slightly greater than stoichiometric, which points to another advantage of operating a primary zone at stoichiometric conditions rather than over-rich. This fact also indicates that the quality of mixture preparation is important in obtaining high heat release rates.

The mechanisms that prevail in and near the reaction zone are extremely complex and are not fully understood. One particular mechanism, the flame propagation mechanism, has been explained in terms of two different processes, the one proposal being a heat conduction mechanism as investigated by Semenov, and the other being active particle diffusion as proposed by Tanford-Pease. This controversial issue does not really hamper the development of theoretical equations, since the equations of heat and mass transfer are of the same

general form. Most turbulent flame theories have involved the use of the concept of a single wrinkled flame front (12). It appears, however, that the highly broken up flame that exists within a gas turbine combustor may well have many flame fronts, this situation should not prevent the application of theoretical equations, since the mechanisms of any individual flame front should be similar.

Volumetric heat release rates are very much higher in laminar flame reaction zones than in the average combustor. Gerstein and Dugger (12) quote the following values:-

Laminar stoichiometric propane flame:- $4 \times 10^8 [\text{Btu/hr ft}^3]$
 Combustor flames:- in order of $10^6 [\text{Btu/hr ft}^3]$

Longwell & Weiss, however, obtained volumetric heat release rates in the order of $3 \times 10^8 [\text{Btu/hr ft}^3]$ in their highly stirred reactor. One may infer from this information that combustors have a long way to go to achieve such heat release rates, but other considerations probably place a limit on the maximum heat release rates in engine combustors, such as:-

- (a) Flame tube wall temperature.
- (b) Combustor pressure drop.
- (c) Stability limits.
- (d) Combustion efficiency.

Clearly then, the Longwell reactor should possibly not be regarded as the ideal to which combustor design should be aimed.

Consideration of the reaction rate theory as opposed to burning velocity, in the formulation of combustor performance correlating parameters (36), has led to relationships such as the following:-

$$\eta_c = f \left[\Phi, \frac{V P_2^{1.75} \exp\left(\frac{T_2}{b}\right)}{\dot{m}_A} \right] \quad \text{--- (26)}$$

where:-

- V = reactor volume
- Φ = equivalence ratio
- f = some function

Comparison of this equation with equation (25) shows remarkable similarity, Lefebvre (36) points out that this is due mainly to the similar assumptions adopted in both derivations, relating to temperature and pressure dependencies. It has been suggested (13) (34) that whilst present and past combustors' performance has been well correlated by parameters such as these, where reactions may be considered to be controlled by reaction rates, at very high pressure, evaporation and mixing rates may well be the limiting factors. An analysis in reference (34) produced an equation which points to this trend:-

$$\left[\frac{\text{Evaporation time available}}{\text{Evaporation time required}} \right] \propto p^{1.68} \quad (27)$$

If this situation proved to be the case, combustion efficiency could well be better correlated in the following way:- (Ref.36).

$$\eta_c = f \left\{ \left[\frac{u_A \sqrt{T_2}}{A_{ref} P_2} \right]^{-1}, \left[\frac{\Delta p_{ft}}{P_2} \right]^{0.5} \right\} \quad (28)$$

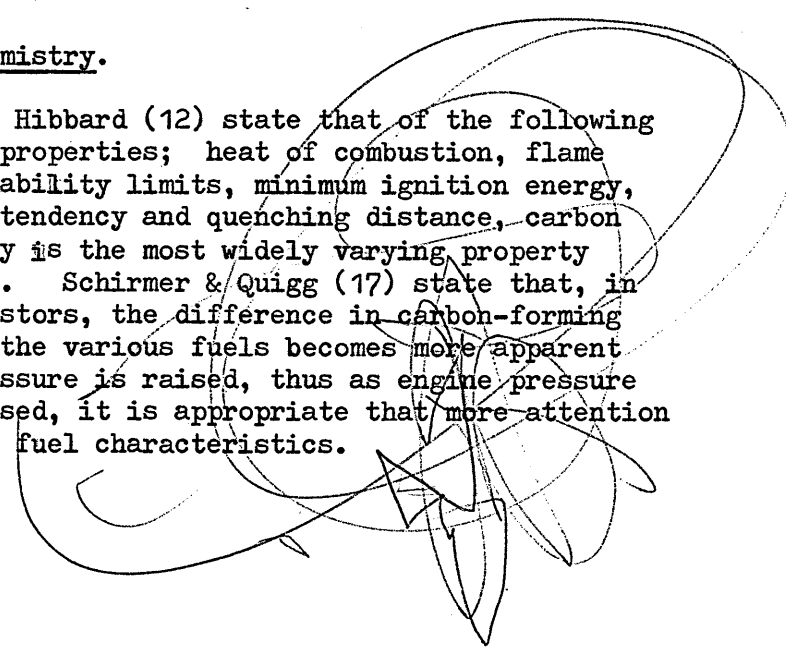
where:-

Δp_{ft} = flame tube pressure drop.

The above non-dimensional groups relate, in effect, to chamber velocity conditions, jet penetration and turbulence levels, which have been shown, in Sections 4.2 and 4.3, to directly affect mixing and evaporation rates.

4.5 Fuel Type and Chemistry.

Schalla and Hibbard (12) state that of the following hydrocarbon fuel properties; heat of combustion, flame velocities, flammability limits, minimum ignition energy, carbon formation tendency and quenching distance, carbon formation tendency is the most widely varying property amongst the fuels. Schirmer & Quigg (17) state that, in gas turbine combustors, the difference in carbon-forming tendency amongst the various fuels becomes more apparent as combustion pressure is raised, thus as engine pressure ratios are increased, it is appropriate that more attention should be paid to fuel characteristics.



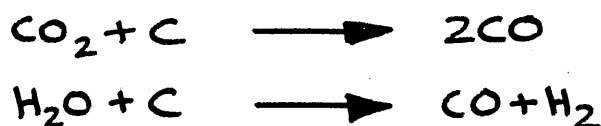
Toone (7) and Lefebvre & Durrant (35), however, state that whilst fuel characteristics are important in carbon control, the design of fuel injectors and combustors has a much more profound effect. This is a rather fortunate situation for civil air line operation, since fuel costs represent a far greater proportion of the cost per passenger mile than the initial engine cost written off over thousands of hours of operating, thus the specification of a more carefully refined and expensive fuel will raise operating costs to a greater extent than the cost of a better engine combustor design. Nevertheless, it is important that the effects of fuel chemistry upon carbon formation should be investigated, since it may be possible to improve fuel specifications by some comparatively inexpensive processing changes to be used in conjunction with appropriate combustor design changes.

Schalla & Hibbard (12) state that carbon forming tendency decreases as follows:-

aromatics > alkynes > olefins > n-paraffins.

They state approximately that olefins are 12 times as smoky as n-paraffins, and aromatics 24 times as smoky as n-paraffins, the alkyne factor varying with chain length between the aromatics and olefins. The proportions of these constituents in the crude oil vary according to the geographical location of the oil field, and the proportions can be modified by varying refining processes. It is beyond the scope of this work to discuss refining chemistry in detail, but it may be assumed that more control over the fuel quality could be obtained if the situation demanded such action.

One approach to the problem of carbon control that shows promise, is in the field of fuel additives. Beckwith (14), however, comments that no additive has been discovered whose use would not entail excessive maintenance charges, due to deposition or corrosion damage during continuous use. He suggests, however, that if local legislation demands it, such additives could be used for short periods, interspaced with long periods of running on untreated fuels. One such additive is a barium compound known as Lubrizol 565, which shows a significant reduction in engine smoke (7). It is believed that the following reactions are positively catalysed to reduce carbon formation:-



This additive, however, deposits large quantities of Barium Oxide in the turbine and jet pipes, which would necessitate far more frequent engine overhaul than normal in order to prevent impaired performance and mechanical damage.

It is interesting to note that lamp tests have been frequently used to determine a measure of a fuel's carbon forming tendency. However, Toone (7) points out that the carbon forming mechanisms in the lamp flame are possibly quite different from those operating in a combustor at pressure. To illustrate this point, lamp tests with Avtur plus Lubrizol 565 and untreated Avtur indicated that the additive should produce more smoke, the reverse being the case. Whereas lamp tests with another additive, ferrocene (dicyclo-pentadienyliron), indicated that this additive should show a significant reduction in exhaust smoke. Testing in a Dart engine, however, showed a negligible reduction in smoke.

It can only be assumed that, whilst lamp tests can give indications of carbon forming tendency for certain fuels, only testing under combustor conditions can reveal the extent of this important fuel property. Schirmer & McReynolds (37) report that engine testing at 15 atmospheres with pure hydrocarbons, toluene (aromatic) and n-Heptane (paraffinic), revealed the following flame radiation data for wavelength band 0 - 6 microns:-

(a) Toluene fuel:

Total radiation was approximately 80% of total heat transfer to the walls.

(b) n-Heptane fuel:

Total radiation was approximately 40% of total heat transfer to the walls.

(c) The flame temperatures were the same for both fuels and thus:-

$$\epsilon_{\text{toluene}} \approx 2 \epsilon_{\text{n-heptane}}$$

(d) The maximum wall temperature was 300° higher for the toluene fuel.

The large difference in emissivity reported is due to the use of a 100% aromatic fuel, the actual proportion of aromatics in fuels in current airline use is very much less than this, and thus the differences in flame radiation properties amongst the fuels in far less than indicated here.

4.6 Operating Conditions.

The operating conditions which largely define the performance of the combustor are as follows:-

- (i) Air fuel ratio.
- (ii) Combustion pressure.
- (iii) Inlet air temperature.
- (iv) Chamber velocity.

These are the directly controllable parameters from an experimental point of view, but the effect of any one of these on the level of flame radiation, emissivity or smoke level, is felt by operation through all or many of the previously discussed combustor processes. Thus the correlation of combustor performance using these operating conditions leads to results that require most careful interpretation by consideration of these processes, since they are not primary variables. Combustion experiments require the most careful design since the operating conditions need to be manipulated such that one of the basic processes becomes the only primary variable. This ideal situation is, in practice, very difficult, and often impossible, to achieve, and thus it is still common practice in the literature to correlate results in terms of operating conditions.

(i) Air-Fuel Ratio.

A decrease in air-fuel ratio increases flame emissivities and flame temperatures, and thus has a great effect on total radiation. The increase in emissivity is generally due mainly to an increase in the luminous component and thus implies that an increase in smoke level will also be attendant. Durrant (8) reported for one chamber operating at 6 atmospheres and 100% reference velocity, an increase in emissivity from 0.10 at 90 AFR to 0.19 at 60 AFR. Reeves (6) using an industrial gas turbine combustion chamber operating at 4.4 atmospheres typically noted a threefold increase in total radiation when the air-fuel ratio was decreased from 50 to 25 for kerosene fuel, viewing just downstream of the primary zone. He noted that the effect of air-fuel ratio reduced towards the tail of the flame, due possibly to the increased rate of carbon consumption in the intermediate zone at the higher flame temperature.

(ii) Pressure.

As has been previously pointed out, increasing attention has been attracted towards the investigation of the effects of combustion pressure upon flame radiation due to the development of engines with high

pressure ratios. For example, the Rolls-Royce RB.211 has pressure ratio 27 : 1.

In general, total flame radiation increases with pressure (17), the increase being due to an increase in both luminous and non-luminous emissivities (9). For example, Reeves (6) found that total radiation at the downstream end of the primary zone increased very nearly linearly with pressure up to about 5 atmospheres, and doubled in magnitude in 2.5 atmospheres. ~~(2), however, found that the combustion found that, pressure was 16/1 total flame radiation varied~~

with combustion pressure according to:-

$$\dot{q}_{TOTAL} \propto p_c^{1.78} \quad \text{--- (29)}$$

He found that flame emissivities varied with pressure as follows:-

$$\epsilon_{TOTAL} \propto p_c^{0.80} \quad (p_c < 70 \text{ lbf/in}^2) \quad \text{--- (30)}$$

$$\epsilon_{TOTAL} \propto p_c^{1.97} \quad (p_c > 70 \text{ lbf/in}^2) \quad \text{--- (31)}$$

These results seem to suggest that below 70 lbf/in² the flame was essentially non-luminous, but above this pressure the carbon particles increased in size, sufficiently to radiate appreciably in the infra-red.

At high combustion pressure, combustor coke deposits are seen to reduce, generally (37), due to the increase in the flame radiation burning away deposits. This may also be due, to some extent, to the reduced penetration of the droplets and the reduction in droplet size. Lefebvre (34) demonstrated that penetration varied with pressure as follows:-

$$S \propto \frac{1}{p_c^{0.33}} \quad \text{--- (32)}$$

where S = penetration distance.

Both these effects combine to reduce the quantity of fuel that will impinge on the liner to be cracked to form coke. This reduction in coke aggravates the increase in heat transfer, since the reduced coke deposits lead to higher metal temperatures and metal loss.

(iii) Inlet Air Temperature.

An increase in inlet air temperature has two main effects on flame radiation and smoke emissions. Consideration of Bahr's empirical equation for droplet evaporation showed that the main factor affecting evaporation was the differential temperature between fuel and air, thus the initial evaporation rate of a spray would be expected to increase with inlet air temperature. This would tend to reduce flame radiation and smoke emissions if liquid phase cracking is more important than vapour phase cracking. This effect is probably small since the major heat supply for evaporation comes via hot gas recirculation and flame radiation.

The main effect on flame radiation is probably that an increase in inlet air temperature will also raise the hot gas temperature, which via the fourth power law will also increase the radiation level.

(iv) Chamber Velocity.

A change in chamber velocity will effect a change in mixing rates via turbulence level. An increase in velocity will increase the mixing rates and thus would be expected to reduce carbon formation, and hence gas emissivities and smoke levels. For a given atomiser and chamber, however, the issue is complicated by the fact that to increase velocity at a fixed combustion pressure and air fuel ratio, necessitates an increase in fuel pressure. The increase in fuel pressure will, of course, improve the atomisation quality, which also would reduce carbon formation, and thus under such circumstances, it is not possible to assess how much the change in radiation is due to changes in mixing rates or atomisation. Tests on an Avon combustor at 5 atmospheres (8) showed a decrease in gas emissivity from 0.3 to 0.1 as velocity was increased from 80% to 140% with a fixed flow number injector.

SECTION 5.

APPROACH TO THE PROBLEM.

5.1 Broad Objectives.

The work to be done was not conceived to be a very narrow investigation into the effects of one particular aspect of combustion performance on flame radiation and smoke emission. The broad objective of the work was rather seen to be the collection of radiation and smoke over as wide a range of conditions as possible, with emphasis, perhaps, on fuel injection characteristics. The fuel injection characteristic that was seen to be of particular interest was the injection method. In view of the current problems and activity in the Industry concerning the control of flame radiation and smoke emission, it was thought most appropriate that a comparison should be performed between swirl atomisers and airblast atomisers under as near identical conditions as possible. Another injection aspect which was considered to be of importance with the conventional swirl atomiser, was the effect of fuel droplet size, as effected via injector flow number.

It was hoped that much of the data could be collected at high combustion pressures, since this is the region of interest in view of the current trends in engine pressure ratio, this, however, was not to be, as explained in Section 5.5.

As it was hoped to confirm the predicted advantages for the airblast atomiser in respect of lower flame radiation and smoke emission, it seemed appropriate that the main drawback to its general application to gas turbine combustors should also be investigated. Accordingly, stability limit comparisons would be made between the swirl atomiser and the airblast atomiser over a range of conditions.

5.2 Development of the Airblast Atomiser Combustor.

The airblast atomiser that was to be used initially was an external expanding fuel flow type, with little fuel swirl, that had previously been used for cold flow testing with water and kerosene. This burner is fully described in Sections 6 and 10, and illustrated in Fig. 9. Since this burner had never been mounted in a combustion chamber, certain modifications were necessary in order to make this possible. The modifications that were necessary were the design of a mounting feature to locate the injector radially in the combustor, and a central air deflector to direct the inner air flow radially outwards to the atomisation lip.

The mounting feature initially conceived was a four-vaned spider, which imparted no swirl component to the air. The general arrangement of the injector installation in its final form is shown in Figs. 10 & 11. On performing initial burning runs at atmospheric pressure with the rear of the rig removed in order to see into the chamber, the flame was seen to be divided into 4 segments which became narrower towards the injector, and were seen to originate from the turbulence generated in the wake of the 4 spider vanes. This clearly required modification for three reasons. Firstly, the segments in the flame were so pronounced that radiation measurements would obviously be dependent on the relation of the spider with respect to the sight path. In addition, there were large areas in the primary zone where no burning was occurring, but to which fuel was being supplied, and thus clearly either the velocity was too high in these regions or the turbulence level too low. Also the shape of the segments led one to believe that the axial velocity component of the air entering through the injection site was too high, and thus reducing the strength of the primary zone recirculation, and moving the burning zone too far downstream. A solution to these problems was provided in the form of a 9 vane 45° outer air swirler, just blocking direct flow, which was attached to the injector body and fulfilled the function of burner support in addition. This swirler completely transformed the flame into a uniform blue toroid sitting well back against the combustor flare, and thus this was considered satisfactory. The direction of air swirl was arranged to oppose the fuel swirl.

The central air deflector was designed following testing upon the water spray rig, illustrated in Fig. 12, with a variety of different geometries. The design adopted is shown in Fig. 10 and is seen to be of a smaller diameter than the atomiser lip thus bringing it well clear of the fuel sheet. Deflectors tried which came close to the atomising lip and the fuel, were seen to provide sites for agglomeration of droplets and thus shed very large droplets, which is very undesirable. A similar phenomenon was noticed by Byran (15) during the development of his airblast atomisers. The deflector was retained by a long 6 BA bolt screwed into a 4 vaned spider which sat at the upstream end of the injector inner air passage, the deflector gap being maintained by three pegs sitting on the atomiser lip. (see Fig. 10). The initial airblast burner used was constructed entirely from brass and bronze, and suffered no ill-effects even at the richest mixtures, which is an indication of the cool temperature at which these atomisers run due to the fact that they are bathed in cold inlet air. One of the important criteria in comparing the performance of the two injection methods was that the chamber aerodynamics should be as nearly identical as possible. To this end, the whole of the chamber downstream of the flare was left untouched, although fairly extensive modification of the snout was required to install the airblast atomiser. This

involved removing the swirler from the standard chamber and welding in a tube to accommodate the injector. Fig. 13 shows the unmodified chamber as used with the simplex atomisers, and Fig. 11 shows the first standard of airblast combustor snout.

In performing the preliminary investigation, it was discovered that at that the flare cooling of the combustor was inadequate to cope with the higher volumetric heat release rate in the primary zone. Following a run at high pressure, the combustor flare was seen to be badly sagging and burnt in several places, particularly in the wake of the igniter plug. The damage is illustrated in Fig. 14. It was decided to modify the snout more extensively to provide a more positively directed cooling air flow to the flare and also incorporate a film cooling strip on the flare itself. The design used is shown in Fig. 15. An additional feature incorporated was a variable area blanking plate so that cooling air flow could be altered if necessary. This later design of snout proved entirely satisfactory at the conditions covered during testing.

Thus an airblast atomiser and suitable combustor was developed with which radiation and smoke investigations could be performed, a few runs with the swirl atomiser and unmodified chamber showed that its performance was satisfactory.

5.3 The Test Programme.

It was decided to perform a preliminary testing programme before attempting a more comprehensive analysis, using the Schmidt Method, for three reasons. Firstly, the delivery of the Spembley Black-Body furnace, a suitable Land fluxmeter and calcium fluoride windows was not due for a period of some three months, so that Schmidt testing could not be performed for some time following the development of the rig to a suitable state for testing. Secondly, the design of the experiment could not be completed until it was known what simplex atomisers were available. Four nozzles and swirl cups were available of different cone angles and flow numbers, but none of them had a sufficiently high flow number to enable rich mixtures at high pressures to be obtained at sensible velocities. It was thus hoped that such large nozzles could be obtained before the commencement of Schmidt Method work. Finally, it seemed expedient that a preliminary comparison between the two injection systems should be made in order to get a rough idea of the magnitude of the difference in atomiser performance, and also to make some sort of estimate of the success of the particular airblast atomiser design initially adopted.

5.4 Preliminary Test Programme.

Whilst the special Land fluxmeter designed for use with the black-body furnace was not available, another Land fluxmeter, type RF. $\frac{3}{4}/30/16$, was available, with which flame total radiation could be measured. Windows of Calcium Aluminate were also available which had an acceptable transmission down to about 5 microns. The Rolls-Royce smoke meter was available and known to be functioning satisfactorily, and thus it was decided to perform experiments appropriate to the equipment immediately available.

The preliminary test programme was thus conceived to be a direct comparison between the airblast atomiser and swirl atomiser measuring total flame radiation, exhaust smoke level and stability limits, the comparison to be performed at three different levels of pressure.

5.5 Schmidt Method Programme.

The first stage in the Schmidt Method work was to develop the associated equipment to a suitable standard for the work. A major part of this work was the calibration and commissioning of the Spembley black-body furnace. It was essential that a suitable running-in period should be completed to prove the reliability of the furnace and its support equipment, this was so since any failure of an internal component would not be heard above the noise of the rig, and any defect would have to reach disastrous proportions before becoming visible. During the latter part of this stage, the various calibrations of the equipment were performed as described in Section 8. Having completed these tasks, further consideration was given to the points mentioned in Section 5.3 in order to design the experiments.

Two major factors influenced the Schmidt work that was accomplished. Firstly, testing at high pressure with swirl atomisers was dependent on obtaining nozzles of large flow number from Industry, since their manufacture requires special machinery and processes. Unfortunately, no such nozzles could be obtained in time to be included in the testing. Thus with the nozzles available, the highest pressure that could be used for the two largest nozzles only, was $60 \text{ lb}_t / \text{in}^2$ if 100% velocity and 60 AFR were to be obtained. Considering the largest nozzle only, the highest pressure level that could be obtained for these conditions was $100 \text{ lb}_t / \text{in}^2$. Thus the effect of flow number between two different swirl nozzles could be performed at design conditions at $60 \text{ lb}_t / \text{in}^2$ combustion pressure, and comparative tests between the largest swirl atomiser and the airblast atomiser could be performed at $100 \text{ lb}_t / \text{in}^2$ combustion pressure. The second factor affecting the work was the performance of the

airblast atomiser obtained during testing. The airblast flame, even at 100 lbf./in², was seen to be still partly blue and very transparent, thus the primary objective of obtaining a clean premixed flame with low flame total radiation and smoke emission, could be considered achieved. However, the fuel distribution from the burner rapidly deteriorated with assembly and disassembly of the burner due to a very bad design feature, which is discussed in Section 10, and thus severe over-heating of the liner and air casing was experienced, which meant that prolonged operation at a rich condition became hazardous. Whilst there was time to take a total radiation reading without undue over-heating, the time required to execute the readings required for Schmidt Method work accurately was not available.

Accordingly, it was decided to design new airblast atomisers and to execute the testing of the swirl atomisers whilst these were being manufactured, the airblast atomiser testing to be completed when the injectors became available. It was also thought necessary to obtain an improved design of airblast atomiser since testing on the fuel spray rig and the water/air rig showed that the atomisation quality, particularly at low air flows, was exceedingly poor, and thus the full advantages of the airblast system would not be realised with the existing burner.

SECTION 6.THE TEST FACILITY.

The general layout of the rig is shown in Fig. 16 and illustrated in Figs. 17, 18 & 19, the individual components are now described.

6.1 Combustion Chamber and Air Casing.

The combustion chambers used for all testing were from the Rolls-Royce Dart R.Da 7 turbo-prop. engine. The design data for this chamber are:-

Mass flow	= 3.18 lb/sec.
Air inlet pressure	= 84 lbf/in ²
Air inlet temperature	= 530 °K
Non-dimensional mass flow	= 0.0271
$\left[\frac{\dot{m} \sqrt{T_2}}{A_m P_2} \right]$	
Reference velocity, $V_{ref.}$	= 60.2 ft./sec.
Hot gas exit temperature	= 1170° K.
Air fuel Ratio	= 57.3
Reference area, A_m	= 32.4 in ²
Reference diameter D_m	= 6.4 in

The alleged air split to the various sections is:-

Swirler flow	= 5%
Flare cooling	= 12%
Flame tube cooling	= 26%
Secondary holes	= 8%
Intermediate & dilution holes	= 47%
Nozzle cooling	= 2%

For testing with standard simplex atomisers, a basically unmodified flame tube was used, but, as described, in Section 5, for use with airblast atomisers, the combustor snout was modified in order to accommodate these larger injectors. The unmodified chamber snout is shown in Fig.13, and the final standard of airblast snout in Fig. 15.

The combustors were housed in a heavy mild steel air casing to withstand the high pressure to which it was to be subjected. Every effort was made to reproduce the same internal air casing and diffuser geometry as on the real engine so that the combustor aerodynamics would remain unaltered as far as possible. The general layout of the working section and air casing is shown in Fig.20. The outer surface cross section of the air casing is octagonal with 8 hole end flanges, so that other viewing positions could be arranged in the future without interfering with the existing window sites, simply by rotating the air casing one octagon pitch, thus maintaining the horizontal sight path. The octagonal nature of the air casing is clearly illustrated in Fig.21.

Due to the accommodation of the sight path tubes, it was not necessary to retain the original combustor retaining and locating features. The combustor was retained by four features, the sight path tubes, the combustor static pressure tapping block, and the exit nozzle housing. Since they were of no further use, the existing interconnector stub pipes were removed and the holes blanked off.

6.2 Air Supply and Metering.

The air supply and metering system is shown diagrammatically in Fig.22. The air was supplied by 5 Howden compressors, each driven by a 500 HP, variable speed, D.C. motor, which could be arranged in various combinations of series and parallel running according to the mass flow and pressure requirements. The air was metered using a 2,500 in. diameter orifice plate in 5.0 in. diameter piping in an installation to BS.1042. The mass flow was controlled by the "cold" Daytona valve, and calculated using air inlet temperature and pressure and manometer deflection in accordance with BS.1042.

6.3 Exhaust Section.

Immediately downstream of the working section was a water cooled pipe, which is illustrated in Fig.21. This had been manufactured from stainless steel throughout, in order to help ensure the integrity of the hot end of the rig at the high temperatures and pressures to which it was

to be subjected. As a secondary, though nevertheless important, factor the water cooling enabled one to stand in complete comfort near the rig when running, thus making operation more easy. At the downstream end of the water cooled section was the "hot" Daytona valve which provided the necessary pressure drop to atmosphere to create the required combustion pressure. The valve is illustrated in Figs. 21 & 22. Downstream of the "hot" valve was an uncooled tail pipe to convey the hot gases outside the test house. It was in this section that the smoke sampling rake was situated, as shown in Fig. 23.

6.4 Expansion Bellows and Entry Chamber.

In between the cold valve and the working section was an expansion bellows and the entry chamber. The expansion unit was a "Teddington" telescopic type and was specified to accommodate any thermal expansion between the anchored working section and inlet pipe work. Downstream of the expansion unit was the entry chamber which fulfilled two functions. Firstly, this section acted as a settling chamber to smooth turbulence generated by the cold valve by a gradual increase in flow area. This function was necessary in order to present a reasonable velocity profile to the combustor diffuser, thus avoiding air maldistribution to the combustor itself. The second function was to provide access for the various burners to the combustor. The plate carrying the burner feed arm was bolted to the entry chamber through elongated bolt holes, thus allowing about 0.50 inch axial adjustment to the burner position in the combustor. This proved to be of great importance for the airblast atomisers as described in Section 11.

6.5 Window Housings.

The window housings had been based on a successful design used by N.G.T.E. for a similar purpose. The main criteria being that the nitrogen gas purge used to keep the window clean should be fed across the surface of the window from the whole circumference to provide maximum shielding, and that the window could be mounted in such a way as to avoid any local clamping of the delicate calcium fluoride. The windows were, in fact, set in an easily removeable outer cover using a synthetic rubber compound, "Silcoset 101".

The shutters required in the Schmidt Method were, in fact, 0.750 inch "Worcester" ball valves, which proved excellent in operation. A small modification was required to these valves due to repeated burning of the P.T.F.E. seals nearest to the flame. This was replaced by an

identical brass component which eliminated the problem without detracting from the smooth operation of the valves.

The window housings shown in Fig. 20 are in fact an earlier design and were not used for any of the testing.

6.6 Window Nitrogen Purge System.

A continuous flow of nitrogen was maintained across the surface of the windows in order to prevent the deposition of dirt and fuel droplets, which had hampered the work in other experiments. The flow was maintained even with the ball valves closed, since it was soon apparent that vapour was capable of leaking past the valves to condense on the cold windows. The nitrogen system is shown diagrammatically in Fig. 24.

It was found necessary to drop the bottle pressure in two stages with a heating coil in between. The reason for this was that the drop in temperature of the nitrogen in the throttling process with a single valve was sufficient to condense and freeze large quantities of atmospheric water on the valve, thus making further adjustment impossible. The heating coil was, in fact, a long length of piping subject to atmospheric heating only, which proved to be adequate to prevent freezing of the valves.

In order to guarantee the safety of the windows during changes of combustion pressure, a "Hale-Hamilton" double dome pressure controller was specified to control the nitrogen feed pressure to a fixed increment above combustion pressure, thus ensuring positive flow at all times.

A small Fischer Porter flow meter was used to monitor nitrogen flow rate to the windows. After initial experiments to determine the minimum flow rate to keep the windows clean and dry, the nitrogen purge system proved to be a complete success with no deposition at any running conditions.

6.7 Fuel Supply System.

The fuel supply system is shown diagrammatically in Fig. 25. A Lucas swash plate variable stroke piston pump was used to generate fuel pressure. At times this pump was asked to deliver up to 1600 lb/in^2 which is well above its normal delivery pressure. The fuel was metered by three Fischer-Porter flow meters whose specification was as follows:-

Small: FP $\frac{1}{4}$ - 25 - G5 Triflat with CD glass sphere float.

Medium: FP $\frac{1}{2}$ - 21 - G10/83 + $\frac{1}{2}$ GUSVT/40 float.

Large: FP $\frac{1}{2}$ - 27 - G10/83 + $\frac{1}{2}$ GNSVT/48/T62 float.

These flow meters were calibrated by determining mass flow rates in given times over the scale range. The fuel used at all times was Avtur/50 without F.S.I.I. to specification D.Eng. R.D. 2494.

6.8 Spembley Black Body Furnace.

This furnace was used to provide the black-body background required for the Schmidt Method. The model used was a 10 KVA vertical furnace with carbon interior, that was originally developed for small sample metallurgical research for the Atomic Energy Authority. Access for samples being obtained through a hatch on the top of the furnace hood.

The furnace was designed to operate at temperatures up to 3000° C, and thus an argon atmosphere is essential for the interior to survive. The furnace was subjected to three successive evacuations and argon purges before power was supplied, and during operation a slow bleed of argon was passed through the furnace. The furnace construction is shown in Fig.26 and the argon supply system is shown in Fig. 27. Fig.26 actually shows only one horizontal sight tube, whereas the furnace used had two diametrically opposite sight tubes, one for the supply of black body radiation to the rig, and the other for the furnace temperature pyrometer to view the interior of the furnace.

The furnace hood is packed with lamp black in order to provide the necessary shielding and insulation for the hot interior. This massive insulation, however, provided considerable thermal inertia, which proved an embarrassment in operation, since quick changes of furnace temperature to a stable level could not be accomplished.

The actual black body target was the 0.5 in. dia. entrance hole to the 1.0 in. dia. spherical cavity in a cylindrical block of carbon. This block sat on the existing furnace hearth as shown in Fig.26. Sealing of the sight tubes was by 0.200 in. thick calcium fluoride windows. The target block was adjusted such that the black body target hole was completely visible through one of the sight tubes, this sight tube then being aligned with the optical sight path using levelling screws mounted on the furnace stand. The other sight tube had an adjustable mounting for the Land MQO 7/50/-EW twin range silicon cell pyrometer, so that it could be accurately aligned with the rear of the target block.

Following the initial running-in and out-gassing processes, the only maintenance required on the furnace was periodical checks on the tightness of the element, operation and reliability being completely satisfactory.

The power supply to the furnace was delivered from a "Voltmobile" three phase transformer unit which provided incremental power supply via four-position coarse, medium and fine controls. The rate of supply at any instant was monitored via a voltmeter on the transformer, and an ammeter driven by an induction coil round one of the supply cables. The furnace, transformer and associated equipment are shown in Figs.17, 18 & 19.

Furnace temperature was monitored on a Control Instruments, Ltd. "DataLine 6" chart recorder, which had been designed for the Land MQO 7/50/-EW silicon cell pyrometer in conjunction with a range selector box. Two ranges were available, 0-1700° C and 0-3000° C. This instrument is clearly shown in Fig.18, a more full description of the operation and calibration of the furnace temperature measuring system may be found in Section 8.

6.9 Main Fluxmeter and Mounting.

The specification of the pyrometer was determined by the length of the sight path and the black-body target size. The length of the sight path was fixed by the width of the rig across the window housings, and the distance of the target from the end of the sight tube, and additional clearances between the equipments required for practical reasons, such as window removal. The maximum target size was fixed by the largest slot width permissible in the furnace carbon element, this slot width being determined by strength and resistance considerations for the element. As previously stated, the maximum target size that could be specified was 0.5 in. in diameter, thus at the focusing distance of 30 in. approximately, very accurate alignment of the main fluxmeter was essential if it was to "see" only the target, the importance of this is discussed in Section 7. Accordingly, a very finely adjustable mounting was designed, as shown in Fig.28, the principal design feature being a sliding spherical surface with the pyrometer lens and aperture at the centre of the sphere. This arrangement eliminated all axial or transverse motion of the lens and aperture relative to the sight path during adjustment.

The fluxmeter to fit the previously mentioned geometry, was a "Land" NRF.14/80/30 pyrometer. The design of this instrument is shown in Fig. 29. Due to the very small target size, the e.m.f. output of this instrument

was very low, being only 1 mv. at a black body radiator temperature of 2000° C. In order to obtain a method of presentation of the output for convenience and speed of operation, it was decided to build a special DC amplifier unit with stable gain values of 1000 and 100 whose output could easily be presented upon a standard milliammeter. This amplifier unit is shown in Figs. 18 & 19, mounted on the right-hand side of the main control panel, and proved to be excellent in operation with very little drift.

6.10 The Smoke Meter.

The equipment used for smoke measurement is shown diagrammatically in Fig.23. The smoke meter used for all testing was built to a specification supplied by Rolls-Royce, Ltd., which was subsequently modified to increase its sensitivity.

The principle of operation is as follows. An uncollimated beam of light is passed down a tube 30 cm. long with windows at each end, to be received by a photo-electric cell. Samples of exhaust gas are passed into the tube at one end and drawn out at the other end by a suction pump, a continuous flow being maintained whilst smoke level is measured. The carbon particles provide an obstruction to the light beam and thus the output from the photo cell reduced. The attenuation to the signal is amplified and presented on a 0 - 50 millivoltmeter.

The calibration of the instrument is effected by interposing a standard blockage and adjusting the gain of the amplifier to give a standard meter deflection. The standard blockage is a 0.025 in. diameter wire which provides a 3% blockage to define one Photosmoke Unit, when placed across the tube diameter, with the increased sensitivity used on the modified smoke meter, the calibrating blockage is provided by a 0.0025 in. diameter wire. It is important to note that since the light beam is uncollimated, the image of the wire on the photocell is blurred, and thus the tenfold reduction in wire diameter does not increase the sensitivity by an exact factor of ten. Accordingly, the smoke results are not presented in the form of Photosmoke units.

The increased sensitivity amplifier was very prone to drift with time, both on zero setting and on gain slightly. Thus the process of setting a fixed number of units exactly for each reading would have been both tedious and time consuming. In addition, due to the large differences in smoke level to be measured, calibration for all levels on say 10 units would mean that a low smoke level would deflect say 2 units and a high level off

scale. Clearly, to accommodate the highest levels on the scale will mean that the low levels will be measured with little accuracy. Thus, making the quite reasonable assumption that the amplifier had a linear characteristic, a system was evolved to use the maximum sensitivity and hence accuracy available for any smoke level, necessitating the definition of a new arbitrary smoke unit. The gain was adjusted such that any sample gave nearly full-scale deflection, and the deflection by the standard wire evaluated at the same sensitivity. The number of smoke units then being evaluated:-

$$\text{S.U. (smoke units)} = \frac{\text{mV for the smoke sample}}{\text{mV for calibration wire}}$$

(at any fixed gain value).

On the original meter, the driving force for sampling was intended to be the 6 volt suction pump. It was, however, decided to speed up the sampling process slightly by recovering a fixed proportion of exhaust pipe total pressure at the sampling rake to drive the sample through the lines and meter. This driving force was arbitrarily fixed at 2 in. of mercury. It was found that variations in the position of the hot valve altered the angular position of the rake at which 2 in. of mercury was recovered, thus a small manometer, as shown in Fig.23, was used to establish the recovery before sampling. As detailed in Section 11, the meter and sampling lines required periodical cleaning due to the deposition of carbon particles with condensed water of combustion.

The sampling rake was $\frac{3}{8}$ " diameter stainless steel tube with $\frac{1}{4}$ " holes across the whole tail pipe diameter at $\frac{3}{4}$ " pitches. It is hoped that isokinetic sampling was achieved, although no rigorous check was made to establish this condition.

6.11 Fuel Injectors.

(i) Swirl Atomisers.

The swirl injectors used for both the preliminary testing and the Schmidt Method work were of the standard simplex type as used on the Rolls-Royce Dart engine. A range of special nozzles were available of varying flow number and cone angle, but as detailed in Section 5, only two of these were used, the data for which are as follows:-

<u>Nozzle</u>	<u>Flow Number</u>	<u>Cone Angle</u>
A	0.37	90°
B	0.77	90°

(ii) Airblast Atomiser.

The airblast atomiser used was an external expanding fuel sheet type with very little fuel swirl. The fuel sheet was made to flow over the outside of a conical lip away from the apex of the cone, thus stretching and thinning the sheet. The fuel metering and distribution was accomplished via 6 finely machined slots on the centre body as shown in Fig.9. The diameter on which these slots were machined was a tight fit inside another diameter in the outer body, see Fig.10, which thus defined the fuel ports in conjunction with the slots. Unfortunately, the screw assembly of the atomiser meant that the two initially tightly fitting diameters soon became slack after several assembly operation, and thus fuel leakage became possible and the fuel distribution suffered considerably. The fuel swirl was imparted by a small spot-faced feature at the end of each fuel slot, these are clearly visible in Fig.9. Whilst these features were successful in providing a continuous fuel film at moderate and high fuel pressures, at low pressures the fuel was seen to issue from the atomising lip in 6 separate streams, as shown in Fig.30 & 31. The atomiser was located axially by the burner feed pipe, and radially by the 9 vane 45° swirler, which was pegged to the outer burner casing. The inner air deflector cone was retained by a long 6 BA. bolt screwing into a 4 vaned spider at the upstream end of the inner air passage, the deflector clearance being maintained by 3 pegs resting against the atomiser inner body. This arrangement is shown in Fig.10. The development of these features is described in Section 5.

SECTION 7.

THE SCHMIDT METHOD.

The flame within the primary zone of a gas turbine combustor is highly stratified in terms of both temperature and composition. The condition of the gases and radicals is far removed from thermal equilibrium due to the low residence times within this region. Accordingly, any definition of flame temperature is complex.

It is, however, possible to measure the radiation from such a gas path and measure the absorptance of the path to black-body radiation. If one then postulates that the flame is a grey body of uniform composition and temperature at the measuring plane, one may then define a flame temperature and a gas emissivity according to the laws of black body radiation. The flame temperature will be different from that defined by calorimetry, but it will nevertheless define the radiation properties of the gas path. Weeks (38) points out that all total radiation pyrometric methods for defining gas temperatures and emissivities rely on such assumptions, and that the Schmidt Method usually implies fewer further assumptions.

7.1 Theory of the Schmidt Method.

The Schmidt Method hinges upon the assumption of thermal equilibrium in the flame, thus allowing the application of Kirchoff's Law. Thring et al. (11) point out that the presence of any cold gas, fuel or carbon will increase absorptivity without increasing emissivity, hence Kirchoff's Law is strictly not applicable, but no further progress can be made without its assumption.

The flame temperature and emissivity of a gas path may be evaluated in the Schmidt Method from three readings of a fluxmeter. The optics are arranged so that the fluxmeter, which should be a grey receiver, may view the flame alone, the black body background alone, or the background as seen through the flame by suitable manipulation of shutters. It is most important that the optics and flame and target sizes are such that the fluxmeter "sees" only the flame or only the black body target, and no other radiation source, since this being so, the fluxmeter output is independent of working distance. This is of prime importance since the flame and target are at different distances from the pyrometer. Fig.33 shows the sight path adopted for this work. The three readings required define a flame temperature and a gas emissivity as follows:-

(i) Reading 1 (R_1)

This reading is the total radiation of the flame alone with a cold background.

$$R_1 = k \left[\int_0^{\infty} \frac{\epsilon_{\lambda F} C_1 \lambda^{-5} d\lambda}{\left[\exp \frac{C_2}{\lambda T_F} \right] - 1} \right] \quad \text{--- (1)}$$

Using the Planck Equation.

$$\text{or } R_1 = k [\sigma \epsilon_F T_F^4] \quad \text{--- (2)}$$

Using the Stephan Boltzmann Law.

where:- k = pyrometer constant

$\epsilon_{\lambda F}$ = spectral flame emissivity

$C_1 = 6.52 \times 10^7 [\text{CHU}/(\text{ft}^2 \cdot \text{hr} \cdot (\text{micron})^4)]$

λ = wavelength [micron]

$C_2 = 14,380 [\text{micron} \cdot ^\circ\text{K}]$

$\sigma = 1.01 \times 10^{-8} [\text{CHU}/(\text{ft}^2 \cdot \text{hr} \cdot ^\circ\text{K}^4)]$

ϵ_F = total flame emissivity

T_F = flame temperature [$^\circ\text{K}$]

The assumption implied here is that the flame is a grey body and thus:-

$$\epsilon_{\lambda F} = f(\lambda) \quad \text{--- (3)}$$

$$\epsilon_{\lambda F} = \text{Constant} = \epsilon_F \quad \text{--- (4)}$$

(ii) Reading 2 (R_2)

This reading is the total radiation of the hot black-body background as seen through the same flame, and thus:-

$$R_2 = k[\sigma \epsilon_F T_F^4] + k \left[\frac{\int_0^\infty (1 - \alpha'_{\lambda F}) C_1 \lambda^{-5} d\lambda}{\left[\exp \frac{c_2}{\lambda T_B} \right] - 1} \right] \quad \text{--- (5)}$$

$$\text{or } R_2 = k[\sigma \epsilon_F T_F^4] + k[\sigma T_B^4] \int_0^\infty (1 - \alpha'_{\lambda F}) d\lambda \quad \text{--- (6)}$$

$$\text{or } R_2 = k[\sigma \epsilon_F T_F^4] + k(1 - \alpha'_F)[\sigma T_B^4] \quad \text{--- (7)}$$

where:- $\alpha'_{\lambda F}$ = apparent spectral flame absorptivity

α'_F = apparent total flame absorptivity

T_B = black body target temperature.

The assumptions implied here are that the flame is a grey absorber and thus:-

$$\alpha'_{\lambda F} = f(\lambda) \quad \text{--- (8)}$$

$$\alpha'_{\lambda F} = \text{Constant} = \alpha'_F \quad \text{--- (9)}$$

(iii) Reading 3 (R_3)

This reading is taken of the black body target alone and thus:-

$$R_3 = k[\sigma T_B^4] \quad \text{--- (10)}$$

(iv) Analysis of Readings.

Substitution of equations (10) and (2) into equation (7) yields:-

$$R_2 = R_1 + (1 - \alpha'_F) R_3$$

Thus:-

$$\alpha'_F = \left[\frac{R_1 + R_3 - R_2}{R_3} \right] \quad \text{--- (11)}$$

Assuming that the gases are in thermal equilibrium, Kirchoff's Law gives:-

$$\alpha'_F = \epsilon'_F \quad \text{--- (12)}$$

Thus:-

$$\epsilon'_F = \left[\frac{R_1 + R_3 - R_2}{R_3} \right] \quad \text{--- (13)}$$

Equation (13) may now be substituted into equation (2) stated for apparent quantities to yield apparent flame temperature:-

$$T'_F = \sqrt[4]{\frac{R_1}{k \sigma \epsilon'_F}} \quad \text{--- (14)}$$

(v) Effect of Background Temperature, (T_B)

Equations (13) and (14) define apparent quantities at the particular background temperature used. The effect of background temperature may be understood by the following argument:-

If the flame emits as much radiation as it absorbs, the fluxmeter will "see" the same flux from the target whether the flame is interposed or not, thus:-

$$R_3 = R_2 \quad \text{--- (15)}$$

Substitution of (15) into (13) gives:-

$$\epsilon_F = \frac{R_1}{R_3} = \left[\frac{k\sigma \epsilon_F' T_F'^4}{k\sigma T_B^4} \right] \quad \text{--- (16)}$$

Clearly then, equations (13) and (14) can only be valid if:-

$$T_F' = T_B \quad \text{--- (17)}$$

And then equation (16) gives:-

$$\epsilon_F = \epsilon_F' \quad \text{--- (18)}$$

Since the flame temperature is initially unknown, an iterative process is required in order to provide a solution. The way in which this is executed is to take a series of values of R_1 , R_2 & R_3 for the same flame at a series of values of background temperature, and compute the corresponding values of T_F' and ϵ_F' . T_F' is then plotted against T_B and the locus of apparent flame temperature drawn. The intersection of this locus with the straight line with unity slope:-

$$T_F = T_B \quad \text{--- (19)}$$

gives the solution, and the corresponding emissivity may then be established by plotting the apparent emissivities against background temperature and taking the solution at the solution black body temperature.

7.2 Modified Schmidt Method.

Practical considerations necessitate modifications to the method previously outlined, since the flame must be contained at pressures greater than atmospheric. Thus windows must be provided to permit radiation measurements to be made. Such windows absorb radiation, and thus this must be allowed for in the analysis.

The choice of window material is a compromise between good optical properties and sufficient strength to withstand high combustion pressures. Unfortunately, the best materials available from an optical standpoint are both fragile and very expensive. In common with many previous workers, calcium fluoride was chosen for all the windows.

The optical property of special interest here is spectral absorption. Calcium fluoride has an almost constant spectral absorptivity from 0 to 8 microns, and then it drops off almost linearly to zero (opaque) at 12 microns.

The absorption characteristic of a calcium fluoride window is not dependent purely on the material properties but also on the character of the radiation it transmits. This situation is best illustrated with reference to black body radiation. As shown in Section 2, as temperature is increased the peak of the spectral radiation distribution curve, as defined by the Planck Equation, shifts towards the visible according to Wein's Displacement Law. Thus the percentage of the total radiation transmitted between 0 and X microns, say, is a function of black body temperature. In between 0 and X microns, the band pass of the window, the window material absorbs a very nearly fixed percentage of the transmitted radiation for all temperatures. Clearly, the total extinction of a window for black body radiation, comprising these two components, is effectively a function of black body temperature. This situation is illustrated in Fig. 34, which shows the absorption of one of the 0.270 in. thick calcium fluoride rig windows for black body radiation as a function of radiator temperature.

In order to modify the Schmidt Method, a further absorption phenomena requires explanation. The absorption of an identical window for black body radiation as seen through another window is different from that previously described. This becomes apparent when one considers that the energy from X to ∞ microns which is lost at the first window, cannot be lost again at the second window and thus cannot contribute to the total absorption of this window. Clearly then, the total absorption of the second window is less than that of the first window, and also is not nearly so much a function of radiator temperature, since the major temperature dependent portion beyond the window cut off point

does not enter the absorption calculation. The window absorption determination is discussed in Section 8.

The modification of the Schmidt Method to include the effects of window absorption is as follows:-

(i) Reading 1 (R_1)

This reading is the total radiation from the flame as seen through the window W_1 between the flame and the fluxmeter which with previous assumptions is:-

$$R_1 = k \epsilon_F \int_0^x (1 - \beta_{1\lambda B}) \Theta d\lambda \quad \text{--- (20)}$$

$$\text{where } \Theta = \frac{c_1 \lambda^{-5}}{[\exp c_2 / \lambda T_F] - 1} \quad \text{--- (21)}$$

where:-

$\beta_{1\lambda B}$ = spectral absorption of W_1 for black body radiation.

x = cut off wavelength, which is approximately 10 microns for calcium fluoride.

In order to proceed, the following assumptions must be made:-

(a) $\beta_{1\lambda B}$ = constant from $\lambda = 0$ to $\lambda = x$

(b) $\int_0^x \Theta d\lambda = \int_0^\infty \Theta d\lambda$

Both these assumptions are valid for calcium fluoride since the spectral absorptance is very nearly constant up to 8 microns, and for a black body temperature of 2000° C, over 98% of the total energy is contained between 0 and 8 microns.

It should be noted that the term absorption as used here implies total extinction which includes reflection losses at the window surfaces.

With the assumptions, equation (20) becomes:-

$$R_1 = k(1 - \beta_{1B})\sigma\epsilon_F T_F^4 \quad \text{--- (22)}$$

where:- β_{1B} = the total absorption of W_1 for black body radiation.

(ii) Reading 2 (R_2)

This reading is the total radiation of the flame as seen through W_1 plus the total radiation of the black body target as seen through W_1 and W_2 .
 W_2 is the window between the flame and the target.

$$R_2 = k(1 - \beta_{1B})\sigma\epsilon_F T_F^4 + k(1 - \beta_{2B})(1 - \beta_{1W})(1 - \epsilon'_F)\sigma T_B^4 \quad \text{--- (23)}$$

where:- β_{2B} = total absorption of W_2 for black body radiation.

β_{1W} = total absorption of W_1 to black body radiation as seen through W_2 .

(iii) Reading 3 (R_3)

This is the total radiation of the black body target alone as seen through W_1 and W_2 .

$$R_3 = k(1 - \beta_{2B})(1 - \beta_{1W})\sigma T_B^4 \quad \text{--- (24)}$$

(iv) Analysis of Readings.

Substitution of (24) and (22) into equation (23) assuming Kirchoff's Law:-

$$\epsilon'_F = \left[\frac{R_1 + R_3 - R_2}{R_3} \right] \quad \text{--- (25)}$$

This is exactly the same as before, but substitution of equation (25) into (22) and re-arranging for apparent flame temperature yields:-

$$T_F' = \sqrt[4]{\frac{R_1}{k(1-\beta_{1B})\sigma \epsilon_F'}} \quad \text{--- (26)}$$

As in the previous analysis without windows an iterative type process is required to solve for the "true" flame temperature, and the method employed is exactly as previously outlined.

7.3 Application to Result Reduction.

In order to apply the results of the analysis in Section 7.2 to the actual reduction of results, two further modifications to the formulae are required.

Firstly, the radiation response characteristic of the Land fluxmeter was derived from the makers' calibration in terms of normal radiant intensity, since this is very nearly what the fluxmeter "sees", rather than total hemispherical radiant intensity as defined in the Stephan Boltzmann equation. This process is described in Section 8. Thus, since equation (26) is based upon the Stephan Boltzmann equation, a factor is required to convert the total hemispherical radiant intensity into normal radiant intensity, as measured with R_1 .

It may be shown that:-

$$E = \pi I \quad \text{--- (27)}$$

where:- E = total hemispherical radiant intensity.

I = total normal radiant intensity.

Thus equation (26) becomes:-

$$T_F' = \sqrt[4]{\frac{\pi R_1}{k(1-\beta_{1B})\sigma \epsilon_F'}} \quad \text{--- (28)}$$

The second modification that was necessary is due to the fact that the furnace and flame are at different distances from the fluxmeter. Whilst, as previously mentioned, the optics were arranged such that the fluxmeter "saw" only the target and flame, and thus output is theoretically independent of working distance, there is a distance effect due to atmospheric water absorption.

The fluxmeter was calibrated at its focal distance of 30 in. away from the reference black body target, by Land Pyrometers, Ltd. To take account of water absorption, they recommend a correction of $\pm 2.5\%$ on output e.m.f. for each foot away from the focal distance. From this recommendation and from data in reference (38), it was decided to use a factor of 3% to allow for the increased output since the flame was nearer to the fluxmeter than the focal distance.

Thus equation (28) becomes:-

$$T_F' = \sqrt[4]{\frac{0.97 \pi R_1}{k(1-\beta_{1B})\sigma \epsilon_F'}} \quad \text{--- (29)}$$

This equation was used with equation (25) to perform the Schmidt Method results reduction. The reduction of one set of Schmidt Method results is shown in Appendix IV.

SECTION 8.

CALIBRATION OF EQUIPMENT.

8.1 Fluxmeter and D.C. Amplifier.

The fluxmeter used for the Schmidt Method was a "Land" total radiation pyrometer type NRF.14/80/30. As pointed out in Section 7, it was essential to know the response characteristic in terms of e.m.f. output for given radiant fluxes. The most satisfactory method of obtaining this characteristic is a direct calibration using a windowless furnace over the appropriate range of black body temperatures. Unfortunately, it was not possible to gain access to such a furnace, and so this ideal calibration could not be performed. However, the makers supplied the calibration for the instrument as a pyrometer in the form of e.m.f. output for a range of black body temperatures, thus, using the Stephan Boltzman law with a factor of $[1/\pi]$ applied to convert total hemispherical to normal total radiant flux, the corresponding fluxes were calculated, which then provided the calibration as a fluxmeter. The calibration of the instrument thus derived, is shown in Fig. 35. The calibration for the RF.3/30/16 instrument used in preliminary testing was derived in exactly the same manner, and is illustrated in Fig. 36. It is interesting to note that both these characteristics are very nearly linear.

The lens of the NRF.14/80/30 fluxmeter was specified to be made in arsenic trisulphide at the recommendation of Land Pyrometers, Ltd. This material was chosen in preference to calcium fluoride because, although arsenic trisulphide has a narrower band pass than calcium fluoride, in lens form, calcium fluoride suffers from excessive chromatic aberration, and thus the overall performance of arsenic trisulphide as a lens is superior. The effect of lens total absorption is, of course, taken account of in the makers' calibration, and thus does not really enter the argument here.

As described in Section 6.9, the very low output from the main fluxmeter required the use of a stable gain D.C. amplifier in order to present a reasonable output on a standard meter. It was essential that the input/output characteristic should be evaluated for both ranges of the instrument. This was accomplished by simulating the pyrometer output e.m.f. by suitable circuitry and measuring this input using a digital voltmeter, the corresponding outputs on the amplifier "Metrix" milliammeter being noted. The whole of the two scale ranges were covered in this

manner to yield the two characteristics shown in Figs.37 and 38. The figures show that the responses are very nearly linear.

8.2 Spembley Black Body Furnace.

As described in Section 6.8, the temperature of the Spembley furnace was monitored by a "Land" twin-range, silicon cell, miniature pyrometer, type MQO.7/50/- EW. This pyrometer viewed the rear of the black body target block, and its output was fed, via a range selector switch, to a Control Instruments "DataLine 6" chart recorder. Again, the manufacturer's calibration tables had to be accepted as correct, since no windowless furnace was available to perform an individual calibration. The calibration tables gave the output from the combined pyrometer and range selector circuits for the two ranges of black body temperatures. The maximum outputs were:-

<u>Range (°C).</u>	<u>Temperature(°C).</u>	<u>Output (mV).</u>
0 - 1700	1700	20
0 - 3000	3000	20

Whilst the maker's calibration for the pyrometer had to be accepted as correct, it was possible to calibrate the chart recorder using the known outputs at the range selector box for the range of black body temperatures from the Land calibrations. Thus these known outputs were fed into the chart recorder from a "Cambridge" potentiometer/mV supply bridge, and the corresponding indicated scale temperatures noted over the ranges of black body temperature, hence providing the chart recorder calibration for instrument and scale error.

As the furnace pyrometer could not be permanently positioned to look into the black body cavity, but was to view the rear of the target block, a further correction became necessary. The pyrometer calibrations supplied were for black body radiation as viewed through a 0.200 in. thick calcium fluoride window, and since the rear of the target could not be regarded as a black body, an emissivity correction was necessary. Accordingly, the pyrometer was now linked to the chart recorder, whose calibration had been established, and over the range of furnace temperatures to be used alternately viewed the target and then the rear of the target block, and the temperature discrepancy between the two positions noted as the emissivity correction.

These various calibrations are more easily understood by consideration of the following analysis:-

Let T_{bb} = true furnace temperature as seen viewing the target.

T_B = apparent furnace temperature as seen at the rear of the target.

T_{bb}' & T_B' = the above temperatures uncorrected for chart recorder error.

$$\text{Let:-} \quad T_B' + E_1 = T_B \quad \text{--- (1)}$$

$$T_{bb}' + E_1 = T_{bb} \quad \text{--- (2)}$$

$$T_B + E_2 = T_{bb} \quad \text{--- (3)}$$

where:- E_1 = correction for chart recorder instrument and scale errors.

E_2 = correction for emissivity due to viewing position.

Experimentally, T_B' was read on the chart recorder, and T_{bb} was the black body temperature required for Schmidt Method work. Thus from equations (1) and (3):-

$$T_{bb} = T_B' + [E_1 + E_2] \quad \text{--- (4)}$$

It should be noted that both E_1 and E_2 are functions of furnace temperature. The corrections E_1 and E_2 were obtained by the methods previously outlined, and the total correction, $[E_1 + E_2]$ is seen in Fig.39 as a function of apparent furnace temperature T_B' .

An important assumption has been essential to perform these calibrations, and indeed to validate the application of the Schmidt Method as a whole, and this is that the target was a good approximation to a black body. The argument for a small hole into a cavity being a black body is well known, but this is only strictly true where the hole is infinitely small compared with the cavity size. Thus intuitively, one would expect that the degree of "blackness" of such a body would be related to the ratio of hole size to

cavity size. For the target used, the ratio of hole diameter to cavity diameter was 0.4. Unfortunately, there exists no optical analytical method to determine the variation of emissivity of such bodies for different ratios of hole size to cavity size, and no empirical data on this subject could be found in order to assess the emissivity of the target used. The whole of the furnace interior is, however, a fair approximation to a black body, and many previous workers have used this as their target for the Schmidt Method. Accordingly, it would seem reasonable to assume that the target used was a good approximation to a black body.

8.3 Windows.

As described in Section 7, the absorption of the calcium fluoride windows is a function of radiator temperature. The ideal calibration of the window absorption could not be performed, again due to the fact that access could not be gained to a windowless black body furnace. A visit to Land Pyrometers, Ltd. did, however, provide an absorption figure for one window at 1400° C, using the pyrometer calibration furnace. The absorption characteristic of the window was derived by calculation from the results of two other workers, Weeks (38) and Preece (39). These workers obtained direct calibrations over a range of black body temperatures for calcium fluoride windows of thickness 0.375 in. and 0.200 in. respectively.

The term absorption, as used here, includes the effects of reflection as well. A survey of the literature and the physical data available revealed that it is not possible to accurately calculate such total absorptions from geometrical and material considerations. It was thus necessary to assume a law relating absorption to thickness at a particular radiator temperature, and solve for constants from the known data of Weeks and Preece, and then calculate the absorption for a window of thickness 0.270 in. as used for this work.

The assumed law relating absorption to thickness for calcium fluoride windows at a particular radiator temperature is as follows:-

$$\beta_T = \eta_1 (d)^{n_1} + \eta_2 (d)^{n_2} + \dots + \eta_n (d)^{n_n} \quad (5)$$

Since only two established characteristics were available for analysis and the solution of constants, only the first term could be considered. Thus:-

$$\beta_T = \eta (d)^n \quad \text{--- (6)}$$

Hence at a fixed temperature, the absorption values for 0.375 in. and 0.200 in. windows were used to simultaneously solve for η and n and these values then used to calculate the absorption at the same temperature for $d = 0.270$ in. This process was repeated over the temperature range, and the absorption characteristic was derived, this being illustrated in Fig.34. The check point at 1400° C. is seen to lie very close to the derived curve, and thus it was assumed that the procedure adopted and the resultant characteristic, were satisfactory. It should be noted that some extrapolation of the Weeks and Preece curves was necessary in order to extend the temperature range. This should not have involved too much error since, at the higher temperatures, the characteristic has flattened off considerably. The effect of the window absorption on the calculation of flame temperature is small since the total absorption is only of the order of 6% to 10%, and thus any errors involved in the assumption of the above absorption/thickness law are minimal accordingly.

SECTION 9.

EXPERIMENTAL TECHNIQUE.

9.1 Combustor Operation.

(i) Ignition Techniques.

The ignition system used was a high energy flush-gap, surface discharge plug driven by an ex-engine, 24 volt igniter box. This system provided a very good spark and proved durable and reliable.

The swirl atomiser combustor proved to be extremely easy to ignite. A low mass flow was set, the igniter switched on, the fuel valve cracked open, and ignition was usually instantaneous. There was no evidence of tail-pipe burning, and light up could be achieved without any excessive tail pipe temperature.

The airblast atomiser, however, proved much more difficult to light up due to the narrow stability limits and very poor atomisation at low air and fuel flows. To obtain a light-up, a slightly higher air mass flow was set, the igniter switched on and the fuel valve opened to give about 0.020 lb./sec. fuel flow. The air flow was then slowly increased until ignition was obtained. Having achieved light-up, the fuel was quickly reduced to about 0.005 lb./sec. and a short period given for excess fuel to burn out in the tail pipe. This burn out of the excess fuel accumulated in the starting procedure, frequently caused tail-pipe temperatures up to 700° C.

(ii) Run-up.

In order to run the rig up to the desired test conditions, the following procedure was adopted. The air and fuel flows were increased simultaneously so as to keep tail pipe temperature approximately constant. Having obtained an air mass flow rate of about 0.8 lb/sec, the hot valve was wound down to raise combustion pressure to 2 atmospheres. The air and fuel flows were then increased to give about 1.6 lb./sec. air flow at constant tail pipe temperature and the hot valve adjusted to give 3 atmospheres. This procedure was followed until the desired pressure had been achieved.

The technique employed was exactly the same for both injector types except that the airblast atomiser required more care if extinction was to be avoided. With the swirl atomiser, the run up tail pipe temperature was less

than 2000° C, whereas with the airblast atomiser, a temperature of 350 - 4000° C was necessary to avoid extinction. The above procedure, in fact, was adopted so that the deviations in reference velocity at any particular pressure level during run-up were minimised and run-up was roughly at constant air fuel ratio.

(iii) Stable Running.

Having reached the approximate test conditions required, a recalculation of the required manometer head for a given mass flow was necessary, since there was a tendency for the air inlet temperature to rise and the air inlet pressure to fall as air was received from the compressors. Thus the head was recalculated and set using the cold valve whilst manipulating the hot valve to maintain the required combustion pressure.

There was considerable interaction between the hot and cold valves, and thus any changes in mass flow required adjustment of the hot valve to maintain combustion pressure. Any changes in air fuel ratio at constant air mass flow and combustion pressure, also required hot valve adjustment. These effects would, in fact, be expected considering the changes in pressure drop across the hot valve with changes in mass flow and gas temperature.

(iv) Fuel Pump.

A characteristic of the Lucas swash plate pump and the associated pipework was that there were only certain delivery pressures that could be set if "water-hammer" effects were to be avoided. In order to obtain steady fuel flows and thus avoid combustion oscillations, it was essential that the pump should be set at one of these steady conditions. These running points were, in fact, dependent on fuel flow and thus final adjustment of the spill valve was frequently necessary in order to achieve steady fuel delivery.

When water-hammer effects were encountered, there was a large rise in fuel temperature, which was also undesirable.

9.2 Spembley Furnace.

(i) Alignment with Optical Sight Path.

Since the maximum diameter of the sight path beam

of the pyrometer was only about 60% of the minimum diameter of the rig component apertures, there was a fair amount of latitude as to the position of the target with respect to the rig. Accordingly, the furnace was aligned by eye viewing through the rig such that the whole of the target was in view and very nearly concentric with the various visible diameters sighting through the rig. The adjustment was achieved by inching the furnace position and using the levelling screws on the base.

(ii) Evacuation and Argon Purge.

As explained in Section 6, the Spembley furnace was operated with an argon atmosphere, and a slow purge of argon was passed through the furnace whilst at temperature. The vacuum and argon circuits are shown in Fig.27.

Following a long period of standing without operation on or after a strip-down, the following procedure was adopted to re-establish the atmosphere and purge flow (refer to Fig.27):-

- (a) Close valves:- A, D & E.
- (b) Open valves:- B & C.
- (c) Argon bottle regulator set to arbitrary 50 lbf/in².
- (d) Start "Genevac" vacuum pump.
- (e) Open valve:- E.
- (f) When acceptable equilibrium vacuum is obtained indicated by the manometer:-
- (g) Close Valve: E.
- (h) Open valve A and bleed in argon until fractionally more than one atmosphere is obtained in the furnace, as indicated by the manometer. Close valve A.
- (i) Repeat (e), (f), (g) and (h) a further twice.
- (j) Open valve D to allow excess argon to bleed away through the oil bottles.
- (k) Re-open valve A and adjust to give argon flow of 2 to 4 bubbles per second through the oil bottles.

(iii) Run-up.

Having established the argon atmosphere and purge flow, the cooling water was turned on and then power could be applied to the element. The power was applied in increments over a time period in order to avoid damage to the delicate carbon interior by large thermal gradients. Carbon resistance decreases with temperature

so that at the upper temperatures, there was a possibility of a thermal run-away, and thus large increases in power were always avoided. The power was applied such that the furnace came to a dull red colour after about 20 minutes and heating to 2000°C in about an hour.

(iv) Running Temperature Adjustment.

The large thermal inertia of the furnace hood meant that a change from one stable temperature to another was time consuming. During the initial proving trials, equilibrium furnace temperatures were determined for the various power settings. Accordingly, the technique for either raising or lowering the temperature was to apply either full power or zero power until about 10 - 15° C above the required temperature was achieved, the equilibrium power setting for the required temperature was then selected, and the thermal inertia of the hood would pull the temperature down to the required level.

At equilibrium temperatures, there was always a continuous slight drift up and down in temperature, and the mean equilibrium temperature for a given power setting varied slightly from day to day. This did cause some inconvenience in that the temperature did sometimes change slightly whilst taking a set of Schmidt readings, but generally an appropriate power adjustment could be used to counteract drift for a period sufficient to take a set of readings.

(v) Shut-down.

To shut the furnace down power was reduced to zero immediately. When the furnace had cooled to below red heat, the argon flow was stopped and the furnace pressurised to about 10 in. of mercury gauge. This pressurisation was merely to counteract the reduction of the argon pressure as the furnace cooled further, when cold the argon pressure was thus only slightly below atmospheric pressure. The cooling water flow was maintained for about 40 minutes after the argon supply was stopped.

9.3 Pyrometers.

(i) RF. 2/30/16.

For the preliminary testing with this pyrometer, the instrument was aligned by eye since there was no critical

directional focussing as the flame target was large. Some care was, however, necessary, since the beam diameter on passing through the window housing was only slightly less than the diameter of the housing and ball valve itself.

The output from this instrument was measured on a "Cambridge" potentiometric bridge. A reading was taken by zeroing the bridge with a cold background in the form of the closed ball valve, and then opening the valve and balancing the bridge to obtain the output mV.

(ii) NRF.14/80/30.

(a) Alignment.

As mentioned in Section 6, since the minimum target size for the instrument was only slightly less than the actual target size itself, directional alignment was critical. A pyrometer mounting was designed as shown in Fig. 28, which allowed extremely fine adjustment via two screws, one for the horizontal plane and the other for the vertical plane. The alignment was checked before each run, since there was a slight tendency for the target to rotate within the furnace, presumably due to thermal cycling and/or vibration from the rig and power supply (which was noticable).

Alignment was accomplished using the furnace at temperature and the D.C.amplifier. The adjusting screws were manipulated individually until a drop in output was noticed turning one way, then, turning the other way, the drop off point was noted and the screw set mid-way between these two positions. The sensitivity of the adjustment was such that there was more than half a turn at peak output without any drop off.

(b) Radiation Measurement.

The D.C.amplifier used to amplify the fluxmeter output suffered from a slight amount of zero drift, and thus before each reading it was essential that the instrument be zeroed, this was more apparent and necessary on the high sensitivity range. Thus a measurement was taken by zeroing the amplifier with the ball valve between fluxmeter and flame closed to provide a cold background, then opening one or both ball valves to obtain the Schmidt readings.

9.4 Smoke Meter.

(i) Rake Adjustment.

The smoke rake was rotatable in order to recover a fixed amount of tail pipe total pressure. The change in flow in the tailpipe with different hot valve positions meant that the rake angle had to be altered in order to recover the same amount of total pressure for each flow condition. The rake was rotated until 2 in. of mercury was recovered and registered on a small manometer, as shown diagrammatically in Fig.23. The smoke meter millivoltmeter was zeroed with clean air being drawn through the cell. The sampling line was then attached to the rake and the sample passed through the smoke meter, the millivoltmeter deflection being noted. The sensitivity was then increased until the deflection was nearly full scale or maximum sensitivity had been reached.

The sampling pipe was then removed, and when the tube was cleared of smoke by the suction pump, the meter was re-zeroed. The zero had to be checked after the sensitivity had been changed, as there was considerable coupling between the two controls. Having zeroed the meter, the calibration wire was positioned across the light beam by a solenoid, and the calibration mV established. The wire was then removed and the sampling line re-connected and the smoke reading mV noted. The smoke level was then evaluated via:-

$$\text{Smoke Level (S.U.)} = \frac{\text{mV smoke}}{\text{mV calibration}}$$

Due to the continued random drift of the meter, the smoke readings frequently had to be repeated several times due to either a failure to return to zero as the tube was cleared of smoke, or the mV calibration before and after the sample did not agree.

9.5 Stability Tests.

The technique employed for determining the weak extinction was similar for both atomisers. The rig was firstly run up to the required mass flow and combustion pressure at some arbitrary air-fuel ratio. The fuel valve was then slowly closed, thus increasing the air-fuel ratio, whilst simultaneously juggling with the hot and cold valves to maintain the air mass flow rate and combustion pressure. As the mixture was weakened off, the hot valve had to be closed down considerably due to the decrease in velocity of the exhaust gases.

As the extinction point was approached, fluctuations in mass flow and combustion pressure were encountered which required a certain amount of deft manipulation, if premature extinction was to be avoided. A mirror was arranged so as to be able to view up the tail-pipe into the combustor in order to establish the precise moment of extinction when the flame glow vanished. The extinction was also detectable by a sudden increase in air mass flow, due to the sudden decrease in pressure drop across the hot valve as the exhaust temperature and velocity fell. The extinction fuel flow was noted, and thus the extinction air-fuel ratio calculated with a knowledge of the air mass flow rate.

9.6 Schmidt Method.

As pointed out in Section 7, the solution for flame temperature and emissivity relies strictly upon the target being at the same temperature as the flame. It would have been convenient to have some method whereby a reasonably accurate calculation of flame temperature at the viewing plane could be made. Unfortunately, this was not possible for two reasons: firstly, there was no information available with which an accurate estimate of primary zone combustion efficiency could be made, and, secondly, the amount of air burning with the known fuel flow could only be guessed. Although an accurate estimate could not be made, a rough estimate was possible, which enabled the furnace temperature to be set at least in the right region.

The procedure was thus to divide the testing for any set of flame conditions into two separate runs. Thus on the first run, a set of readings were taken at each flame condition, for one appropriate furnace temperature. Having calculated these results, on the second run each flame condition was investigated with two or three furnace temperatures such as to span the flame temperature indicated on the first run. Generally, the true flame temperature was spanned on the second run, although sometimes a further check was necessary if the initial estimate was too far out.

The third reading, R_3 , required for the Schmidt Method, being the radiation from the target alone, meant that the flame had to be shut down. This provided the inconvenience of having to reset the same flame condition for each furnace temperature, rather than being able to stabilise the flame and investigate a series of flame temperatures. This process was both time consuming and an additional possible source of error. It was thought possible initially that a complete calibration for R_3 could be made over the range of furnace temperatures, and thus remove the necessity of shutting down the flame by obtaining R_3 for the particular furnace temperature from a graph. Initial trials and reference to

the literature (38) showed that this procedure would not be recommended due to the effects of window fouling and any possible alteration of the fluxmeter response characteristic with time. Thus it was thought worth the extra time and trouble to shut the flame down and obtain a "local" calibration by taking R_3 readings before and after each set of R_1 and R_2 readings at a particular furnace temperature.

This procedure was not as wasteful in time as might at first be thought, since it was quickly discovered that it took less time to relight and set the flame condition than to alter and stabilise the furnace temperature. Thus it was possible to arrange the order of flame conditions investigated such that there was an overlap of the required furnace temperatures. Thus, say, twelve different flame conditions could be investigated with only four or five changes in furnace temperature.

Thus the procedure to obtain a set of Schmidt Readings for one flame condition and furnace temperature was as follows:-

- (a) Set and stabilise furnace temperature T_B .
- (b) Take R_3 at T_B .
- (c) Light up the flame, set and stabilise the required flame condition.
- (d) Take R_2 (both ball valves open).
- (e) Take R_1 (ball valve between fluxmeter and flame open).
- (f) Repeat R_2 .
- (g) Repeat R_1 .
- (h) If there is a discrepancy between the first and second set of R_1 and R_2 , check furnace temperature and flame conditions and take further readings.
- (i) Shut down the flame.
- (j) Take R_3 at T_{B2} .
- (k) Take T_{B2} .
- (l) If $T_B \neq T_{B2}$ adjust furnace power and repeat (1) If $T_{B1} \neq T_{B2}$ adjust furnace power and repeat (a) to (k).

The reduction of a typical set of such readings is illustrated in Appendix IV.

SECTION 10.

DESIGN OF AIRBLAST ATOMISERS.

10.1 Initial Considerations.

The considerations that prompted and guided the design studies described in this section were as follows:-

- (i) The existing external, cone-flow airblast atomiser had proved unsatisfactory for extensive analysis via the Schmidt Method (see Section 5). Disregarding its demonstrated performance, it was considered that the design concepts could be improved upon.
- (ii) In Section 4, the problems of applying airblast atomisers to gas turbines for aircraft application were discussed. The narrow burning stability limits of these injectors poses a problem for the ground ignition, altitude relight, and maybe even ground-idle cases. Two possible solutions were envisaged, on the one hand an uncompromised airblast atomiser with a pilot swirl atomiser and a duplex fuel system, and on the other a compromised simplex air blast atomiser.

The writer considered that the former solution was the more satisfactory for two reasons. Firstly, the flow number of a simplex airblast atomiser that is to obtain sufficient atomisation at ignition fuel flows, must entail variations in fuel pressure of the same order as that experienced with simplex swirl atomisers. Thus one is faced with providing inordinately high fuel pressures, and one of the desirable advantages claimed for the airblast atomiser in the form of low pressure fuel systems, is lost.

Secondly, and perhaps more importantly, by definition one cannot extend stability limits without creating carbon forming, fuel rich zones, and thus the main reason for considering the airblast atomiser in the control of smoke and radiation is negated. The great advantage of the duplex system considered here is that the fuel rich zones may be removed at will for the important take-off and cruise conditions. It could well be that in the short term a satisfactory compromise could be achieved between obtaining satisfactory stability limits and acceptable flame radiation and smoke emissions, but in the long term, remembering the continued upward trend of engine pressure ratio, the duplex system would appear to be a more permanent solution. Accordingly, the aim of this design study

is to produce airblast atomisers that provide the maximum amount of premixing of fuel and air with as small a droplet size as possible, with one of the atomisers incorporating a pilot swirl atomiser in order to be able to investigate the requirements of a duplex airblast/swirl system.

10.2 Design Features.

The design considerations were:-

- (i) High velocity air should be supplied to both sides of the fuel sheet in order to obtain maximum atomisation and avoid stagnation zones.
- (ii) The air passages should be as aerodynamically clean as possible, with high coefficients of discharge in order to obtain the maximum velocity at the pressure drop available.
- (iii) The site of fuel release for atomisation should be well removed from stagnation areas so that agglomeration of droplets would be avoided. The fuel lip should be thin to avoid coanda effects as experienced by Bryan on his early injector (15).
- (iv) The fuel release from the metering ports should be onto an internal surface so that no restrictions are placed upon the amount of fuel swirl that could be employed if necessary during development work. Fuel swirl was considered necessary in order to minimise gravity effects and create a uniform fuel sheet in as short a burner length as possible.
- (v) The internal surface should be expanding so as to thin the fuel sheet as far as possible, and also to avoid an abrupt change of fuel flow direction at the atomiser lip in order to create a suitable cone angle.
- (vi) The fuel should have an axial component as well as a swirl component at the metering ports in order to avoid the very large cone angles experienced by Bryan (15) at low air flows. Bryan's injector had no direct axial component.
- (vii) Tests on an atomiser of a roughly similar configuration showed that the outer, or shroud air was more effective in obtaining good atomisation than the inner air. Accordingly, of the total air supply to the injector, two-thirds would be supplied as outer shroud air. (Facility was included on the duplex atomiser for varying this air split).

- (viii) On the duplex atomiser, the pilot nozzle should be a standard "Dart" simplex type so that the flow number and cone angle could be easily changed using the range of nozzles already available.
- (ix) Swirl should be applied to the outer shroud air in light of experience on the existing airblast atomiser (see Section 5).

10.3 Summary of Design Calculations.

(i) Air Passage Design.

Assume an arbitrary total combustor air mass flow rate of 7 lb./sec. (the maximum available from the compressors at 250 lbf./in² pressure).

2.5% of the total flow is to pass through the injector:-

Thus:-

$$\dot{m}_i + \dot{m}_s = 7.0 \times 0.025 = 0.175 \text{ lb/s} \quad \text{--- (1)}$$

where:- $\dot{m}_i$ = inner injector air.

$\dot{m}_s$ = outer or shroud air.

Split of air between shroud and inner passages is 2 : 1.

Thus:- $\dot{m}_s = 2 \dot{m}_i \quad \text{--- (2)}$

Solving equations (1) and (2) :-

$$\dot{m}_i = 0.0583 \text{ lb./sec.} \quad \text{--- (3)}$$

$$\dot{m}_s = 0.1167 \text{ lb./sec.} \quad \text{--- (4)}$$

For the inner air passage assume a coefficient of discharge of 0.7, and for the outer passage 0.5:-

$$\text{Thus } \dot{m}_i = 0.7 \rho A_i \sqrt{\frac{2g\Delta p}{\rho}} \quad \text{--- (5)}$$

where:- A_i = inner passage limiting area.

$$\text{And:- } \dot{m}_s = 0.5 \rho A_s \sqrt{\frac{2g\Delta p}{\rho}} \quad \text{--- (6)}$$

where A_s = the outer passage limiting area.

Thus from equations (5) and (6) using equation (2) :-

$$A_s = 2.8 A_i \quad \text{--- (7)}$$

Assuming inlet air conditions:-

inlet air pressure = 250 lbf./in².

inlet air temperature = 340° K.

The air density ρ = 1.1 lb./ft³.

Assuming a 5% pressure loss flame tube

$$\Delta p = 0.05 \times 250 = 12.5 \text{ lbf./in}^2.$$

Thus substitution of appropriate values in equations (6) and (7) reveal:-

$$A_i = 0.106 \text{ in}^2 \quad \text{--- (8)}$$

$$A_s = 0.297 \text{ in}^2 \quad \text{--- (9)}$$

The limiting air passage areas were thus designed on these area values.

10.4 Fuel Port Design.

The design flow number is 2.0. Thus at a fuel pressure differential of 200 lb/in² the fuel mass flow for an overall air-fuel ratio of 120 is:-

$$\dot{m}_f = 0.058 \text{ lb./sec.} \quad \text{--- (10)}$$

using:- $\dot{m}_f = C_d \rho_f A_n \sqrt{\frac{2g\Delta p}{\rho_f}}$

Assuming that the fuel ports have a coefficient of discharge of 0.3 and the fuel density is 50 lb./ft³:

$$A_n = \frac{0.058}{50 \times 0.3} \times \frac{50}{2g \times 200 \times 144}$$

$$\text{thus } A_n = 29 \times 10^{-4} \text{ in}^2 \quad (11)$$

Thus the fuel ports were specified from this area value according to the number of ports used.

10.5 The Designed Injectors.

The injectors designed are shown in Figs. 40 & 41. The simplex airblast atomiser in Fig. 40 has four fuel ports and is located radially by a 10 vane, 45° air swirler, the axial location being determined by the fuel feed arm. The centre body is a tight fit in the outer body to seal the fuel passages and ports machined in the centre body. Shims are provided on the pintle stem in order to vary the inner/outer air split. Fig. 41 shows the duplex atomiser which has six fuel ports for the airblast atomiser main fuel flow and a simplex swirl nozzle mounted in the central pintle for the pilot fuel supply. The two fuel feed pipes again provide the axial location and an outer air swirler the radial location. In contrast to the previous design, the fuel metering slots are contained in a simple ring component that could easily be exchanged for development purposes. Component 3 (see Fig. 41) is also a simple ring that can be exchanged in order to alter the main flow number without the expense of manufacturing another swirler (component 1).

SECTION 11.

EXPERIMENTAL RESULTS.

11.1 Spray Testing and Initial Running.

The airblast atomiser, as shown in Fig. 9, was tested on the kerosene spraying, and the water/air spray rig, in order to assess its atomisation performance before being installed in the combustor for burning tests.

Tests in the kerosene spraying showed that its performance without air assistance was very poor. Figure 30, at a fuel pressure differential of 20 lbf./in², shows that there is no atomisation at all. The fuel is seen to issue in six streams of very large drops corresponding to the six fuel metering slots, with no tendency to form a uniform sheet at the atomiser lip. Since the burner was mounted vertically, the gravity effects here were negligible. Subsequent tests on the water/air spray rig with the burner mounted horizontally, as shown in Fig. 12, showed, however, that at 20 lbf./in² water pressure, even at quite high air flow rates, there was hardly any fuel being released at the upper portion of the atomiser lip, due to pronounced gravity effects. The importance of gravity effects at low fuel pressure with the airblast atomiser was thought to be due to the low swirl applied to the fuel and the large diameter of the fuel release area. This poor performance is in complete contrast to the swirl atomiser, which achieves fair atomisation with little gravity effect at such low fuel pressures. The problem of obtaining ignition with the airblast atomiser without the use of large fuel flows is no doubt a direct consequence of the poor low pressure performance.

Figure 31, at 100 lbf./in² fuel pressure, shows that a uniform fuel sheet is produced at the lip. Ripples in the fuel sheet are visible and the break-up mechanisms are well illustrated. It will be noticed that there is still a large population of very large droplets in the resultant spray. Tests on the water-air spray rig at this fuel pressure showed much better atomisation quality with air blast applied.

Figure 32, at 300 lbf./in², shows atomisation occurring from the moment the fuel leaves the injector lip. The unassisted atomisation quality can still be perceived to be only fair, with six "streaks" of coarse droplets corresponding to the six fuel ports. Again, with airblast applied, the quality of atomisation improved substantially.

Having developed the airblast burner and combustion chamber, as described in Section 5, the flame was inspected

running at atmospheric pressure with the rear of the rig removed. The vast difference in quality and geometry of the flames produced by the airblast and swirl injectors was immediately apparent. The swirl atomiser flame was yellow, bright and extended for some way down the chamber, whereas the airblast atomiser flame was a clean blue colour and seated well back in the primary zone. This difference is clearly illustrated in Figs. 42 and 43 (the frontispiece).

Whilst the swirl atomiser was positively located in the standard combustion chamber, about 0.5 in. axial adjustment was available on the airblast atomiser. Beyond a certain distance from the flare, further movement downstream did not alter the flow area defining the shroud air flow, since the limiting area occurred between the injector body and the snout tube (see Fig.15). Further movement did, however, alter the flame geometry somewhat. As the injector was moved downstream, the flame became more clearly defined and moved closer to the flare, under these circumstances of best flame geometry, the liner in the region of the secondary air holes was seen to glow red hot. This was considered undesirable and so the best flame geometry could not be maintained for testing, for a position was chosen for the burner as a compromise between over-heating and satisfactory flame geometry. If the injector was moved too far upstream until the shroud air flow was beginning to be reduced, the flame became very "woolly" and had a yellow luminous tails, which was equally undesirable remembering the attempt to reduce luminous radiation.

It was noticed that with the injector well downstream in the position of best flame geometry, low frequency combustor oscillations were encountered. In Reference 12, Blackshear and Rayle state that low frequency oscillations are usually driven by the combustion process involving some chemical work cycle, rather than being acoustically driven as high frequency oscillations appear to be. Such oscillations appear to be pressure and velocity excursions within the chamber which may involve movement of the reaction zone with reaction rates varying in some manner with the pressure and temperature variations. Very little is known about such phenomena, since the interaction of the combustion and flow processes is extremely complex.

There do not appear to be generally accepted opinions as to the consequences of such oscillations, some workers report increases in combustion efficiency, presumably through increased mixing rates, whilst others report narrowing of stability limits and mechanical damage. In the light of these uncertainties, it was thought expedient to operate away from such oscillations. It may be of more than passing interest to note that Deacon and Bamford (31), testing an airspray atomiser, noticed fluttering, particularly near the extinction point.

11.2 Preliminary Testing.

As described in Section 5, a preliminary investigation was carried out to compare swirl atomisers and airblast atomisers with regard to total flame radiation, exhaust smoke level and weak extinction at three combustion pressure levels. At each pressure level, measurements were made at constant air mass flow and over a range of air fuel ratios for each atomiser. The radiation measurements were made through calcium aluminate windows of 0.270 in. thickness. The author was unable to establish any reliable figures for the variation of total absorption for these windows with radiator temperature, the flame temperatures in question being unknown with any accuracy anyway. Accordingly, the radiation levels quoted are slightly lower than the true radiant fluxes from the flame, since no correction factor for window absorption has been applied. Estimates show that the radiant fluxes quoted are between 8% and 14% low.

(1) Total Flame Radiation.

The three pressure levels chosen for the comparison were 70 lbf./in², 135 lbf./in² and 195 lbf./in², and the comparative results are shown in Figs. 44, 45, and 46, with the conditions as stated below the figures.

These curves show that there is a considerable pressure effect for both atomisers, although at all similar conditions the airblast atomiser has a significantly lower radiation level than the swirl atomiser.

The shapes of the characteristics are of interest, and are thought to be explicable in terms of volumetric heat release rates, the shift in the flame geometry with air fuel ratio and the fact that radiation measurements were only taken at one plane as shown in Fig. 20. With the lower volumetric heat release rates of the swirl atomiser, at the richer mixtures the peak flame temperature occurs well downstream of the viewing plane in the intermediate zone. This was also noticed by Leathley & Talbot (41) in an unpublished Lucas Report of 1962, where the peak temperature and radiation occurred in the intermediate zone at low air-fuel ratios. Whilst maximum flame emissivities do not necessarily occur at the same point as the peak flame temperature, the fourth power law of total radiation will almost certainly ensure that peak radiation will occur very near the point of maximum temperature. Thus at 70 lbf./in², the peak radiation point moves downstream with reducing air-fuel ratio, and appears to pass the viewing plane at about 150 AFR (see Fig. 44). Hence the radiation level at the viewing plane begins to drop

off with further richening of the mixture. Countering this trend for the peak radiation point to move downstream and thus the radiation level at the viewing plane to decrease as the peak passes, is the overall increase in flame temperature as the mixture is richened. It is known that at higher combustion pressures the flame shift becomes less, and thus it seems reasonable to assume that at some pressure level the two trends will equalise one another and no significant change in radiation would occur varying the mixture strength. This appears to be the case at combustion pressure 135 lbf./in², where little change is seen in the radiation level as mixture strength varies (see Fig. 45). Accordingly, at a higher pressure level, by this argument, one would expect the effects of flame shift to become secondary to the increase of flame temperature and emissivity with mixture strength, and thus total radiation at the viewing plane would increase continuously with the reduction in AFR. This, in fact, appears to be the case at 195 lbf./in² where the total radiation does continue to increase as AFR reduces. At 195 lbf./in² (see Fig. 46), it will be noted that mixture strengths less than 150 AFR could not be investigated, due to the size of the largest flow number swirl nozzle available, remembering the limited fuel pump pressure available, but the steep upward trend of the radiation is fairly clear from the points obtained.

It would, perhaps, be difficult to carry the comparison of the three swirl atomiser curves too far, since the three tests were carried out at three different velocity levels with a fixed flow number atomiser, and thus much greater fuel pressures at the higher combustion pressures. As will be shown later, both velocity and atomisation quality, as effected through fuel pressure, have a significant effect on flame emissivities and total radiation.

For the airblast atomiser, however, it appears that flame shift with mixture strength is not a significant factor in the same way as for swirl atomisers. This would be expected since the volumetric heat release rate is much higher, due to partial premixing. Accordingly, a continuous rise in the total radiation with mixture strength was experienced at all three pressure levels, (see Figs. 44, 45 and 46), with a considerable pressure effect at the rich mixture conditions particularly. Flame shift phenomena were important in a different way with the airblast atomiser. Observation through the windows showed that at the weak mixtures one could see right through the flame to the other side of the chamber with blue flame tails clearly visible. Thus one can only assume that at weak mixtures the point of maximum

temperature and radiation was probably upstream of the viewing plane. As the mixture was richened, however, the flame was seen to move downstream, although even at the highest pressure and mixture strength, the flame was still partially blue and transparent. Whilst it is appreciated that emissions in the visible part of the spectrum are not always a good guide to the emissions in the infra-red with all types of flame, it is felt that the blue colour of the airblast atomiser flame compared with the very bright yellow of the swirl atomiser flame (see frontispiece) was, in fact, indicative of the difference in the total radiation that was measured.

(ii) Exhaust Smoke Level.

The smoke level was measured in the exhaust tail pipe, as shown in Fig. 23, and described in Section 9. It would be very difficult to directly relate the smoke level as measured in the tail pipe to the carbon concentration in, say, the reaction zone.. This situation is due to two primary factors, the quantitative effects of which cannot be determined. Firstly, sampling was carried out without any precautions, such as nitrogen dilution, to prevent the condensation of water vapour in the sampling lines which can cause the agglomeration of carbon particles into droplets and also, by wall deposition, prevent some of the carbon reaching the smoke meter. The importance of agglomeration is that the smoke meter by virtue of its optics effectively measures according to some function of particle (radius)², i.e. a projected area, whereas mass concentration is a function of (radius)³. Thus any changes in particle (or droplet) size effectively alters the calibration of the instrument as a mass concentration measuring device. Toone (7) points out that since calibration of the Rolls-Royce smoke meter has not altered as a mass concentration measuring device over a period of several years, and from this he concludes that the size of carbon particles from engines has not substantially changed with increases in pressure ratio and turbine inlet temperature, which is of interest as a side issue. Thus, clearly, with any droplet agglomeration through condensation, the smoke meter will not give a true indication of carbon mass concentration.

The other important factor involved is the phenomena of carbon particle burn-out. Carbon burning is probably taking place from the moment that the particles are formed and continues in the intermediate and dilution zones, and perhaps even in the tail pipe itself. This subject has been more fully discussed in Section 3.

It is thought that there are two sets of conflicting mechanisms involved in determining the smoke level as measured in the tail pipe. Firstly, it is accepted that as mixture strength is increased at constant mass flow and combustion pressure, more carbon will be produced in the primary zone, but also the flame temperature and flame length is increasing so as to increase the rate of carbon consumption via higher temperatures and residence times. Also as mixture strength and primary zone carbon is increasing, so is the amount of water of reaction available for condensation. Under these circumstances, it would seem to be presumptuous to attempt to read too much into the smoke results obtained, apart from as a direct comparison between the two injection systems under the same operating conditions, since the importance of these various mechanisms is not known.

Figure 47 presents the smoke results for all the preliminary test runs with both atomisers. No smoke was detectable at any time with the airblast atomiser for any operating condition. The smoke level from the swirl atomiser was seen to reduce, at any particular mixture strength, with increasing combustion pressure, this, of course, is directly contrary to established trends of the carbon concentration in the primary zone, and thus precludes any attempt to relate smoke level to the primary zone radiation measured. Thus the only firm conclusion that may be drawn from these results is that the airblast atomiser offers considerable advantages in terms of exhaust smoke emissions over pressure swirl atomisers.

(iii) Weak Extinction.

Weak extinctions were determined over a range of reference velocities at three pressure levels for both atomisers, the results of these tests are shown in Fig. 48. The curves were obtained from many points, with each point being repeated at least three times in order to cope with the inevitable scatter that occurs during weak extinction determinations.

Although it has been projected that the airblast atomiser would offer significant advantages over swirl atomisers in terms of flame radiation and smoke emissions by virtue of partial premixing, it could also be projected that the weak extinction would be inferior to swirl atomisers. Figure 48 illustrates that the airblast atomiser used was, in fact, markedly inferior, the extinction air-fuel ratio being roughly one-tenth of that for the swirl atomiser.

It is interesting to note there is little pressure or velocity effect with the airblast atomiser, whereas there is with the swirl atomiser. This is, however, consistent with the difference in the method by which the fuel is distributed for the two systems. In the airblast atomiser combustor, the fuel is essentially air borne and thus the momentum imparted to the fuel by the injector plays a very small part in the fuel placement. Thus the different fuel pressures used for the different pressure and velocity levels had very little effect on the extinction AFR. With the swirl atomiser, however, the fuel placement is determined largely by the initial fuel momentum at the injector, and thus since a constant flow number nozzle was used at all times, there were considerable differences in the fuel pressures at the extinction points. Accordingly, the quality of atomisation and penetration of the fuel varied, thus altering the mixture strength in the fuel rich zones which are the last strongholds of burning. For the swirl atomiser at a given pressure level, increasing the chamber velocity would imply increasing the fuel pressure, and although the penetration would increase accordingly, the more important effect appears to be the increase in evaporation rates due to the better atomisation quality, causing the fuel rich zone in the centre of the spray cone to be enriched. Thus the extinction AFR is seen to rise with chamber velocity.

The effect of an increase in combustion pressure with the swirl atomiser is to increase the extinction AFR. This situation may well be explicable also by the improved atomisation and hence initial evaporation, due to a higher fuel pressure, with the tendency for increased penetration being offset by an increase in droplet drag with high air densities.

With the airblast atomiser, however, since the airflow patterns are the same at a given velocity irrespective of combustion pressure, fuel placement would not be expected to change with combustion pressure. Accordingly, one would expect little change in extinction AFR with changes in combustion pressure, if the effects of atomisation quality and fuel pressure are assumed unimportant. One would, however, expect the effects of chamber velocity to be very important remembering the mechanisms of atomisation and fuel placement with the airblast atomiser. The results indicate that this is not the case, since very little change in extinction AFR was noticed over the range of chamber velocities investigated.

It can thus only be assumed that the changes in fuel placement and atomisation quality were such as to

oppose one another and show little velocity effect on the weak extinction.

(iv) Effect of Velocity at Constant AFR and Combustion Pressure.

Tests were carried out with both the swirl and airblast atomisers, in order to assess the effect of chamber velocity at Constant AFR, combustion pressure and flow number, upon total flame radiation and smoke emissions. The results of these tests are shown in Figs. 49 and 50.

Figure 49 shows that both the radiation and smoke levels of the swirl atomiser are substantially affected by chamber velocity. Since a fixed flow number nozzle was used, it would be difficult to determine whether the change in fuel pressure, and thus atomisation quality, was more important than the change in mixing rates, in producing the effects shown. It is, however, very interesting to note the very definite similarity in the smoke and radiation curves, which might, in fact, have been expected since the changes in radiation encountered should have been almost entirely in the luminous component. This is so since the temperature and concentration of the carbon dioxide and water vapours should not have altered substantially to change non-luminous radiation. The fact that the tail pipe smoke level appeared to follow the highly probable trend in primary zone carbon concentration, may be due to the flame temperature being very nearly constant (carbon burn-out) and the water vapour concentration (agglomeration) being constant, since AFR was unchanged, although residence times are known to be roughly inversely proportional to velocity.

Figure 50 shows that radiation from the airblast atomiser is virtually unaffected by chamber velocity at fixed flow number. Since fuel pressures, mixing rates and airblast velocity reduce with chamber velocity, and all these trends would tend to increase carbon formation, one can only assume that the flame was very nearly non-luminous at all velocities. It has already been stated that non-luminous radiation would not be expected to change with velocity. There is, in fact, a slight upward trend of radiation at the lowest velocities, which may have denoted the onset of carbon formation. The exhaust smoke level was again at all times undetectable.

11.3 Schmidt Method Results.

The Schmidt Method work that could be accomplished was determined by the fuel injectors available, as described in Section 5. The number and flow numbers of the swirl injectors precluded a detailed analysis of the effects of, say, combustion pressure whilst maintaining the other primary variables constant. It was thus decided that the work that should be done would be a series of tests arranged such that most of the important variables would be examined, but only briefly and with little emphasis on any one particular variable except, perhaps, the effects of fuel injection methods. Accordingly, the effects of atomisation quality were examined over a range of operating conditions, at 60 lbf./in² combustion pressure, using injectors of flow number 0.37 and 0.77. The effects of combustion pressure were also investigated by raising the pressure level to 100 lbf./in² and collecting a set of data for the 0.77 flow number injector using the same fuel pressure differentials at a given operating condition as for the 0.37 flow number injector at 60 lbf./in² thus giving the same atomisation quality. Thus two comparisons were possible, in effect requiring four sets of data, but the conditions were so arranged that these were possible with only three sets of test data.

Within each set of test data, the effects of the operating conditions of air fuel ratio and chamber loading (velocity) were examined. Sets of results were obtained at air fuel ratios 60, 90 and 120, all at percent design velocities of 100, 80, 60 and 40. The need to examine air fuel ratio is fairly obvious, but the requirement for data at low velocities needs to be justified. Had large flow number injectors become available to enable testing at high pressure levels to be accomplished, the maximum air mass flow rate available from the compressors at pressures of, say, 250 lbf./in², would imply that the combustor could be operated at a maximum velocity of only 55%. Thus, if comparisons were to be made, it was essential that data at low velocities should also be collected at the low combustion pressures, since chamber loading has been shown to have a significant effect upon flame radiation. The results of these three sets of testing conditions is presented in Tables 15, 16 and 17, and illustrated graphically in Figures 51 to 58.

(i) Results at Constant Combustion Pressure (60 lbf./in²).

Inspection of Figures 51, 52, 53 and 54 show that at nearly all the operating conditions, the smaller flow number burner displayed lower total flame radiation, flame emissivities and exhaust smoke levels than the larger injector. These effects are due entirely to the better atomisation quality, as effected by the higher fuel pressure differentials necessary, with the lower flow number, to obtain the same fuel mass flow

rate. The results clearly indicate the importance of good atomisation quality in the control of flame radiation.

At all fixed chamber velocities, the flame total radiation as seen at the viewing plane increased with air-fuel ratio. This is in line with the findings of the preliminary test results (see Fig. 44) and, as previously explained, is explicable in terms of the shift of the flame, which is now confirmed, as shown in Fig. 53, by the decrease in the flame temperature at the viewing plane as the mixture is richened. The scatter in the flame temperature data for the 0.77 flow number injector shows that these values are dubious, but the data for the 0.37 injector is much more satisfactory. The increase in flame radiation with AFR at constant velocity is clearly due to an increase in both emissivity and flame temperature. Accompanying the increase in emissivity is a corresponding increase in the smoke level, which would seem to imply that the emissivity at all points in the flame increased as the mixture is weakened. This, however, is extremely unlikely, and it is thought much more likely that the increase in emissivity as seen at the viewing plane is due entirely to the shift of the flame and the corresponding emissivity profile upstream. The emissivity of the flame in the region of maximum radiant heat transfer increases with mixture strength, as is shown at higher pressure where the increased reaction rates reduce the effect of flame shift (see Fig. 56). In the light of these points, it may well be re-stated that the method and position of smoke sampling was such as to make the correct interpretation of the results extremely difficult, and may only have any value in comparing two identical running conditions. The effect that AFR exhibited upon total flame radiation and emissivity decreases as velocity increases, this probably being due to the fact that the poorer mixing at low velocities implies that a change in mixture strength will become more apparent, and also that at the higher velocities the flame emissivity was tending towards the non-luminous ideal minimum anyway.

Increasing the chamber loading at all air fuel ratios for both injectors decreased total radiation, flame emissivity and smoke level, whilst increasing the flame temperature. The reductions in flame total radiation and emissivity are almost certainly due to the reduction in the luminous component of radiation owing to the reduction in carbon formation with the improved mixing and atomisation quality. The reduction in the carbon particle concentration or size is apparently reflected in the smoke results, which show a reducing smoke level as velocity increases. The better mixing and evaporation rates consequently cause an increase in the volumetric heat release rate, and this is reflected in the increase of flame temperature as velocity is

increased. Accordingly, there is also a flame shift phenomena associated with changes in chamber loading.

(ii) Results with Constant Atomisation Quality (at 60 lbf./in² and 100 " " "

Atomisation quality was assumed to be constant so long as the fuel differential pressure was constant, with the effects of flow number itself being assumed negligible. This would appear to be a reasonable assumption considering the empirical droplet size equations described in Section 4. The effects of the change in working fluid properties with combustion pressure and inlet air temperature, since they have not been fully investigated, are also assumed negligible. The success in matching the fuel pressure differentials may be inspected in Tables 16 and 17, and was considered to be satisfactory within the overall accuracy of the experiment. The results of these tests are illustrated in Figures 55 to 58.

The effect of the increase in combustion pressure is immediately obvious in that the flame total radiation is significantly higher by a factor of approximately 1.5 to 2.0 depending on operating conditions. The increase in radiation appears to be mainly due to an increase in flame emissivities with small differences in flame temperature, except at 60 AFR where the temperatures at 100 lbf./in² are reduced but the emissivities increased by a factor of about 3.0 at the higher velocities. The increase in flame emissivities (luminous) is not generally reflected in an increase in exhaust smoke level, since the smoke levels are higher at the lower pressure. It is, however, interesting to note that the change in the shape and relation of the emissivity curves with the increase in combustion pressure is reflected in the smoke curves. Whilst discussing the shape of the characteristics, it is apparent that there is a remarkable symmetry shown in the total radiation and emissivity curves between the two pressures (see Figures 55 and 56). The author is, however, unable to suggest any fundamental reason for this situation.

The total radiation at the viewing plane at 100 lbf./in² is again seen to reduce as the mixture strength is increased at constant velocity, again due to flame shift. The preliminary investigation showed that this effect could have been reversed had testing at combustion pressures in excess of about 135 lbf./in² been possible. (See Figs. 45 and 46). The flame emissivity, however, is now seen to increase with mixture strength at the higher velocities, perhaps indicating the increased

dependence of the carbon formation mechanisms on mixture strength as the combustion pressure rises. Alternatively, the shift in the emissivity profile could have equally accounted for a large proportion of the changes, since this probably closely follows the reduced flame shift with the higher reaction rates.

(iii) Airblast Atomiser Tests.

As discussed in Section 5, some aspects of the airblast atomiser's performance had proved unsatisfactory. The fuel patterning deteriorated, leading to a persistent hot spot which meant that the combustor could be run for short periods only at rich mixtures, providing insufficient time for the rig to be accurately stabilised on condition if a set of readings were to be taken in addition. The time available for data collection was barely adequate to provide a good set of reproducible Schmidt readings. Testing indicated that the emissivities were very low at all conditions, thus making the calculation of flame temperatures all the more sensitive to error, (see Appendix IV). The combination of all these factors was such as to give unacceptable scatter in the apparent flame temperatures as the background temperature was changed, this making a satisfactory solution impossible by the present method of analysis. This problem can be overcome for future work by a modified method as proposed in Section 12. In criticising the performance of this airblast atomiser, it should always be remembered that it had been asked to perform in a flame tube that had been developed and cooled for a flame of much lower volumetric heat release rate, and thus the cooling in the primary zone area could hardly be expected to be completely adequate to cope with the new injector.

Experience with the swirl atomiser showed that the change of apparent flame emissivity with background temperature was not excessively great, so that it was thought acceptable and appropriate that some apparent emissivities for the airblast atomiser should be presented for a background temperature which would not be too far removed from likely flame temperatures. Accordingly, a set of values at a background temperature of 1825° C are presented in Figs. 59 and 60. The performance of a swirl atomiser at the same operating conditions is also presented for comparison at the same combustion pressure of 60 lbf./in². In making comparisons, it must, however, be emphasised that the airblast flame emissivities are apparent values and, until the flame temperatures are discovered, can thus only be regarded at best as a reasonable estimate.

Total radiation from the airblast atomiser flame was seen to increase at all chamber velocities with increasing mixture strength, as was also found in the previously described preliminary testing. This is due to the higher volumetric heat release rates which greatly reduce the effects of flame shift with mixture strength. Chamber velocity had very little effect on the flame total radiation, thus making the difference between the injectors very much greater at low velocities. The apparent emissivities for the airblast atomiser also show a small increase with mixture strength but with very little velocity effect.

In comparing the two injection systems and attempting to form any estimate of the reductions in luminous component of radiation possible with the airblast system, the situation is severely complicated by the fact that the results presented do not often represent the conditions of maximum heat transfer. This situation is due entirely to the single, fixed viewing plane used which was upstream of the point of maximum heat transfer at rich mixtures, particularly for the swirl atomiser. Any comparisons drawn accordingly tend to favour the swirl atomiser. The swirl atomiser is also favoured from the point of view of flow number and fuel pressure differentials, although previous discussion points to the fact that the flow number concept may be of less importance for airblast atomisers.

Throughout these tests, the effects of air inlet temperature and fuel temperature have been ignored. The variations encountered in these variables were comparatively small and thus this situation may be justified. The inlet air temperature was always, however, way below the values encountered in real engines. This fact will directly influence the flame temperatures and total radiant flux. The effects on emissivity are less certain, Sterry (21) found that there was little or no effect of flame temperature on emissivity, although he confessed errors of 6% to 10% in flame temperature estimates. A further factor which may have influenced the results to an unknown extent is the fact that the combustors were probably operating on the rising portion of the Θ /combustion efficiency curve, particularly at 60 lbf./in², thus affecting flame temperatures. There is also no guarantee that the Θ curves for both swirl and airblast combustors are identical, which could influence any comparisons drawn between the two systems on the basis of results at 60 lbf./in².

11.4 Analysis of Results.

In attempting to cover as wide a range of variables as possible, it was inevitable that the quantity of data concerned with the effects on radiation parameters of any one particular variable whilst holding all the others constant, would be limited. Very often only two points were covered, for example combustion pressure and flow number, with a maximum of four for velocity. Accordingly, it would be extremely difficult, if not misleading, to attempt a comprehensive analysis of such few data with the aim of formulating some empirical relationship with the hope of general application. Nevertheless, an attempt was made to do a certain amount of simple analysis to be supplementary, though secondary, to the curves presented, in order to perhaps facilitate the understanding of the implied trends therein. Thus an attempt was made to develop an empirical equation to correlate at the flame total emissivity data obtained in this investigation.

In order to obtain an initial guide for the attempt, a dimensional analysis was performed including all the variables deemed to have an important effect on flame emissivities. This analysis is presented in Appendix III and resulted in the following expression:-

$$\epsilon_F = \Phi \left\{ (AFR)^L, \left(\frac{\dot{m}_A \sqrt{RT_{in}}}{D^2 p_c} \right)^j, \left(\frac{\Delta p_c}{p_c} \right)^k \right\} \quad \text{--- (1)}$$

Suitable manipulation as shown in the Appendix, modified the above expression to the following form for a given combustor using air:-

$$\epsilon_F = \Phi \left\{ (AFR)^p, \left(\frac{\dot{m}_A \sqrt{T_{in}}}{p_c} \right)^q, \left(\frac{p_c}{T_{in} F^2} \right)^r \right\} \quad \text{--- (2)}$$

One could, perhaps, have sensed the form of equation (1) in that it includes all the groups that would be expected to affect emissivity. The non-dimensional air mass flow for a given combustor effectively defines chamber loading (velocity); the fuel differential pressure governs the atomisation quality, and initial ratio of fuel momentum to air momentum, whilst combustion pressure is known to have a significant effect on reaction rates and the carbon formation mechanisms; air fuel ratio defines the concentrations of carbon dioxide and water vapour which determine non-luminous radiation and will also govern the potential carbon concentration in carbon forming zones; all these factors have a primary effect on emissivity.

The expression which was found to give a fair correlation of all the emissivity data obtained was as follows:-

$$\epsilon_F = \left[\frac{(P_c)^{1.2} \left(\frac{AFR}{90}\right)^{(80-P_c)0.03} \times 3.8 \times 10^{-4}}{\left(\frac{\dot{m}_A \sqrt{T_{in}}}{A_{ref} P_c}\right)^{1.0} (\Delta P_c)^{0.5}} + 0.06 \right] \quad (3)$$

The correlation given by this equation is shown in Figure 61. The term describing the effect of air fuel ratio is of a form that takes into account the fact that for the two pressure levels investigated, the effect of AFR was reversed at constant velocity.

It must be emphasised that any success that this equation achieves in correlating the test emissivities is in no way indicative of its general validity, and it could only be applicable to this set of results since it is based on tenuous data.

The emissivities evaluated and presented in the curves are total emissivities comprising both luminous and non-luminous components. It was thought appropriate in the context of this work that some estimate of the luminous component should be made. In addition to this, it may well have been that a correlation involving some function of the luminous and non-luminous components would have given a more meaningful relationship. Accordingly, the non-luminous emissivity at each of the test conditions was evaluated using the Reeves (6) formula obtained from data from the Hottel charts. The emissivities thus obtained must only be regarded as estimates since some of the test conditions were slightly outside the range of conditions within which the charts, and thus Reeves' correlation, was obtained. For example, the results at 100 lbf./in² (6.12 atmospheres) are above the 5.0 atmosphere upper limit for the Hottel correction factor. In addition, Reeves' correlation of the chart data was for a range of effective optical path lengths down to 0.5 ft., whereas the effective optical path length, l , of the Dart combustor is given by:-

$$l = \frac{6.4}{12.0} \times 0.6 = 0.32 \text{ feet.}$$

where:-

$$\begin{aligned} d_{eff} &= 6.4 \text{ in.} \\ 0.6 &= \text{radiation configuration factor.} \end{aligned}$$

However it was felt that since the calculations were not grossly outside the range of valid conditions, such calculated emissivities would at least give a reasonable estimate of the non-luminous component.

The Reeves formula for distillate fuels may be stated:-

$$\epsilon_n = 1 - \exp \left\{ - \frac{P(q\ell)^{0.5} \times 16}{(T_F/100)^{1.5}} \right\} \quad (4)$$

where P = combustion pressure (atmospheres).

q = primary zone fuel-air ratio.

ℓ = optical path length (feet).

T_F = flame temperature ($^{\circ}$ K).

Accordingly, the parameter in brackets in the above equation was calculated from the test data and the corresponding total flame emissivity plotted in Figure 62. Also shown on Figure 62 is the locus of corresponding non-luminous emissivities as defined by equation (4).

From the design data for the combustor given in Section 6, the quantity of air entering the primary zone was calculated according to the following assumption:-

$$\begin{aligned} (\text{Primary Zone Air}) &= (\text{Swirler Air}) + (\text{Flare Cooling}) + 0.5(\text{Secondary Air}). \\ &= 12\% + 5\% + 0.5(8\%). \\ &= \underline{21\%} \text{ (of the total mass flow).} \end{aligned}$$

Inspection of Fig. 62 shows that the emissivity ratio varied considerably, this ratio here defined:-

$$\text{Emissivity Ratio} = \frac{\text{Total Emissivity}}{\text{Non-luminous Emissivity}}.$$

This ratio bears a close relationship to the luminosity Factor proposed by Lefebvre and Herbert as previously shown by equation (17), Section 2. The emissivity ratio is seen to vary from 0.42 to 5.47, with 41% of the test data between 1.0 and 2.0, indicating the important effect of operating conditions in a given combustor for swirl atomisers. It is interesting to note that three test results measured were below the corresponding non-luminous values. Neglecting experimental errors, the reason for this could be the application of the Reeves formula outside the conditions for which

it is valid. In addition, it is implied in the application of the Hottel data that the uniform flame spans the combustor diameter; and that combustion is complete at the viewing plane with carbon dioxide and water vapour as the only products. It may be significant to note that all three of the low values are at 60 AFR where the maximum temperature is in the intermediate zone, thus equilibrium temperatures and composition will not prevail at the viewing plane. A correlation attempt using emissivity ratio yielded no more information than the previous one for total emissivity, and remembering the severe limitations of any such correlations based on such few data, the result is not presented here.

Clearly then, the little analysis carried out yielded little more information than may be obtained by inspection of the graphical characteristics, and thus the main findings of this investigation may be considered to be embodied in these characteristics.

11.5 Accuracy and Errors.

The application of the Schmidt Method relies on the assumption that the combustor flame is uniform in structure and composition, and is a grey body at thermal equilibrium. None of these assumptions are correct. The average highly loaded combustor flame is highly stratified in both composition and temperature with the very low residence times ensuring that the flame is far from equilibrium. In addition to this fact, the flame is sheathed in layer of colder air providing the film cooling. Without referring to a specific flame whose material and thermal structure is known, it would be very difficult to form any reasonable estimate of the effect of these factors upon the apparent flame temperatures and emissivities. The presence of cold media which absorb more radiation than they emit, will certainly imply that the measured emissivities and temperatures will be too high. For the purposes of combustor cooling design, this may be of little importance, since the apparent values will be adequate for calculating the nett heat transfer in similar situations, but for research purposes these sources of error must be considered a nuisance. Where the flame is highly stratified in temperature, the fourth power law heavily weights the apparent overall flame temperature in the favour of the high temperature regions, and probably gives a higher flame temperature than would be given by calorimetry.

The presence of small carbon particles in the flame is known to affect the absorption of the flame, since these particles, which are too small to emit significant radiation in the important infra-red, scatter the radiation preferentially at wavelengths according to their size.

The possible sources of experimental error were many. Apart from the inevitable errors in the operation of a complicated piece of equipment, the important possible sources of error were as follows:-

- (i) The calibration of nearly all the Schmidt Method instrumentation was, of necessity, achieved by indirect methods often hinging on the "Land" pyrometer calibrations. Whilst the "Land" calibrations are thought to be accurate, they are not individual calibrations over the whole operating range. The "Land" calibrations are in fact obtained by calculation from established thermopile characteristics with individual check points to assess manufacturing tolerance effects, at a few temperatures only. Thus there is a possibility of an accumulation of errors in the calibrations which could have had some effect on the accuracy of the Schmidt Method results. The assessment of these errors and the rigorous calibration of the equipment will only be achieved when access is gained to a windowless black body furnace. With the low emissivities encountered at the comparatively low combustion pressures investigated, the total radiant fluxes were correspondingly low. This implied that only the lowest portion of the fluxmeter response curve was used for the conversion of thermopile outputs to the corresponding radiant flux when looking at the flame alone. Since the accuracy of the Schmidt results hinged on the accuracy of this lowest portion, it is felt that an individual calibration of this area alone would have considerably reduced the possibility of errors in the Schmidt method.
- (ii) With the method of application of the Schmidt technique adopted for this work, whereby the rig was shut down to obtain background alone readings in between each test point, the reproducibility of the same flame conditions became a possible source of error, whilst eliminating some of the possible Schmidt errors. With the swirl atomisers, where unlimited time was available for accurate stabilisation at the desired condition, the reproducibility of radiation readings was good. Reeves (6) reported variations of Schmidt readings of the order of 10% sometimes and 50% occasionally. Variations of this order were not often encountered, but when they were, the cause of the trouble was usually discovered to be the slow drift of the combustion conditions with time, and the solution was readjustment and a new set of readings. At all times there was a certain amount of low frequency flame "noise" superimposed upon the low frequency "noise" of the D.C. amplifier unit used to amplify the fluxmeter outputs. This situation meant that to obtain a reading, some short period was required to assess the mean value of

the meter fluctuations. This was undoubtedly a contributory factor to inaccuracy where limited time was available. Thus it is felt that acceptable accuracy was achieved for the swirl atomiser tests.

With the airblast atomisers, where only a limited time was available for rig stabilisation, the flame reproducibility, as reflected in the radiation readings, was often unsatisfactory and this is probably an important reason for the bad scatter in the test data as described.

SECTION 12.

CONCLUSIONS AND RECOMMENDATIONS.

12.1 Conclusions.

An investigation was carried out in order to examine the phenomena of radiative heat transfer and smoke emissions in combustors typical of aircraft gas turbine engines. The objectives were to examine the effects of operating conditions and fuel injection parameters on these phenomena with emphasis on the use of the airblast atomiser in the control of luminous flame radiation and smoke emissions. The findings of the work were:-

- (i) The airblast atomiser offers considerable advantages in terms of reduced flame radiation and exhaust smoke emissions over conventional swirl atomisers whilst suffering from a poorer weak extinction.
- (ii) Atomisation quality at fixed operating conditions has a significant effect on flame radiation for swirl atomisers.
- (iii) Whilst the flame radiation from the swirl atomiser was significantly affected by the operating conditions of air fuel ratio and chamber velocity, the airblast atomiser was sensitive to air fuel ratio but chamber velocity had virtually no effect.
- (iv) Flame radiation, particularly at rich mixtures, was significantly increased for both atomiser types with increasing combustion pressure.
- (v) Whilst the overall radiant heat transfer to the flame tube is reduced with the airblast atomiser, the very high volumetric heat release rates will concentrate the cooling problem to the primary zone area.
- (vi) There was no easily determined relationship between primary zone carbon concentration and smoke level measured in the exhaust tail pipe.

12.2 Recommendations for Future Work.

- (i) It would be highly desirable that in order to estimate the maximum radiant fluxes in the combustor, more viewing ports be positioned downstream of the existing site, particularly for swirl atomiser work. This would

enable one to establish the axial flame temperature and emissivity profiles and thus make a reasonable estimate of the maxima. If testing at high combustion pressure becomes possible, the existing site may be adequate due to reduced flame shift through higher reaction rates, but for low pressure work the existing single site is inadequate.

- (ii) In order to facilitate swirl atomiser testing at high combustion pressures, it is suggested that a Rolls-Royce "Spey" injector should be modified to operate in the combustor on main fuel only, since there is known to be a good range of high flow number nozzles easily available.
- (iii) If it is desired to continue the testing of the air-blast atomiser in the Dart combustor, the cooling in the primary zone area should be improved to allow long time running at rich mixtures. It is hoped that the new injectors designed will help in achieving this end.
- (iv) The Schmidt Method should be modified to eliminate the reliance on a calculation and graphical method for a solution for flame temperature. The method that should be used relies on the fact that in a fixed environment, the thermal response of the Spembyl Furnace to a given change in power input is constant. N.G.T.E. use this method and have found it satisfactory. The necessary instrumentation is shown in Figure 63.

The flame is stabilised, the furnace is stabilised at a temperature well below flame temperature. A step increase in furnace power is applied and as the temperature rises, the valve between the flame and furnace is alternately opened and closed, giving an intermittent output of R_1 and R_2 on the recorder trace. When the temperature has risen well above flame temperature, the rig is shut down and the furnace returned to the original start temperature and stabilised. The same step input is applied to the furnace again without any flame interposed, and a continuous trace of R_3 taken. The solution flame temperature is then obtained at time, t , on both traces where $R_2 = R_3$, and thus $T_{\text{furnace}} = T_{\text{flame}}$. The local value of R_1 is extracted and the emissivity evaluated according to:-

$$\epsilon_f = \frac{R_1}{R_3}$$

This is the only calculation required to estimate flame temperature and emissivity.

- (v) The accurate calibration of the N.R.F.14/80/30 flux meter at low fluxes should be carried out to cover this

important region which is not adequately covered by the "Land" calibration. A suitable furnace which would cover this low range is available at B.I.S.R.A.

- (vi) In view of the inadequacy of the smoke measurement technique used for this work, more useful information could be obtained by sampling in the combustor itself with a dilution technique to eliminate the condensation problem. This would enable correlations between the prevailing carbon concentrations and the luminous component of radiation to be made.

REFERENCES.

- | <u>No.</u> | <u>Author.</u> | <u>Title.</u> |
|------------|----------------------------------|---|
| 1. | Harrison, T.R. | "Radiation Pyrometry & its
underlying Principles of Radiant
Heat Transfer".
John Wiley & Sons, Inc., Publishers. |
| 2. | McAdams. | "Heat Transmission".
McGraw-Hill Book Co. |
| 3. | Hodgson, J.P. | "A Survey of the Infra-red
Radiation Properties of Carbon
Dioxide".
A.R.C. C.P. No. 981. |
| 4. | Penner, S.S. | "Quantitative Molecular Spectroscopy
and Gas Emissivities".
Addison-Wesley Publishing Co., Inc. |
| 5. | Hottel, H.C. | "Radiative Transfer in Combustion
Chambers".
The Melchett Lecture for 1960. |
| 6. | Reeves, D. | "Flame Radiation in an Industrial
Gas Turbine Combustion Chamber".
N.G.T.E. Mem.No. M.285. |
| 7. | Toone, B. | "A Review of Aero Engine Smoke
Emission".
Presented at the 1967 Cranfield
International Propulsion Symposium. |
| 8. | Durrant, T. | "Flame Radiation in the Aero Gas
Turbine Combustion Chamber".
Presented at A.R.C. Combustion
Sub-Committee meeting, February
9th, 1962. |
| 9. | Schirmer, R.M. &
Miller, E.C. | "Radiation from Jet Combustor
Flames".
Phillips Petroleum Co.
Am. Chem. Soc., May, 1958. |
| 10. | Foster, P.J. | "The Emission & Attenuation of
Luminous Radiation in Flames".
A.R.C. 23,471. C.F.587. |

<u>No.</u>	<u>Author.</u>	<u>Title.</u>
11.	Thring, N.W., Foster, P.J., McGrath, I.A. & Ashton, J.S.	"Prediction of the Emissivity of Hydrocarbon Flames". Presented at the 1961 International Heat Transfer Conference.
12.	-	"Basic Considerations in the Combustion of Hydrocarbon Fuels with Air". N.A.C.A. Report 1300. Lewis Flight Propulsion Lab. 1957.
13.	Lefebvre, A.H.	"Theoretical Aspects of Gas Turbine Combustion Performance". C. of A. Note, Aero No. 163.
14.	Beckwith, C.G.	"Smoke & Noise". Pratt & Whitney Aircraft Paper presented at 1967 Jet Engine Maintenance & Overhaul Conference.
15.	Bryan, R.H.	"An Experimental Study of an Airblast Atomiser". C. of A. Thesis, 1967.
16.	Miller, D.	"Control of Gas Turbine Exhaust Smoke using Airblast Fuel Atomisation". C. of A. Thesis, 1965.
17.	Schirmer, R.M. & Quigg, H.T.	"High Pressure Combustor Studies of Flame Radiation as Related to Hydrocarbon Structure". Phillips Petroleum Co. Ltd. Progress Report No. 3.
18.	Lefebvre, A.H. & Miller, D.	"The Development of the Airblast Atomiser for Gas Turbine Applica- tion". C. of A. Report. Aero No. 193.
19.	Hawthorne, W.R. & Olsen, W.T.	"High Speed Aerodynamics & Jet Propulsion". Volume XI. Oxford University Press, 1960.
20.	Bowen & Joyce.	"The Effects of Cone Angle, Pressure & Flow Number on Particle Size of a Pressure Jet Atomiser". Shell Tech. Report No. I.C.T.17.

<u>No.</u>	<u>Author.</u>	<u>Title.</u>
21.	██████████	
22.	-	"Aviation Week & Space Technology". Page 51. February 24th, 1969.
23.	-	"Adaption of Combustion Principles to Aircraft Propulsion". Vol.II. N.A.C.A. R.M. E.55G28.
24.	Whelan, P.F.	"The Mechanism of Carbon Formation in Combustion". Internal Combustion Engine Group, Inst. Mech. Eng., December, 1960.
25.	Schirmer, R.M.	"Measurement of Total Radiant Energy from Jet Combustor Flames". S.A.E. 1961, 379.E.
26.	Nukiyama, S. & Tanasawa, Y.	"Experiments on the Atomisation of Liquids in an Airstream". Trans. Soc. Mech. Engs. (Japan), Vols. 4, 5, 6, 1938-40.
27.	Eisenklam, P., Dombrowski, N. & Hasson, D.	"Drop Formation from Rapidly Moving Liquid Sheets". Imperial College Report, J.R.L.No.44.
28.	Wigg, L.D.	"The Effect of Scale on Fine Sprays Produced by Large Airblast Atomisers". N.G.T.E. R.236.
29.	Wigg, L.D.	"Drop Size Prediction for Twin-Fluid Atomisers". N.G.T.E. memo. No. M.343.
30.	Lefebvre, A.H.	"Radiation from Flames in Gas Turbine & Rocket Engines". Unpublished C. of A. Note.
31.	Deacon, W. & Bamford, J.A.	"Altitude Tests on Three Highly- Loaded Annular Combustion Chambers Designed to Rolls-Royce R.B.93 Requirements". N.G.T.E. Report No. R.211.

<u>No.</u>	<u>Author.</u>	<u>Title.</u>
32.	Bater, K.M. & Poulton, W.R.	"The Performance of an Airspray Atomiser in the Primary Zone of a Gas Turbine Combustion Chamber".
33.	Joyce, J.R.	"The Atomisation of Liquid Fuels for Combustion". Shell Tech. Report.
34.	Lefebvre, A.H.	"Factors Controlling Gas Turbine Combustion at High Pressures". Presented at the 1967 Cranfield International Propulsion Symposium.
35.	Lefebvre, A.H. & Durrant, T.	"Design Characteristics Affecting Gas Turbine Performance". Presented S.A.E. Los Angeles, October 10th - 14th, 1960.
36.	-	Unpublished C. of A. Propulsion Department Notes.
37.	Schirmer, R.M. & McReynolds, L.A.	"Radiation in Flames in Gas Turbine Combustors". Phillips Petroleum Report.
38.	Weeks, D.J.	"Radiation from Liquid Fuel Flames". D.A.E.R./EN/10/1.
39.	Preece, R.J.	"Flame Radiation in a Gas Turbine Combustion Chamber". C. of A. Thesis.
40.	Fuller, B.A. & Russell, D.T.	"Combustion System Durability - A Civil Operator's Experience". Unpublished C. of A. Note.
41.	Leathley, B.W. & Talbot, D.	Unpublished Lucas Gas Turbine Equipment, Ltd. Report.

APPENDIX I.

Combustion System Durability - A Civil Operator's Experience.

D.T. Russell & B.A. Fuller.

1. Introduction.

A visit was made to the powerplant overhaul and repair facilities of a large British civil airline, on the 26th March, 1969. The purpose of this visit was to assess the extent, nature and causes of durability problems in present generation combustion systems. The airline is currently operating the following aircraft engine combinations:-

<u>Engine Type.</u>	<u>Thrust (S.S.L.)</u>	<u>Aircraft Type.</u>
R-R Conway 508	17,500 lbf	Boeing 707
R-R Conway 540	21,000 lbf	Standard VC10
R-R Conway 550	22,500 lbf	Super VC 10

2. Importance of Combustion System Durability.

Even though the combustion system is one of the major, but mechanically simplest, portions of the gas turbine, its maintenance and repair costs represent an important part of operating costs. Directly, the cost of flame tube repairs represents 5 - 8% of total engine maintenance costs, and indirectly, as a cause of premature removal, represents a loss of about £4. 5s. for each hour of unexpired engine life to scheduled overhaul.

Combustion system faults are frequently the cause of NGV and turbine damage through distorted thermal profiles and also by direct debris damage. Apparently 10% of the scrap to NGV and turbine blades is due to combustion system debris.

The full approved life of an engine is rarely realised, owing to unscheduled repairs, the average achieved being about 85% of BCAR approved life. Data is presented in the Appendix illustrating the proportion of unscheduled removals attributed to the combustion system.

✓ 3. Combustion System Defects.

The environmental factors which initiate and propagate combustion system defects are:-

Steady high temperature
High temperature gradients.
Temperature induced strain.
Thermal shock.
Mechanical vibration.
Thermal cycling.
Corrosion and
Erosion.

which result in the following characteristic abnormalities:-

Cracking
Buckling
Burning
Fretting and
Coke deposition.

It should be noted that it is difficult, or impossible, to distinguish amongst the environmental factors which may contribute to a given abnormality.

On any one particular standard of components, whilst failure patterns can be detected, the damage is usually distributed throughout all areas of the flame tube, flare and discharge nozzles, with cracking, distortion and fretting of various degrees. To illustrate diffuse nature of the damage, the following data described the condition of a Conway 550 combustion system after 4500 hours:-

(a) Flame Tube Head Assemblies.

All assemblies fretted 0.020 in. on the flame tube support diameter. No cracking or distortion.

(b) Flame Tubes. (C.263 material). All tubes featured:

- (i) 0.030 in, fretting on I.D. mating with head assembly.
- (ii) Dowel peg slot 0.030 in. wear.
- (iii) Slight distortion of inner flare and inner flare cracks 0.2 in.
- (iv) Cracks up to 0.250 in. on downstream edge of first section.
- (v) Small cracks in flute stitch welds joining second, third and fourth liner sections.

(vi) Very severe wear on liner rear support frame.

(vii) Wear on one side baffle.

One tube had a hole 0.75 in. diameter in the outer flare. Several tubes has extensive cracking around the interconnector stub pipes. Tube 7 cracked and overheated in region of second section air holes. Tubes 2 and 5 had axial cracks 3 in. and 4 in. long in fourth section corner radius. Eight outer baffles broken off due to stitch weld failure. Five inner baffles broken off due to cracked welds.

(c) Radial Support Channels.

All severely fretted at contact area of discharge nozzles with pieces up to 5 in. long missing. All locating pins deeply grooved.

(d) Flame Tube Outer Support Segment.

All heavily worn up to sharp edging on inner wall of locating groove. Five segments had signs of burning at nozzle locating lips, with slight distortion and cracking.

(e) Discharge Nozzles. (C.263 material).

All heavily fretted up to 0.100 in. at side inner locations. Four outer locating brackets broken away. Cracks adjacent to side rubbing pads. Two had circumferential crack 2.0 in. long. Most nozzles had cracking at rear frame butt weld.

Visual inspection of such components shows little or no carbon build up anywhere except on the inner flare. As would be expected in a system in a well developed state, there was very little evidence of burning and hot streaks. A large proportion of the cracking was seen to initiate from electrical resistance, roll-seam, roll-stitch and spot welds, which are, of course, more difficult to control and inspect metallurgically than argon butt welds. Other cracking is seen to occur in regions of extensive metal deformation during manufacture, pointing to residual stresses and work hardening.

The burners examined were all of the duple type with shroud air. There were extensive carbon deposits on all faces but, apparently, not enough to be detrimental to their performance in terms of cone angle, distribution or flow number

The main faults with burners from service were slight erosion and primary filter blockage. Repair is by replacement.

Interconnector defects were confined to wear and fretting at the connection with the flame tubes. This would be expected since their thermal environment is less severe than that of other components and they are thus less susceptible to thermal defects.

4. Inspection and Detection.

(a) In the Aircraft.

Major failures are obviously detectable from aircrew and ground crew reports of abnormalities. The main method of detecting combustion system defects is the in-situ X-ray. Tangential X-ray films are taken of each chamber which can show up cracks and missing material. The most skilled interpretation of these photographs is necessary since to look at the chamber to be considered, parts of at least two other chambers will be seen superimposed on the photograph.

In recognition of the combustion chamber problem, the X-ray schedule for the Conway 540/550 engines begins at 3200 hours with further photographs at 600 hour intervals until repair becomes necessary, or an unscheduled removal occurs for other reasons.

It appears that intro-scope techniques cannot yet be applied to combustion chambers on this engine.

(b) Engine Strip.

Upon stripping the engine after removal from the airframe, the combustion system is put through a cleaning process with little or no attention paid to the inspection of carbon deposits. The components are then examined visually with no recourse to more searching processes, such as X-glo crack detection.

5. Repair Techniques.

The engine manufacturer supplies this operator with all combustion system sub-components, so that flame tubes, for example, can be reclaimed by rebuilding with new components where necessary. In the case of localised or minor damage, a series of standard welding patches is used to effect repair. The visitors saw flame tubes which had only one or two of the original components left, the rest being new. Dismantling of

the damaged components is effected by the saw and hand grinder.

Considerable efforts are made to salvage parts wherever possible. This policy clearly reflects the importance of combustion system repair costs. On scheduled approved-life overhaul, the cost of combustion system repairs is 50% to 60% of the cost of complete replacement with new parts.

The Conway design is such as to make repair to fretted and worn faces by metal spraying uneconomical, these being repaired by cutting out the damaged faces and welding in new ones.

6. Design and Development.

For a very long time after service initiation, an engine undergoes modification and development of varying degrees in the light of accumulated experience. That the combustion system figures strongly in this process is again illustrated by reference to the Conway engines. After several years in service, a completely new flame tube, owing much to the Spey, has been designed in an effort to increase flame tube life. The estimated life of these new flame tubes is 8000 hours, with repair costs 15% to 20% of the new replacement cost at scheduled approved life overhaul. The lives of the existing flame tubes are:-

<u>Engine.</u>	<u>F/T material.</u>	<u>Life (hours).</u>
Conway 508	N 75	3500
" 540	C 263	6500
" 550	C 263	5500 *

* Full life sampling of the 550 is not yet completed.

The cooling had been completely redesigned to include a double flare, an extra wiggle strip in the second section, cooling interconnector stubs, a heavier gauge material and a return to N 75 as a tribute to the design. A thermal paint analysis shows a drop of 200° C on the maximum metal temperature (ref.1).

The importance of the low lives obtained on previous standard flame tubes, is emphasised by the fact that the operator is prepared to accept a weight penalty of 120 lbs. for the increased life given by the new flame tubes.

As illustrated in Section 3, much of the damage to combustion system components is due to wear and fretting. It is convenient that when a component becomes ready for repair by virtue of cracking, it is also ready for fretting

repair since in-situ X-ray film can be used to detect cracks but not fretting. However, the new standard flame tubes for the Conway retain exactly the same design as the earlier ones in the location and support areas. Consequently, the fretting problem could be expected to be unimproved. The writers observed some examples of the new standard flame tubes after 2000 hours which showed no cracking or distortion, but they were badly fretted. This situation is undesirable from two standpoints. Firstly, the advantages of the improved design are lost from the point of view of life of the component. Secondly, since there is no method of detecting fretting, the flame tubes will tend to be left in the engine until loss of location and support areas due to fretting. Clearly any component is only as good as its worst point, and all the combustion chamber problems are not heat transfer ones.

7. Conclusions.

- (a) The repair and maintenance costs of combustion system components represent an important proportion of total overhead expenses.
- (b) Combustion system condition is frequently the cause of premature removal of the engine from the aircraft.
- (c) Of the damage sustained by nozzle guide vanes and turbine blades, 10% is due to combustion system debris.
- (d) Whatever the cause of unscheduled removal, upon strip there is always repair work required on the combustion system.
- (e) Important defects in the combustion system may be classified as cracking, buckling and fretting. Burning and coke deposition are lesser defects. Such defects are liberally distributed throughout the system with no component less susceptible than any other, with the exception of the burner, which is rarely a cause of trouble. Wear and fretting damage represents a significant portion of the defect problem.
- (f) The main method of discovering defects in the combustion system is the in-situ X-ray, which can reveal cracking and metal loss but cannot reveal fretting directly.
- (g) Repair is effected wherever possible by various salvage techniques.
- (h) Much effort is still being expended to increase the life of Conway flame tubes and discharge nozzles.

8. References.

1. 8th Rolls-Royce Conway Operators Conference, Sept. 1968.
2. Private statistics provided by a large British Civil Airline.
3. Rolls-Royce Summary of Operation - Conway Engines, December, 1968.

APPENDIX. IA.Analysis of Engine Failures for a British
Operator's Conway Engines.

Compiled from Ref. 2.

The tables show the proportion of engine failures which were attributed to failure of the flame tube and discharge nozzles of Rolls-Royce Conway engines operated by a large British Civil Airline. The total number of engine failures excludes those attributed to the following:-

Bird ingestion.	Overhaul discrepancies.
Metallic body ingestion.	No defect found.
Stones & hard body ingestion.	Maintenance error.
Foam ingestion.	Manufacturer's error.
Accident.	Awaiting investigation.
Local rectification.	

Conway 508 - Boeing 707.

Year	Flame tube and discharge nozzle failures.	Total engine failures.	Percentage.
60/61	0	29	0
61/62	0	20	0
62/63	0	36	0
63/64	6	42	14.3
64/65	35	62	56.5
65/66	42	69	60.9
66/67	19	56	33.9
67/68	35	78	44.9
68/69	27	58	46.6

Conway 540-Standard VC 10.

63/64	0	3	0
64/65	6	20	30
65/66	20	48	41.7
66/67	3	43	7.0
67/68	16	39	41.1
68/69	16	48	33.4

Conway 550 -Super VC 10.

Year	Flame tube and discharge nozzle failures.	Total engine failures.	Percentage.
65/66	0	15	0
66/67	1	48	2.1
67/68	8	33	24.2
68/69	10	56	17.9

Note that these figures do not include engine failures which are attributed to other defects, but in undergoing rectification secondary defects are normally discovered. All Conway engines which have run for 2000 hours have some defects to flame tubes and discharge nozzles. All Conway engines which have run for 4000 hours have many defects to all flame tubes and discharge nozzles.

Analysis of Engine Failures for all
Operators of Conway Engines.

Compiled from Ref. 3.

The table shows the proportion of engine failures which resulted in premature removal of the engine from the airframe which were attributed to failure of the flame tube and discharge nozzles of Rolls-Royce Conway engines operated by Civil Airlines. The total number of engine failures includes only those attributed to basic major engine faults.

Conway 508 and 509.

	<u>1967</u>	<u>1968</u>
Flame tube defects.	39	39
Total basic defects.	204	219
Percentage.	19.1	17.8

Conway 540.

	<u>1967</u>	<u>1968</u>
Discharge Nozzle.	13	16
Total basic defects.	48	57
Percentage.	27.1	28.1

Conway 550 and 550 B.

	<u>1967</u>	<u>1968</u>
Discharge Nozzle.	6	7
Total basic defects.	47	70
Percentage.	12.8	10

APPENDIX II.

Relation Between the Ratio of Fuel Momentum
to Air Momentum and Fuel Pressure at Constant
Velocity and Air-Fuel Ratio.

$$\text{Let } R = \frac{\text{fuel momentum}}{\text{air momentum}} = \frac{\dot{m}_f u_f}{\dot{m}_A u_A} \quad \text{--- (1)}$$

where $\dot{m}$ = mass flow

u = velocity

subscript f refers to fuel

subscript A refers to air

At constant chamber velocity:-

$$u_A = \text{constant} \quad \text{--- (2)}$$

at constant air fuel ratio:-

$$\frac{\dot{m}_f}{\dot{m}_A} = \text{constant} \quad \text{--- (3)}$$

Substituting (2) and (3) into (1) :-

$$R \propto u_f \quad \text{--- (4)}$$

Equating the initial strain energy in the fuel at fuel pressure to the final kinetic energy in the spray, thus neglecting initial kinetic energy and final strain energy:-

$$\text{Constant} \times [\Delta p_f] = \frac{\rho_f u_f^2}{2} \quad \text{--- (5)}$$

Therefore:-

$$u_f \propto (\Delta p_t)^{1/2} \quad \text{--- (6)}$$

Substituting (6) into (4) :-

$$R \propto (\Delta p_t)^{1/2} \quad \text{--- (7)}$$

Thus the ratio of fuel momentum to air momentum at constant velocity and air fuel ratio is proportional to the root of the fuel pressure differential across the nozzle.

APPENDIX III.

Dimensional Analysis of the Major Combustor
Parameters Affecting Flame Emissivity.

Let it be assumed that the following variables are the only important combustor parameters that affect flame emissivity for geometrically similar chambers operating with the same fuel:-

<u>Variable.</u>	<u>Symbol.</u>	<u>Units.</u>
Air inlet temperature.	T_i	$[\theta]$
Air mass flow rate.	$\dot{m}_A$	$[MT^{-1}]$
Fuel mass flow rate.	$\dot{m}_f$	$[MT^{-1}]$
Combustion pressure.	p_c	$[ML^{-1}T^{-2}]$
Fuel pressure differential.	Δp_f	$[ML^{-1}T^{-2}]$
Gas constant.	R	$[L^2T^{-2}\theta^{-1}]$
Characteristic dimension.	D	$[L]$

Let the flame emissivity be related to these variables in the following manner:-

$$\varepsilon_f = f\left\{(T_i)^a (\dot{m}_A)^b (\dot{m}_f)^c (p_c)^d (p_f)^e (R)^f (D)^g\right\} + \dots \quad (1)$$

Thus inserting units:-

$$[M^0 L^0 T^0 \theta^0] = [\theta]^a \left[\frac{M}{T}\right]^b \left[\frac{M}{T}\right]^c \left[\frac{M}{LT^2}\right]^d \left[\frac{M}{LT^2}\right]^e \left[\frac{L^2}{T^2 \theta}\right]^f [L]^g \quad (2)$$

For this equation to be dimensionally correct:-

$$M :- \quad 0 = b + c + d + e \quad \text{--- (3)}$$

$$L :- \quad 0 = -d - e + 2e + g \quad \text{--- (4)}$$

$$T :- \quad 0 = -b - c - 2d - 2e - 2t \quad \text{--- (5)}$$

$$\Theta :- \quad 0 = a - f \quad \text{--- (6)}$$

Solving these equations retaining c , e and f :-

$$\varepsilon_F = f \left\{ (T_i)^t (\dot{m}_A)^{(-c+2t)} (\dot{m}_f)^c (p_c)^{(2t-e)} (\Delta p_f)^e (R)^t (D)^{-4t} \right\} \quad \text{--- (7)}$$

Thus:-

$$\varepsilon_F = f \left\{ \left(\frac{\dot{m}_f}{\dot{m}_A} \right)^c, \left(\frac{\Delta p_f}{p_c} \right)^e, \left(\frac{\dot{m}_A \sqrt{RT_i}}{p_c D^2} \right)^{2t} \right\} \quad \text{--- (8)}$$

$$\text{Let } Q = \left(\frac{\dot{m}_A \sqrt{RT_i}}{p_c D^2} \right) \quad \text{--- (9)}$$

=(non-dimensional mass flow.)

$$\frac{\dot{m}_f}{\dot{m}_A} = \frac{1}{AFR} \quad \text{--- (10)}$$

=(air fuel ratio)

Thus substituting (9) and (10) into (8) :-

$$\varepsilon_F = f \left\{ (AFR)^i, (Q)^j, \left(\frac{\Delta p_f}{p_c} \right)^k \right\} \quad \text{--- (11)}$$

This expression may be reduced to a more practical form by manipulation of the last group $\left(\frac{\Delta p_f}{p_c} \right)^k$ in the following manner:-

$$\begin{aligned}
 \left(\frac{\Delta p_c}{p_c}\right)^k &= \left[\frac{\Delta p_c}{\dot{m}_c^2} \cdot \frac{\dot{m}_A^2}{p_c} \right]^k (AFR)^{-2k} \\
 &= \left[\frac{\Delta p_c}{\dot{m}_c^2} \left(\frac{\dot{m}_A^2 R T_1}{A^2 p_c^2} \right) \frac{p_c A^2}{R T_1} \right]^k (AFR)^{-2k} \\
 &= \left[\frac{p_c}{F^2} \cdot \frac{A^2}{R T_1} \right]^k (Q)^{2k} (AFR)^{-2k}
 \end{aligned}$$

where F = flow number.

Thus:-

$$\epsilon_F = f \left\{ (AFR)^p, (Q)^q, \left(\frac{p_c}{T_1 F^2} \cdot \frac{A^2}{R} \right)^r \right\} \quad \text{--- (12)}$$

Thus for a given combustor using air:-

$$\epsilon_F = f \left\{ (AFR)^p, (Q)^q, \left(\frac{p_c}{T_1 F^2} \right)^r \right\} \quad \text{--- (13)}$$

APPENDIX IV.

A Sample Schmidt Method Calculation.

This reduction is for the following conditions:-

Swirl atomiser FN	=	0.37
Combustion pressure	=	60 lbf./in ² .
Air mass flow rate	=	1.82 lb./sec.
Chamber velocity	=	60%.
Air fuel ratio	=	120.

The Schmidt readings were as follows:-

	<u>Apparent Furnace Temp.</u>	<u>R₃</u>	<u>R₂</u>	<u>R₁</u>
	T _B (° C).	(mA)	(mA)	(mA)
1.	1400	0.143	0.216	0.108
2.	1500	0.190	0.251	0.113
3.	1595	0.257	0.297	0.110

The correction for background temperature, ($E_1 + E_2$), is obtained from Fig. 39 and the conversion of the amplifier readings to flux-meter outputs from Fig. 37.

N.B. For the actual reductions, large scale accurately drawn graphs were used.

The conversions are:-

$E_1 + E_2$ ($^{\circ}\text{C}$)	<u>True</u> <u>Furnace</u> <u>Temp.</u> T_{bb} ($^{\circ}\text{C}$)	R_3 (mV)	R_2 (mV)	R_1 (mV)
-9	1391	0.151	0.224	0.118
-7	1493	0.199	0.259	0.122
-3	1592	0.263	0.304	0.120

From the fluxmeter readings, the apparent emissivities are evaluated according to:-

$$\epsilon_F' = \frac{R_3 + R_1 - R_2}{R_3} \quad \text{--- (1)}$$

The conversion to radiant flux being obtained from Fig. 35, the results being:-

	<u>Apparent</u> <u>Flame</u> <u>Emissivity.</u> ϵ_F'	<u>Total</u> <u>Radiant</u> <u>Flux.</u> ($\text{CHU}/\text{ft}^2\text{hr} \times 10^{-4}$)	<u>Window</u> <u>Transmittance.</u> (Fig. 34). ($1-\beta$)
1.	0.298	1.000	0.923
2.	0.312	1.030	0.925
3.	0.301	1.010	0.927

From these values, the corresponding apparent flame temperatures are calculated according to:-

$$T_F' (^{\circ}\text{C}) = \left\{ \sqrt[4]{3.05 \times 10^8 \left[\frac{q_{R1}}{(1-\beta)\epsilon_F'} \right]} \right\} - [273]$$

	$\frac{T_{bb}}{(\text{° C}).}$	$\frac{\epsilon_F'}{}$	$\frac{T_F}{(\text{° C}).}$
1.	1391	0.298	1527
2.	1493	0.312	1535
3.	1592	0.301	1563

From these values, T_F' is plotted against T_{bb} and the solution flame temperature obtained at the intersection with the line $T_F' = T_{bb}$. The "true" flame emissivity is extracted at the solution temperature as shown in Fig. 64. The solution, as shown in Table 16, is:-

Flame Temperature, T_f = 1544 (° C).

Flame Total Emissivity, = 0.308.

TABLE 1.

Combustion Pressure	= 70 lbf./in ² .
Swirl Atomiser FN	= 0.77
Mass Flow (nominal)	= 2.12 lb./sec.
Air Inlet Temperature	= 12°C.

$\dot{m}_A$ lb/sec.	AFR	P_B lbf/in ²	J.P.T. °C.	Smoke level (S.U.)	Total Radiation (CHU/ft ² hr.)
2.12	200	100	120	6.50	0.735
2.10	189	100	125	7.25	0.765
2.12	149	120	130	11.50	1.135
2.12	139	150	158	10.50	1.115
2.14	104	200	212	6.00	1.000
2.14	89	260	263	4.83	0.735
2.12	75	340	320	3.40	0.490
2.11	66	400	400	3.60	0.420
2.13	77	340	305	3.50	0.550
2.12	91	250	233	5.20	0.775
2.14	110	190	170	8.50	1.035
2.13	125	150	125	10.50	1.120
2.13	148	130	102	11.00	1.200
2.07	188	100	123	7.75	0.795
2.13	213	90	105	6.75	0.660
2.09	190	80	120	7.25	0.710
2.12	178	75	95	9.00	1.095

(see Figures 44 and 47).

TABLE 2.

Combustion Pressure	= 70 lbf./in ² .
Airblast Atomiser, FN	= 2.00
Mass Flow (nominal)	= 2.10 lb./sec.
Air Inlet Temperature	= 16°C.

$\dot{m}_A$ lb./sec.	AFR	p_B lbf/in ²	J.P.T. °C.	Smoke level (S.U.)	Total Radiation. (CHU/ft ² hr.)
2.130	95	83	228	0	0.210
2.105	84	90	275	0	0.248
2.096	73	97	318	0	0.260
2.094	69	100	334	0	0.270
2.094	64	110	365	0	0.285
2.093	59	115	400	0	0.310
2.093	54	120	430	0	0.330
2.093	58	115	400	0	0.305
2.093	66	100	343	0	0.285
2.093	75	95	292	0	0.260
2.093	80	92	275	0	0.255
2.110	86	90	252	0	0.240
2.110	95	85	222	0	0.220
2.110	108	80	193	0	0.180
2.110	123	75	157	0	0.120
2.110	149	70	120	0	0.085
2.110	145	-	-	0	0.090
2.110	113	-	192	0	0.152

(see Figures 44 and 47)

TABLE 3.

Combustion Pressure	= 135 lbf./in ² .
Swirl Atomiser, FN	= 0.77
Mass Flow (nominal)	= 4.44 lb./sec.
Air Inlet Temperature	= 16°C.

$\dot{m}_A$ lb./sec.	AFR	P_B lbf/in ²	J.P.T. °C	Smoke level (S.U)	Total Radiation. (CHU/ft ² hr.)
4.49	206	280	100	0.950	0.88
4.45	173	340	130	0.615	0.93
4.43	151	405	155	0.539	0.98
4.43	133	470	173	0.423	1.00
4.49	129	510	180	0.333	0.94
4.40	96	860	270	1.000	1.07
4.50	86	1080	295	1.370	1.09
4.44	112	650	205	0.393	1.07
4.43	95	850	260	1.080	1.15
4.49	118	600	180	0.592	1.05
4.40	117	550	190	0.429	1.07
4.43	121	550	185	0.358	1.07
4.40	126	500	180	0.464	1.11
4.43	134	470	165	0.407	1.07
4.43	142	430	155	0.438	1.05
4.45	158	370	130	0.438	1.03
4.47	189	300	110	0.643	0.93

(see Figures 45 and 47).

TABLE 4.

Combustion Pressure = 135 lbf./in².
 Airblast Atomiser FN = 1.57
 Mass Flow (nominal) = 4.45 lb./sec.
 Air Inlet Temperature = 20°C.

mA	AFR	P_B	J.P.T.	Smoke	Total
lb./sec.		lbf/in ²	°C	level (S.U)	Radiation (CHU/ft ² hr.)
4.47	129	250	196	0	0.17
4.44	153	210	136	0	0.08
4.44	141	-	-	0	0.10
4.44	148	-	-	0	0.09
4.50	139	-	-	0	0.11
4.56	129	240	190	0	0.15
4.44	119	270	230	0	0.20
4.44	95	315	295	0	0.34
4.44	104	290	250	0	0.29
4.45	82	390	340	0	0.46
4.47	67	500	380	0	0.60
4.44	60	560	432	0	0.64
4.47	119	260	200	0	0.24
4.44	126	240	186	0	0.19
4.47	135	230	172	0	0.13
4.46	143	215	150	0	0.12
4.47	147	-	-	0	0.09
4.47	60	-	-	0	0.69
4.47	66	-	-	0	0.58
4.46	72	-	-	0	0.52
4.47	80	-	-	0	0.45
4.47	94	-	-	0	0.37
4.47	103	-	-	0	0.27
4.44	118	-	-	0	0.21
4.44	129	-	-	0	0.17
4.47	138	-	-	0	0.12
4.44	150	-	-	0	0.09

(see Figures 45 and 47).

TABLE 5.

Combustion Pressure	=	195 lbf./in ² .
Swirl Atomiser FN	=	0.77
Mass Flow (nominal)	=	6.04 lb./sec.
Air Inlet Temperature	=	65°C.

$\dot{m}_A$ lb./sec.	AFR	P_B lbf/in ²	J.P.T. °C	Smoke level (S.U)	Total Radiation (CHU/ft ² hr.)
6.10	175	1050	150	0	0.75
6.02	170	1100	154	0	0.77
6.06	153	1200+	168	0	0.91
6.02	152	"	174	0	0.93
6.03	157	"	165	0	0.87
6.03	170	1120	154	0	0.78
6.04	193	1090	133	0	0.61
6.04	183	1050	150	0	0.67
6.05	208	925	130	0	0.50
6.03	232	740	120	0	0.37
6.03	263	700	118	0	0.22
6.04	249	660	115	0	0.27

(see Figures 46 and 47).

TABLE 6.

Combustion Pressure	= 193 lbf./in ² .
Airblast Atomiser FN	= 1.57
Mass Flow (nominal)	= 6.06 lb./sec.
Air Inlet Temperature	= 56°C.

mA	AFR	<i>P_B</i> lbf/in ²	J.P.T. °C.	Smoke level (S.U).	Total Radiation (CHU/ft ² hr.)
lb./sec.					
6.02	162	310	185	0	0.10
6.05	127	370	240	0	0.18
6.16	123	390	215	0	0.17
6.07	106	-	255	0	0.36
6.07	94	500	300	0	0.66
6.07	79	-	-	0	1.07
6.07	121	-	200	0	0.19
6.10	107	390	260	0	0.42
6.05	98	440	270	0	0.51
6.05	92	-	292	0	0.66
6.07	84	510	320	0	0.96
6.05	77	-	-	0	1.16
6.10	65	-	-	0	1.18
6.05	62	-	-	0	1.21
6.10	69	-	400	0	1.01
6.05	79	-	338	0	0.73

(see Figures 46 and 47).

TABLE 7.

Combustion Pressure = 79 lbf./in².
 A.F.R (Nominal) = 131
 Swirl Atomiser, FN = 0.77
 Air Inlet Temperature = 130° C

mA	AFR	<i>po</i> lbf/in ²	J.P.T. °C	Smoke level (S.U.)	Total Radiation (CHU/ft ² hr.)
lb./sec.					
3.455	128.5	390	170	0.93	0.73
3.520	132.4	390	171	0.87	0.70
2.493	131.2	230	137	0.83	1.42
2.830	133.5	260	125	2.14	1.18
3.170	131.0	340	175	1.22	0.92
3.880	130.3	470	150	0.23	0.50
4.280	132.7	540	113	0.28	0.40

(see Figure 49).

TABLE 8.

Combustion Pressure = 78 lbf./in².
 A.F.R (nominal) = 83
 Airblast Atomiser, FN = 1.57
 Air Inlet Temperature = 190° C

mA	AFR	<i>pb</i> lbf/in ²	J.P.T. °C	Smoke level (S.U.)	Total Radiation (CHU/ft ² hr.)
lb./sec.					
4.600	82.3	320	225	0	0.20
4.290	83.9	270	192	0	0.19
3.910	83.2	240	197	0	0.22
3.530	85.9	210	212	0	0.23
3.165	84.4	190	235	0	0.23
2.840	83.2	170	287	0	0.26
2.470	82.4	150	280	0	0.32

(see Figure 50).

TABLE 9.

Combustion Pressure = 70 lbf./in².
 Swirl Atomiser, FN = 0.77
 Air Inlet Temperature = 21°C.

$\dot{m}_A$ lb./sec.	% Design Velocity.	Extinction AFR
3.96	128	1470
3.55	114	1420
3.50	113	1400
2.97	96	1190
2.29	74	890
1.62	52	650

(see Figure 48).

TABLE 10.

Combustion Pressure = 70 lbf./in².
 Airblast Atomiser, FN = 1.57
 Air Inlet Temperature = 16°C.

$\dot{m}_A$ lb./sec.	% Design Velocity.	Extinction AFR
3.45	111	119
3.32	107	125
3.17	102	148
2.96	95	150
2.77	89	158
2.53	81	152
2.26	73	155

(see Figure 48).

TABLE 11.

Combustion Pressure	=	115 lbf./in ² .
Swirl Atomiser, FN	=	0.77
Air Inlet Temperature	=	20° C

mA lb./sec.	% Design Velocity.	Extinction AFR
4.62	91	1720
4.32	85	1570
4.00	79	1450
3.65	72	1330
4.76	94	1730
4.84	96	1760

(see Figure 48).

TABLE 12.

Combustion Pressure	=	115 lbf./in ² .
Airblast Atomiser, FN	=	1.57
Air Inlet Temperature	=	20° C

mA lb./sec.	% Design Velocity	Extinction AFR
5.87	115	113
5.53	109	112
5.38	106	117
4.90	96	118
4.55	89	115
4.20	82	116
3.76	74	120

(see Figure 48).

TABLE 13.

Combustion Pressure = 180 lbf./in².
 Swirl Atomiser, FN = 0.77
 Air Inlet Temperature = 66° C

mA lb./sec.	% Design Velocity	Extinction AFR
5.02	63.1	1478
4.77	60.0	1400
5.28	66.3	1550
5.74	72.1	1690
6.15	77.2	1810

(see Figure 48).

TABLE 14.

Combustion Pressure = 180 lbf./in².
 Airblast Atomiser, FN = 1.57
 Air Inlet Temperature = 53° C

mA lb./sec.	% Design Velocity	Extinction AFR
6.71	84.3	134
6.30	79.2	133
5.91	74.2	136
5.52	69.4	156
5.11	64.2	153
4.67	58.7	208

(see Figure 48).

TABLE 15.

Combustion Pressure = 60 lbf./in².
Swirl Atomiser, FN = 0.77.
Inlet Air Temperature = 30° C.

MA lb./sec.	% Design Velocity	AFR	Total Radiation (CHU/ft ² hr.)	Flame Emissivity ϵ_F	Flame Temperature T_F (°C)	Smoke level (S.U.)	Injector Pressure; P_B (lbf/in ²)
3.04	100	60	0.356	0.073	1665	0.79	1000
		90	0.421	0.140	1440	0.60	580
		120	0.811	0.200	1620	2.00	280
2.43	80	60	0.399	0.088	1635	1.05	620
		90	0.789	0.235	1500	2.60	300
		120	1.287	0.377	1505	5.50	190
1.82	60	60	0.585	0.236	1400	2.50	370
		90	1.300	0.490	1415	6.20	190
		120	1.588	0.548	1453	9.60	130
1.22	40	60	1.232	0.464	1510	7.00	190
		90	1.886	0.720	1400	15.00	110
		120	1.306	0.790	1200	18.00	90

(see Figures 51, 52, 53 and 54.)

TABLE 16.

Combustion Pressure = 60 lbf./in².
Swirl Atomiser, FN = 0.37
Inlet Air Temperature = 26° C.

lb./sec.	% Design Velocity	AFR	Total Radiation. (CHU/ft ² hr.)	Flame Emissivity. ΣF	Flame Temperature T_F (°C)	Smoke level (S.U.)	Injector Pressure. P_0 (lbf./in ²)
INSUFFICIENT PUMP PRESSURE AVAILABLE.							
3.04	100	60					
		90	0.432	0.110	1500	0.20	1550
		120	0.495	0.105	1712	0.20	720
2.43	80	60	0.450	0.145	1465	0.45	1560
		90	0.557	0.128	1638	0.45	850
		120	0.655	0.134	1700	1.20	460
1.82	60	60	0.492	0.180	1432	0.73	1100
		90	0.784	0.226	1515	1.70	460
		120	1.093	0.308	1544	4.75	280
1.22	40	60	0.712	0.330	1325	3.55	460
		90	1.180	0.445	1400	7.52	230
		120	1.710	0.655	1410	18.00	160

(see Figures 51 - 58).

TABLE 17.

Combustion Pressure = 100 lbf./in².
Swirl Atomiser, FN = 0.77.
Inlet Air Temperature = 25° C.

$\dot{m}_A$ lb./sec.	% Design Velocity	AFR	Total Radiation (CHU/ft ² ·hr.)	Flame Emissivity. ϵ_f	Flame Temperature T_f (°C)	Smoke Level (S.U.)	Injector Pressure. p_0 (lbf/in ²)
INSUFFICIENT PUMP PRESSURE AVAILABLE.							
5.06	100	60					
		90	0.739	0.220	1490	0.260	1500
		120	0.735	0.143	1750	0.070	720
4.05	80	60	0.795	0.385	1300	0.690	1550
		90	0.911	0.253	1540	0.400	860
		120	0.965	0.200	1695	0.200	505
3.36	64.4	60	0.950	0.404	1355	0.770	1200
		90	1.192	0.360	1510	0.545	600
		120	1.380	0.330	1615	1.170	380
2.25	44.4	60	1.257	0.730	1230	3.67	600
		90	1.987	0.840	1330	3.67	305
		120	2.345	0.875	1350	8.63	210

(see Figures 55, 56, 57 and 58).

TABLE 18.

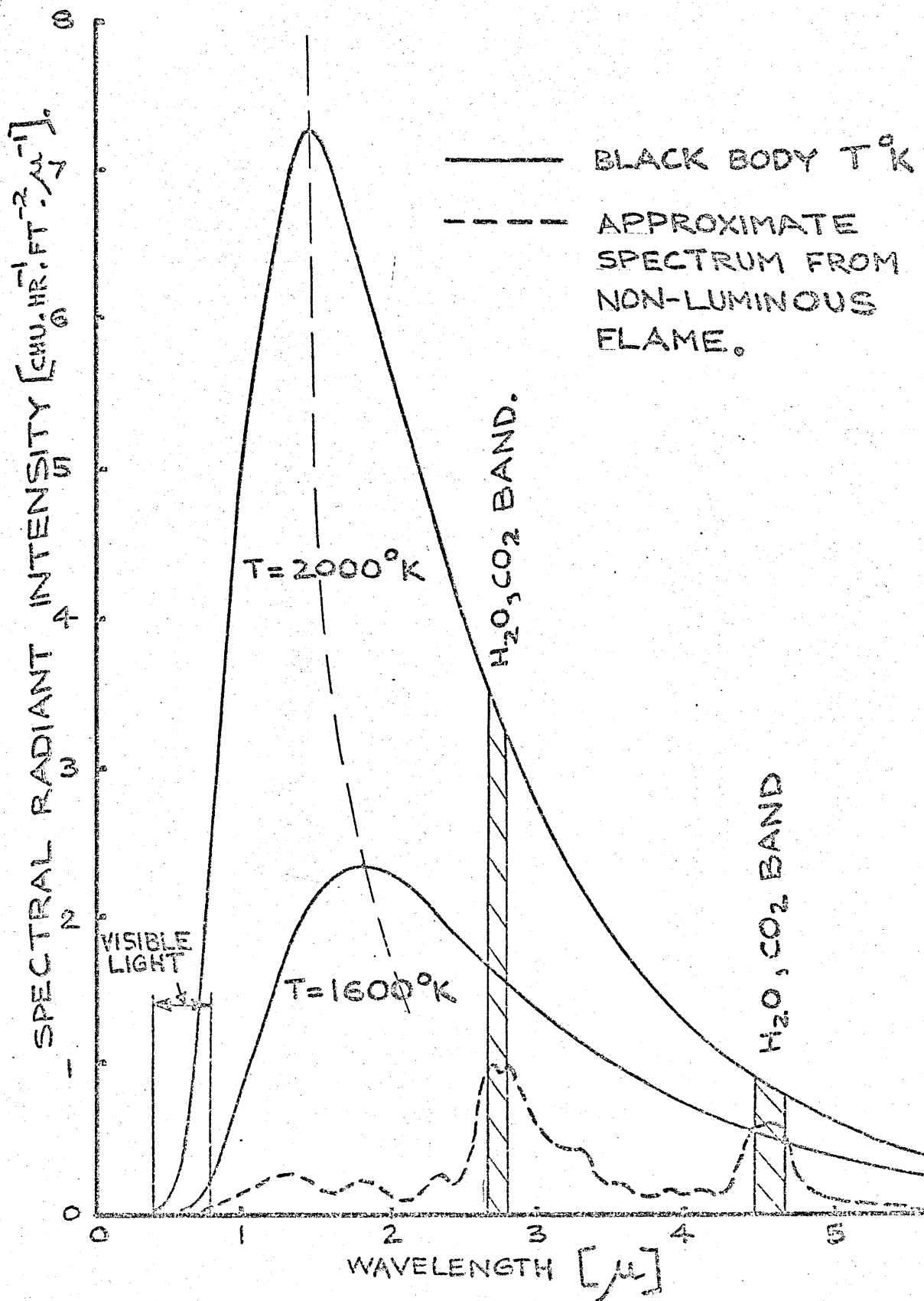
Combustion Pressure = 60 lbf./in².
 Airblast Atomiser, FN = 1.57
 Air Inlet Temperature = 340° C.

mA lb./sec.	% Design Velocity.	AFR	Total Radiation. (CHU/ft ² hr.)	* Apparent Flame Emissivity.	† Apparent Flame Temperature	† Smoke level (S.U.)	† Injector Pressure. lb (wt/in ²)
3.04	100	60	0.426	0.111	1647	0	340
		90	0.387	0.494	1650		207
		110	0.165	0.072	1381		130
2.43	80	60	0.455	0.105	1675		230
		90	0.393	0.079	1313		136
		110	0.181	0.063	1457		105
1.82	60	60	0.462	0.095	1730		146
		90	0.286	0.060	1653		97
		110	0.233	0.067	1580		80
1.22	40	60	0.501	0.229	1335		100
		90	0.415	0.073	1710		70
		110	0.274	0.071	1577		63

* Uncorrected for window absorption.

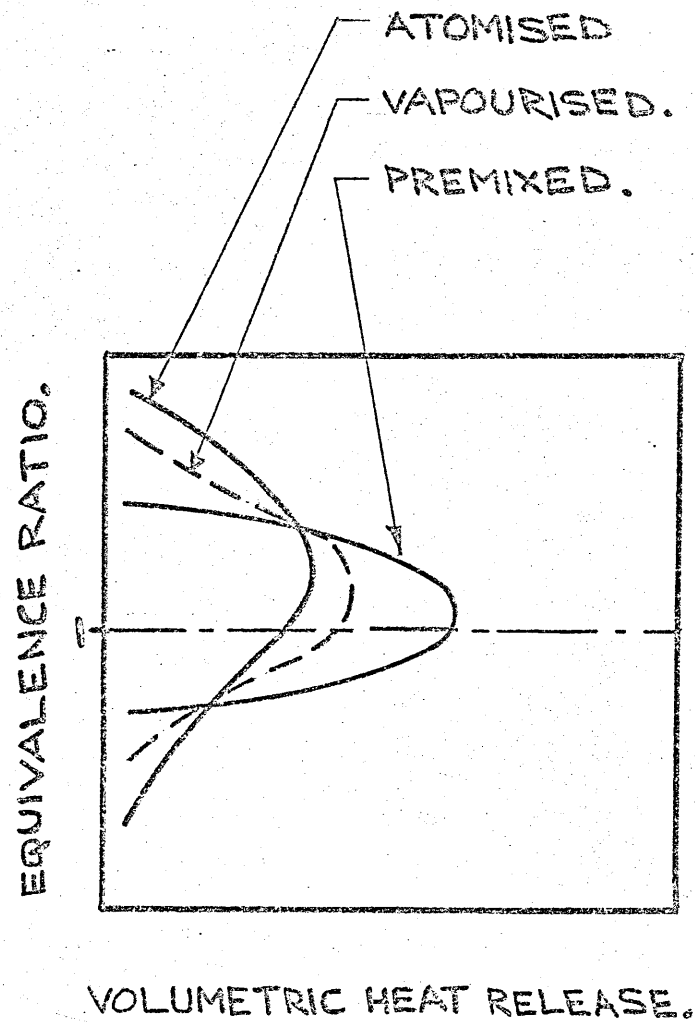
† Apparent values at background temperature of 1825° C.
 (see Figure 59).

FIG. I



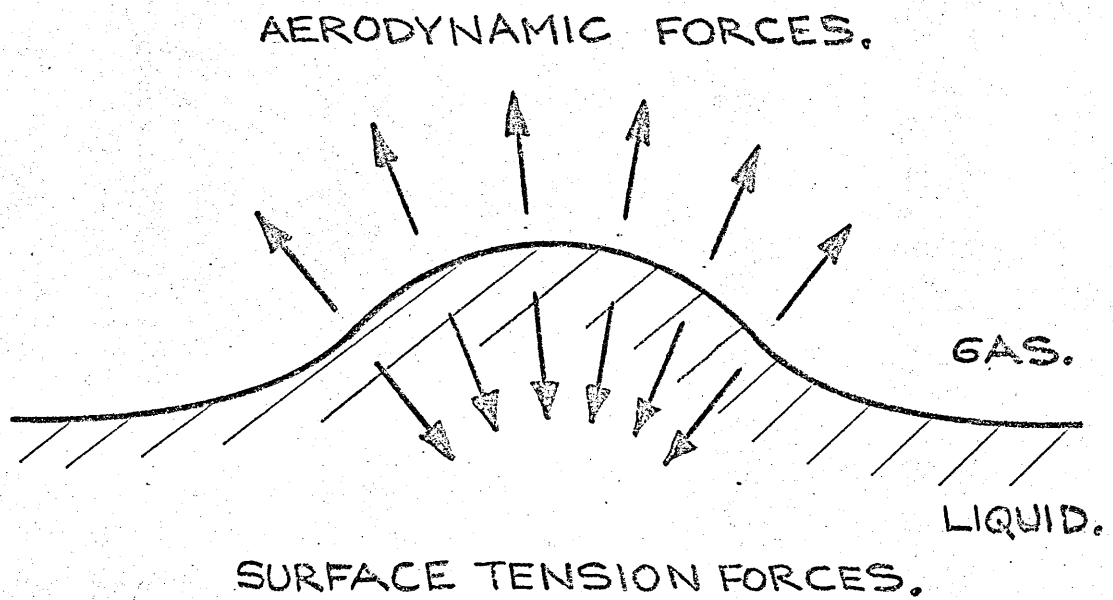
SPECTRAL DISTRIBUTION OF RADIANT ENERGY.

FIG. 2



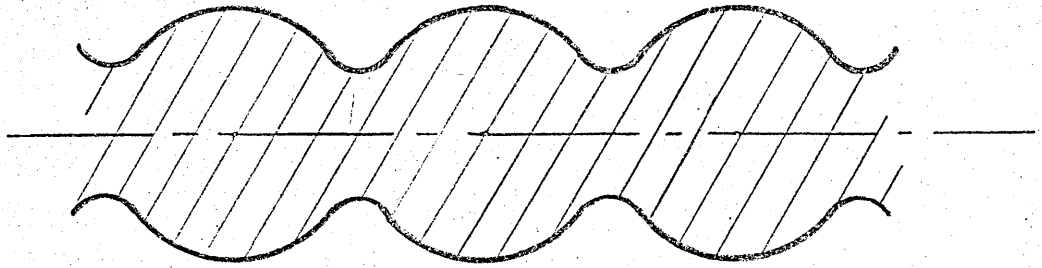
VOLUMETRIC HEAT RELEASE RATES AS A FUNCTION
OF MIXTURE STRENGTH AND PREPARATION METHOD.

FIG. 3



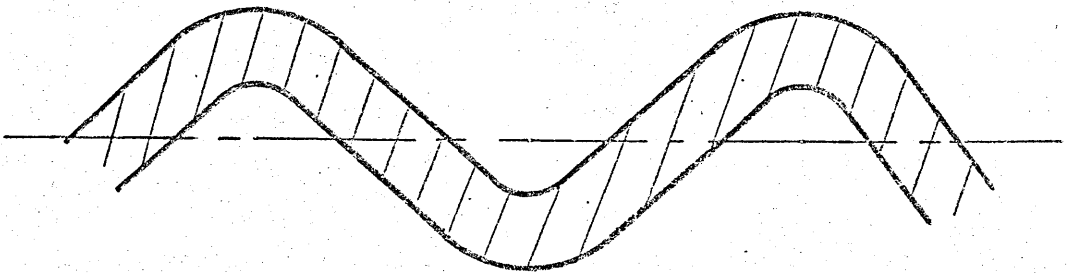
FORCE SYSTEM AT A LIQUID-GAS INTERFACE IN
THE REGION OF A SURFACE DISTURBANCE.

FIG. 4



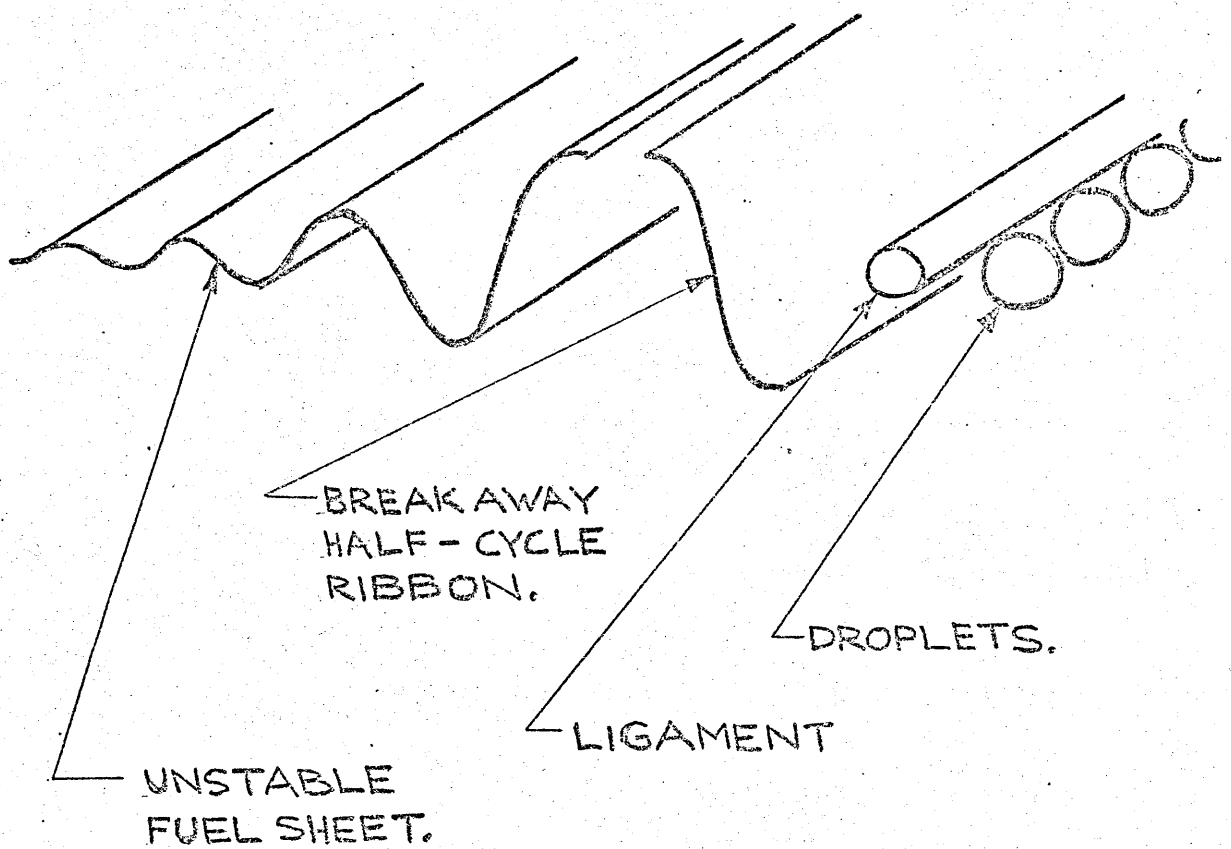
SYMMETRICAL WAVE MOTION.

FIG. 5



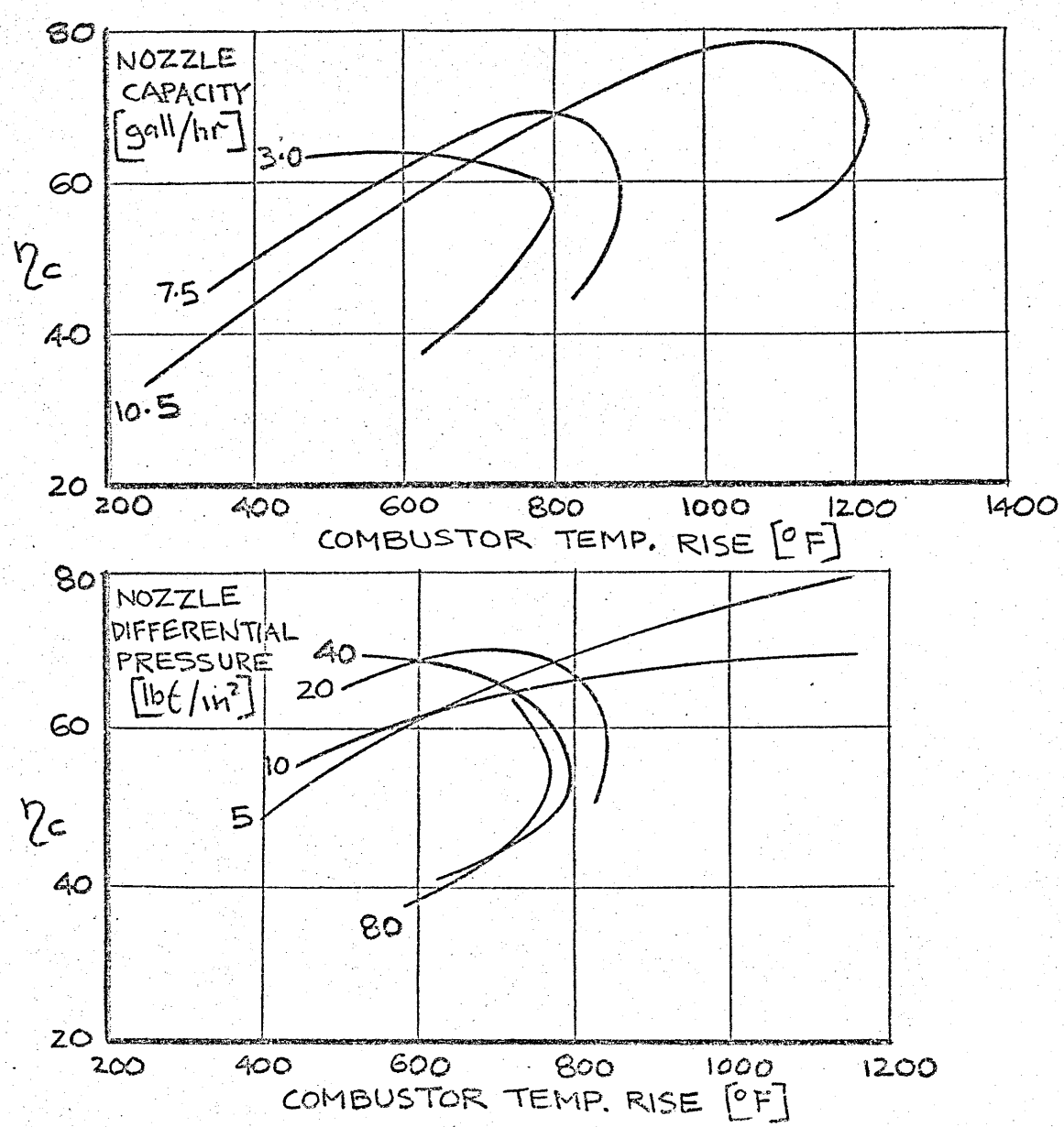
ANTI-SYMMETRICAL WAVE MOTION.

FIG. 6



BREAK-UP MODEL FOR AN INFINITE
TWO-DIMENSIONAL LIQUID SHEET.

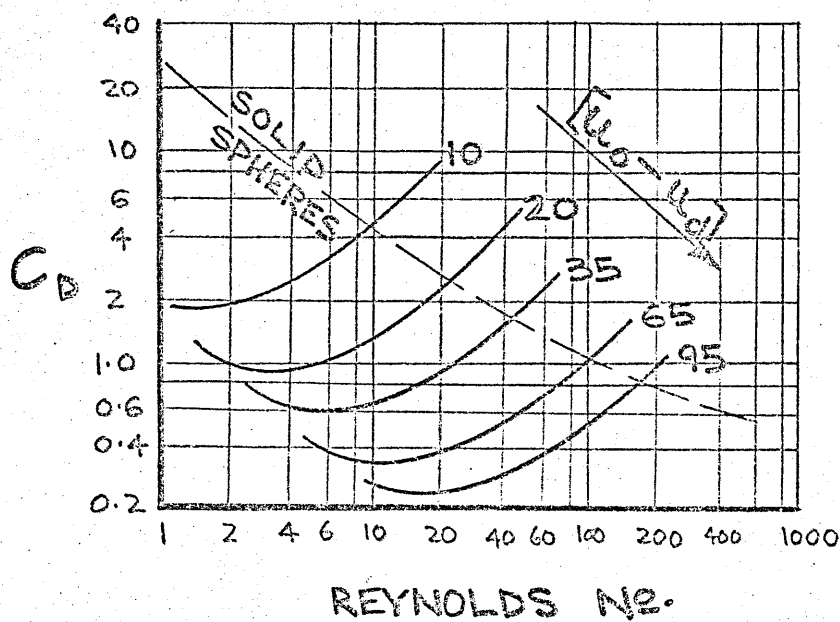
FIG. 7



EFFECT OF FUEL-NOZZLE CAPACITY AND INJECTION
PRESSURE DIFFERENTIAL ON COMBUSTION EFFICIENCY.

(From Ref. 23).

FIG. 8

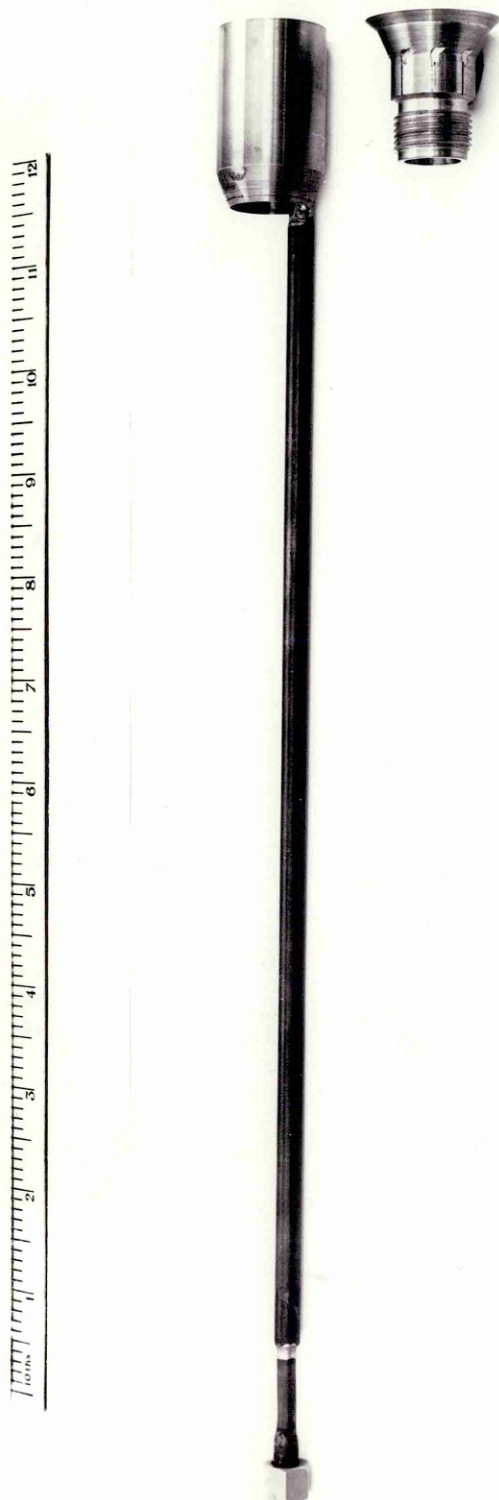


ISO-OCTANE DROPLET DRAG COEFFICIENT AS A

FUNCTION OF REYNOLDS NUMBER.

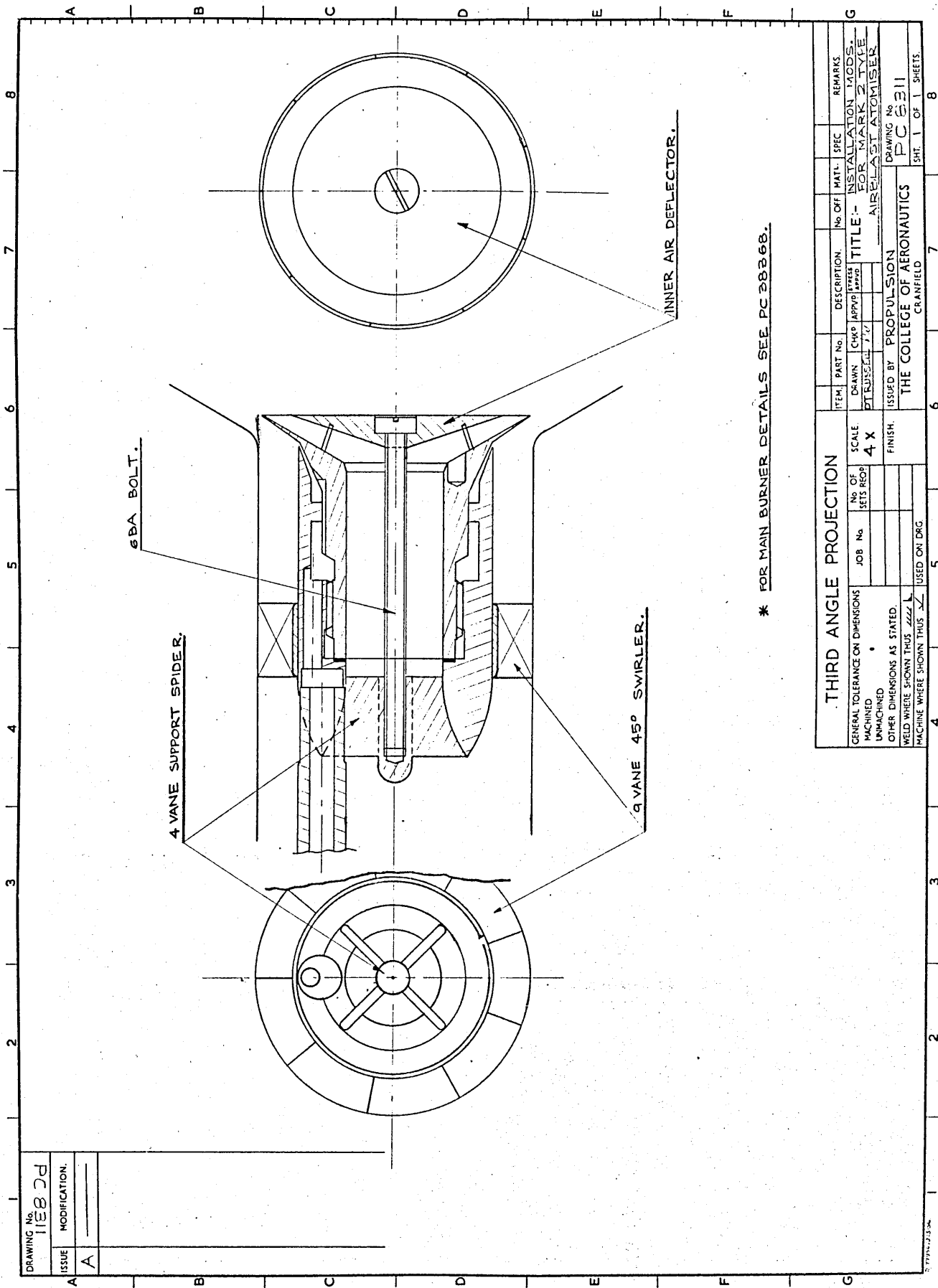
(From Ref. 19).

FIG. 9



BASIC CONSTRUCTION OF THE TEST AIRBLAST ATOMISER.

FIG. 10



THE INSTALLATION OF THE AIRBLAST ATOMISER.

FIG. 11

FIRST STANDARD OF MODIFIED 'DART' SNOUT
FOR THE AIRBLAST ATOMISER.

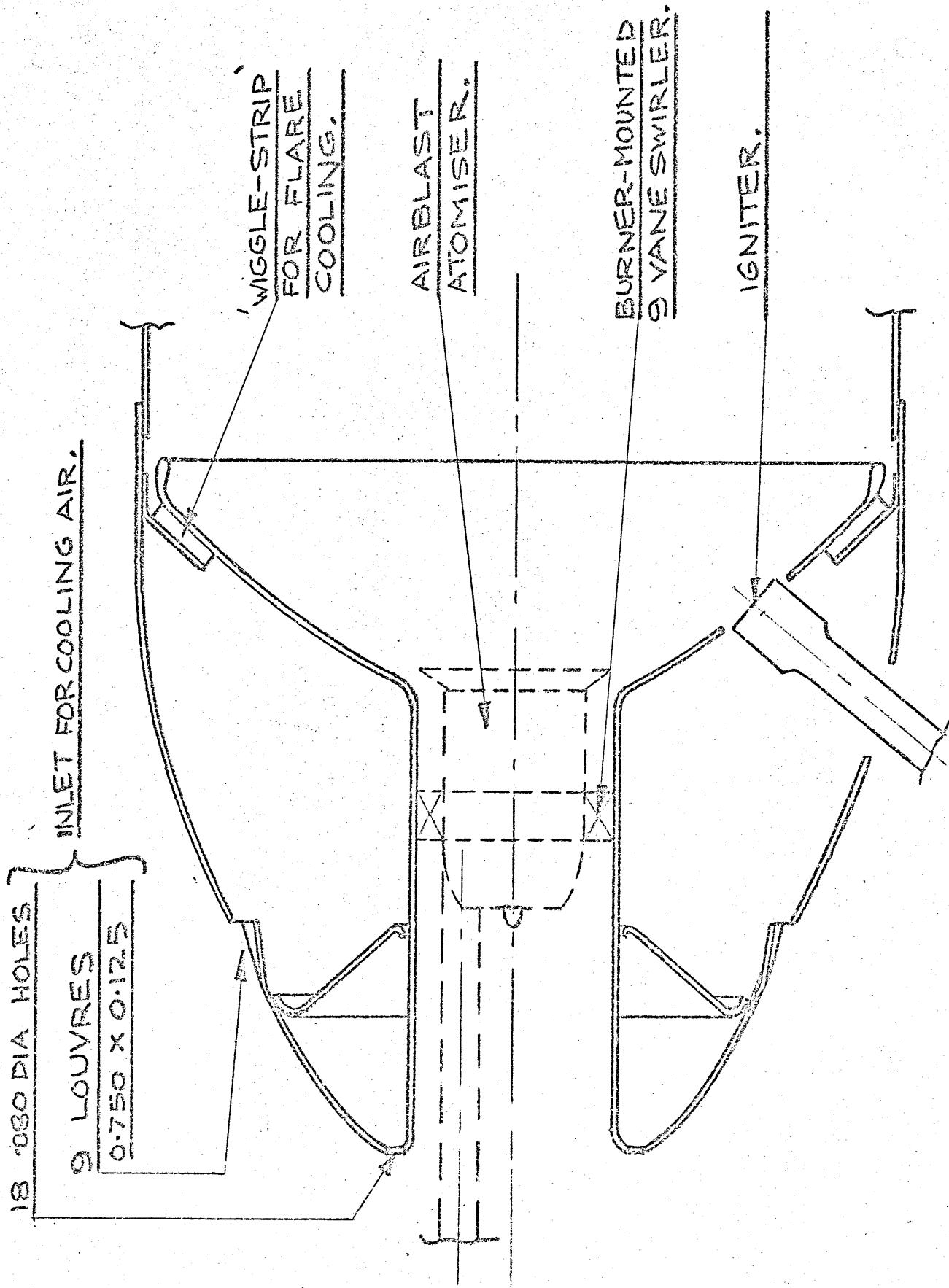
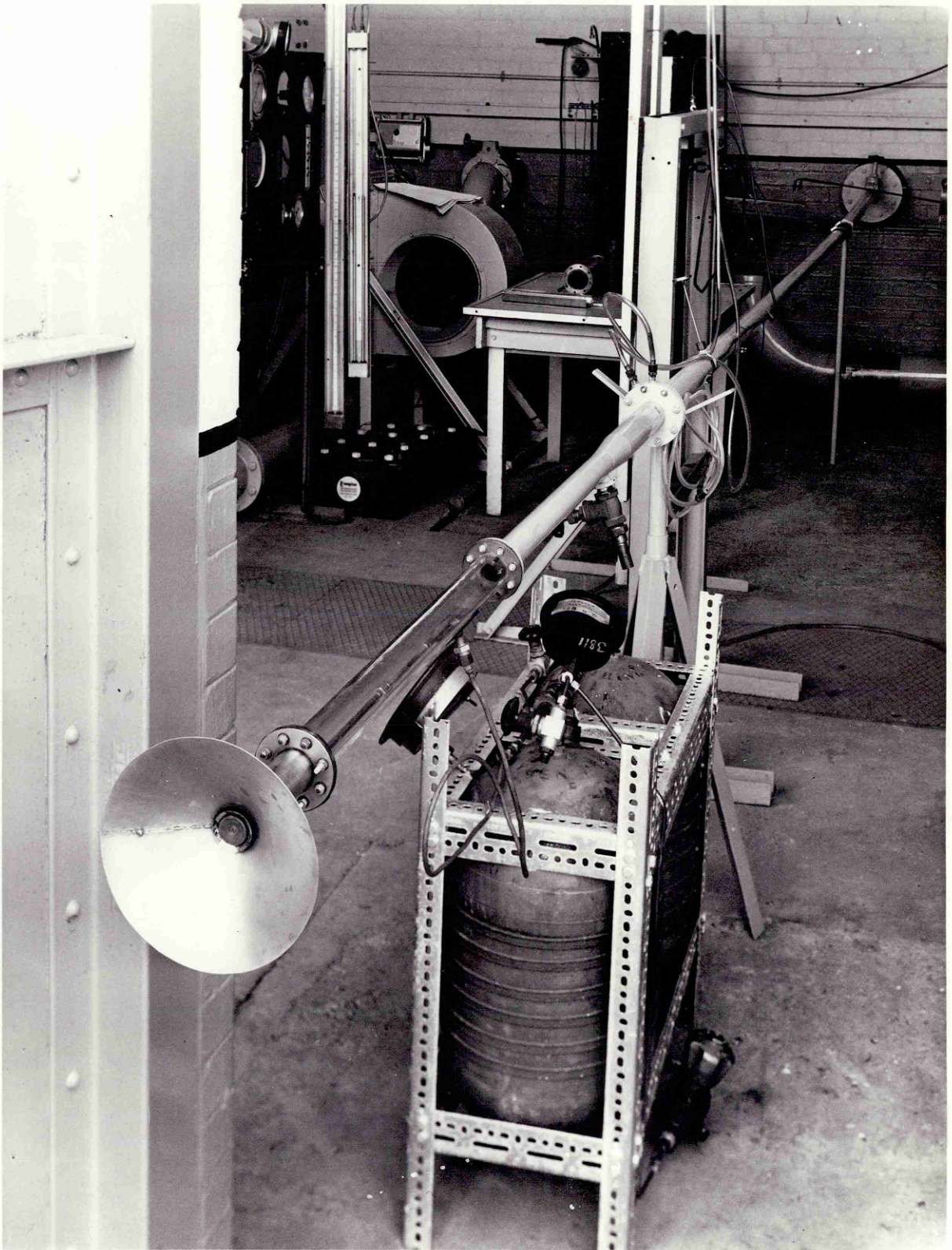


FIG.12



AIRBLAST ATOMISER WATER/AIR SPRAY TEST RIG.

FIG. 13

UNMODIFIED 'DART' COMBUSTION CHAMBER
SNOUT.

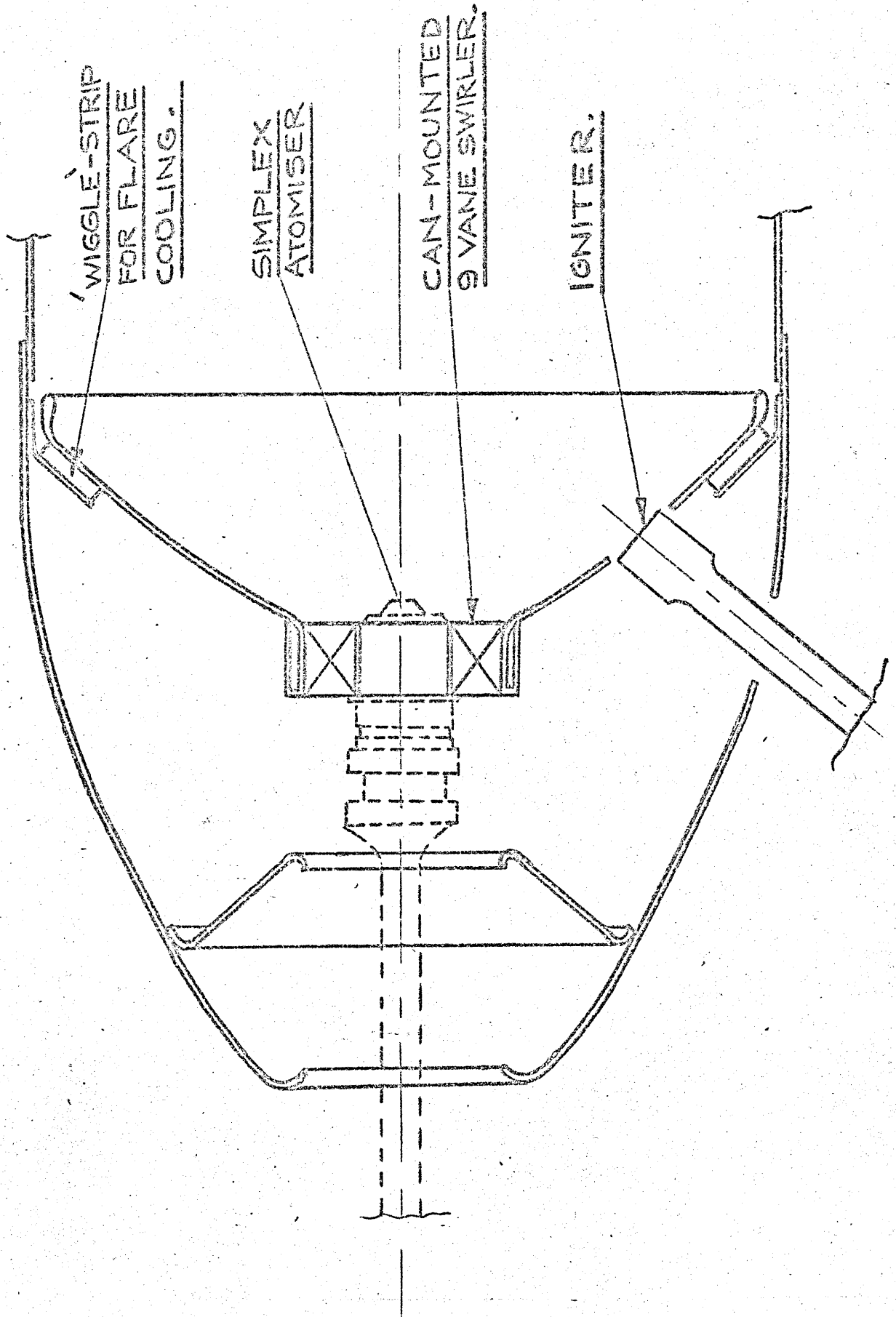


FIG.14



OVERHEATING DAMAGE TO THE INITIAL STANDARD
OF AIRBLAST ATOMISER SNOOT ASSEMBLY.

FIG. 15

SECOND STANDARD OF MODIFIED 'DART' SNOUT
FOR THE AIRBLAST ATOMISER.

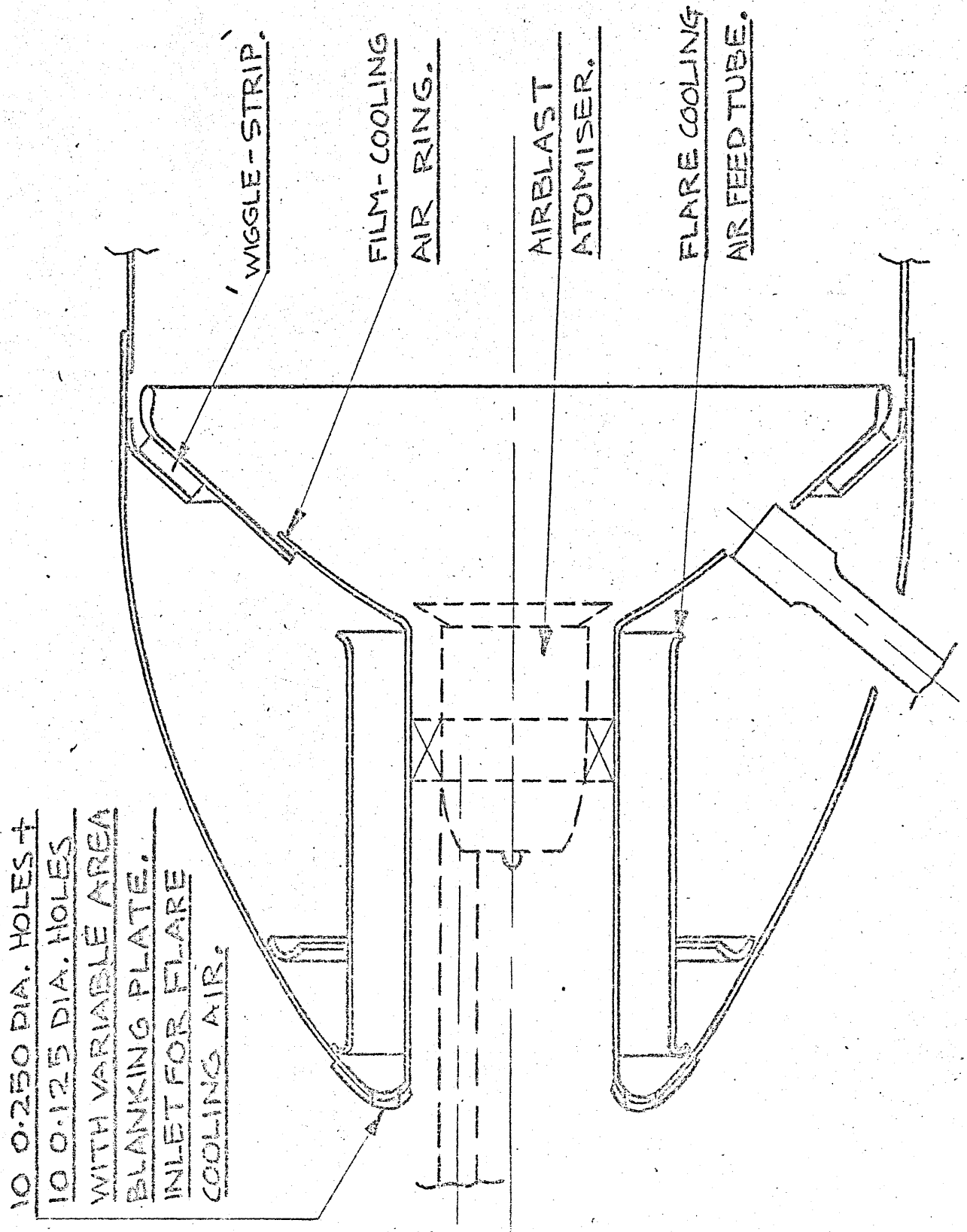
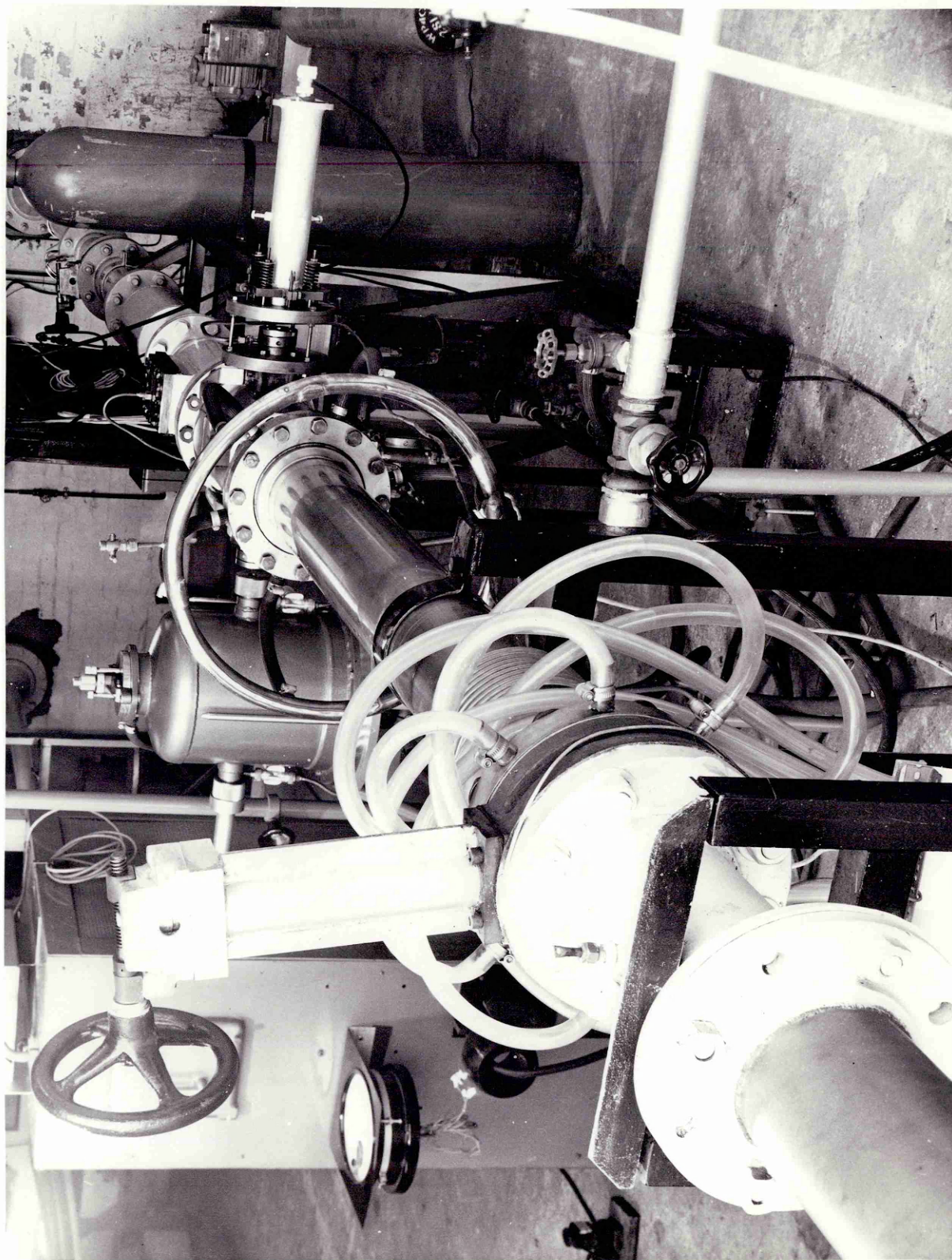
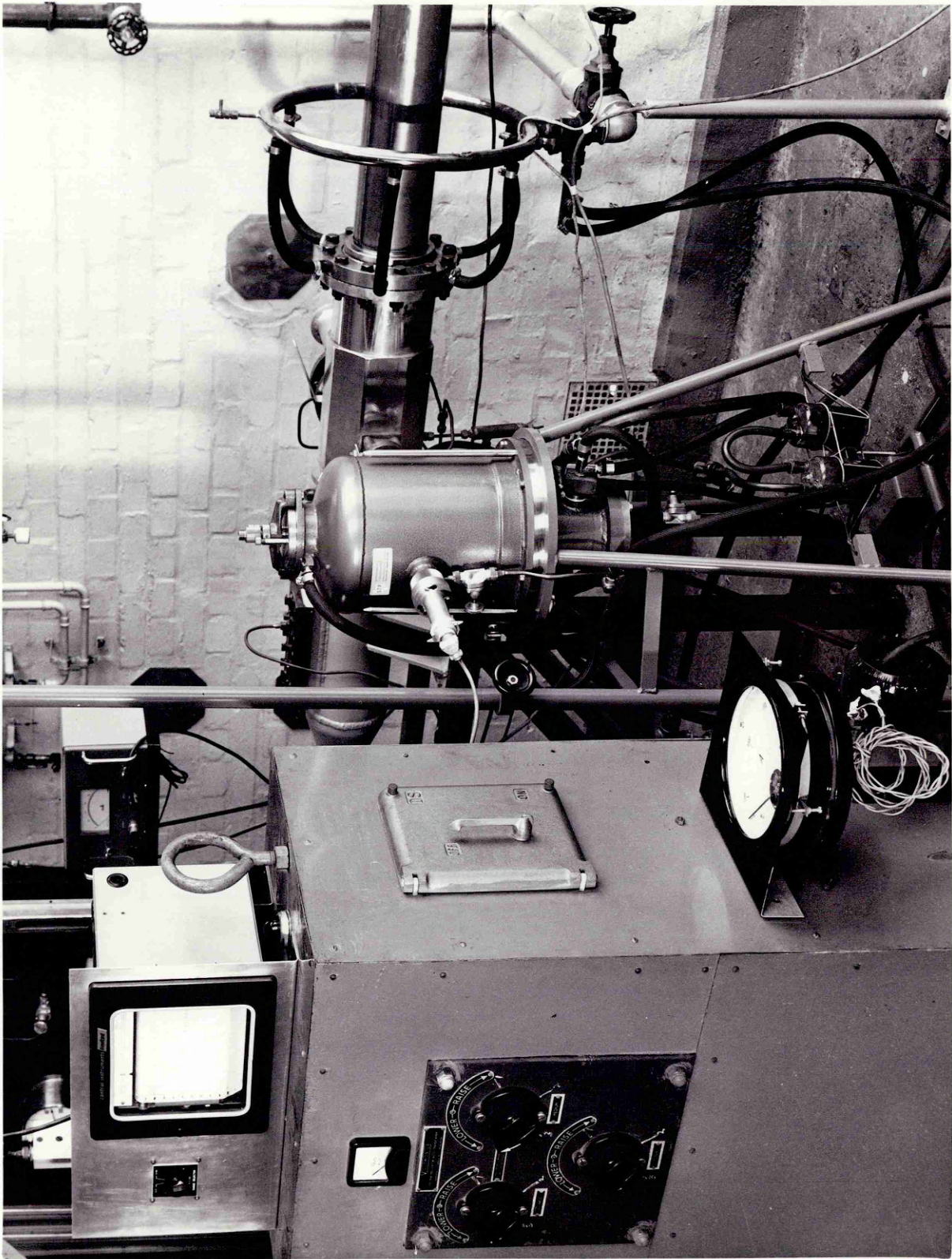


FIG. 17



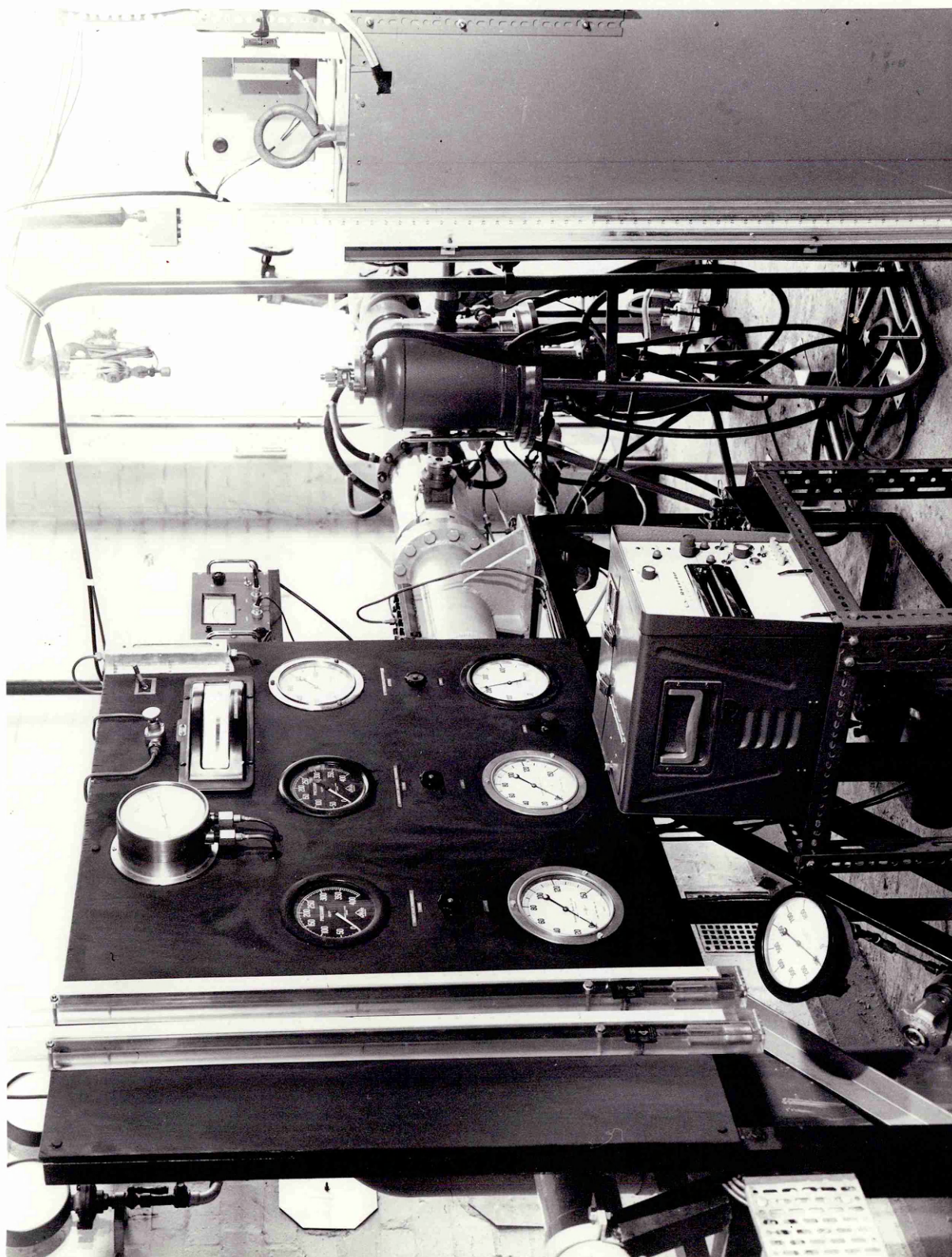
VIEW OF THE WORKING SECTION OF THE COMBUSTION RIG.

FIG. 18



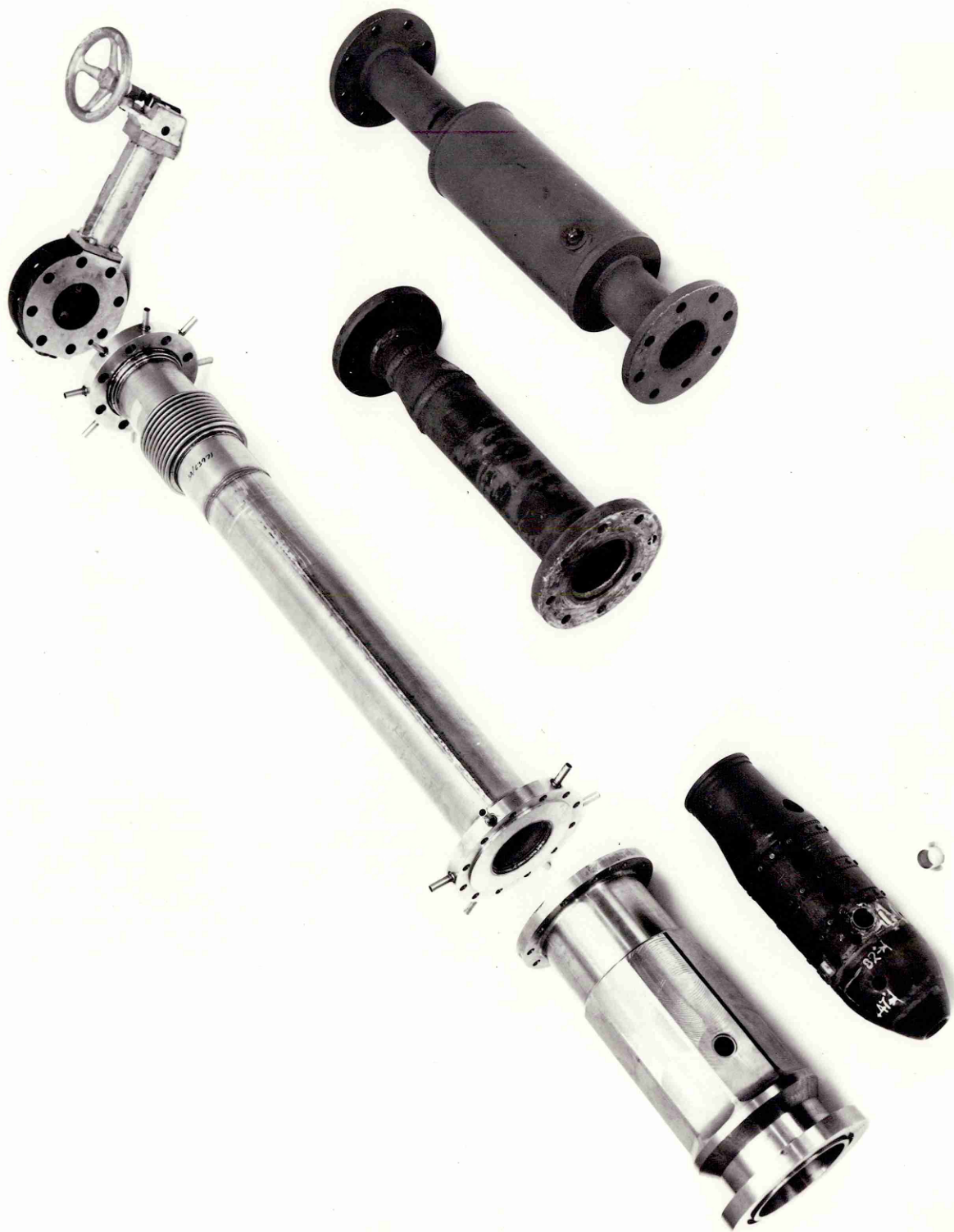
VIEW OF THE BLACK BODY FURNACE.

FIG.19



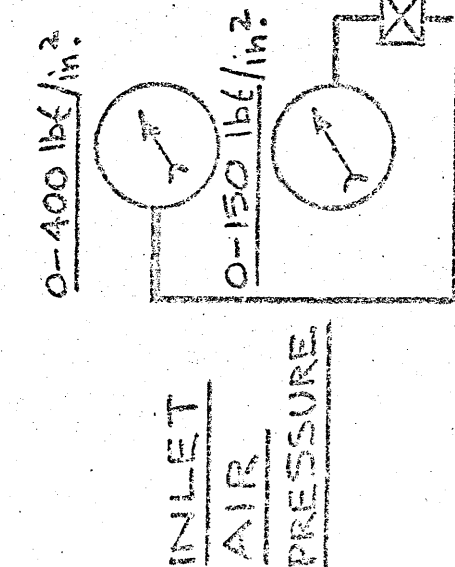
VIEW OF THE RIG AND CONTROL PANEL.

FIG. 21

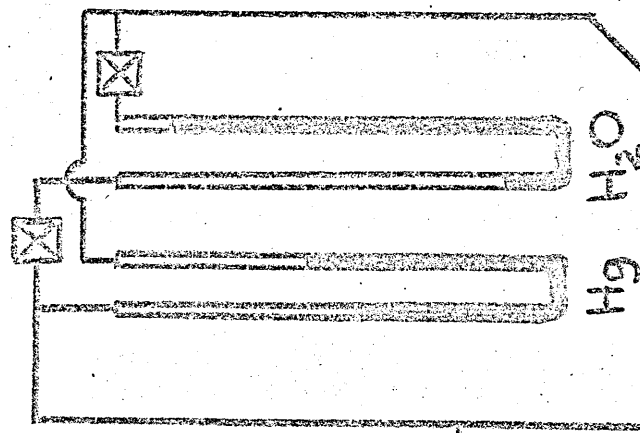


VIEW OF THE DISMANTLED HOT COMPONENTS.

MASS FLOW MANOMETERS.



AIR INLET TEMP
0-120 °C.



COMBUSTION
PRESSURE.

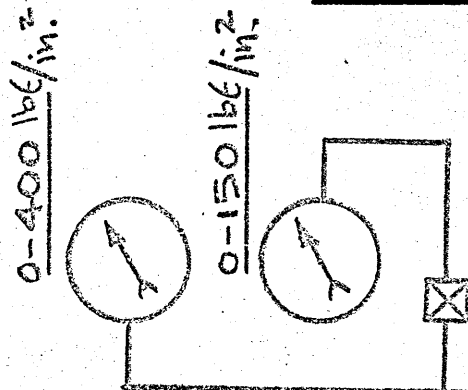


FIG. 22

AIR SUPPLY SYSTEM.

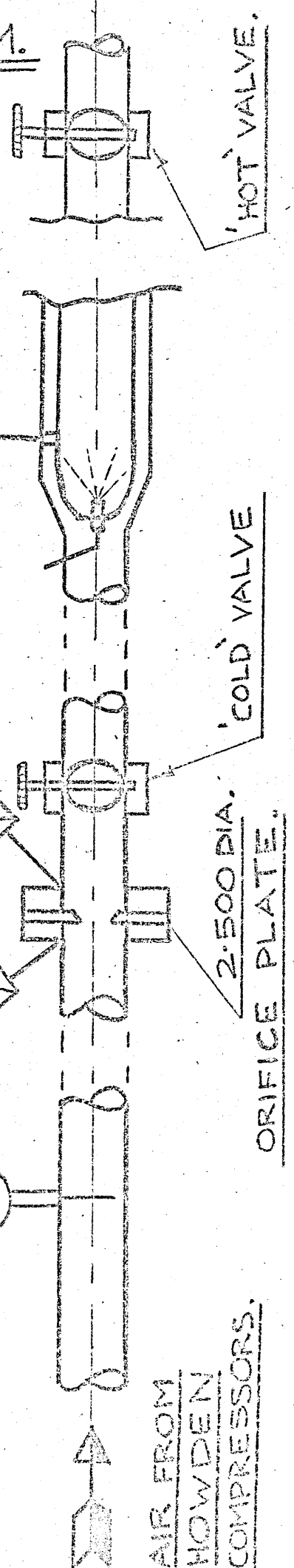


FIG. 23

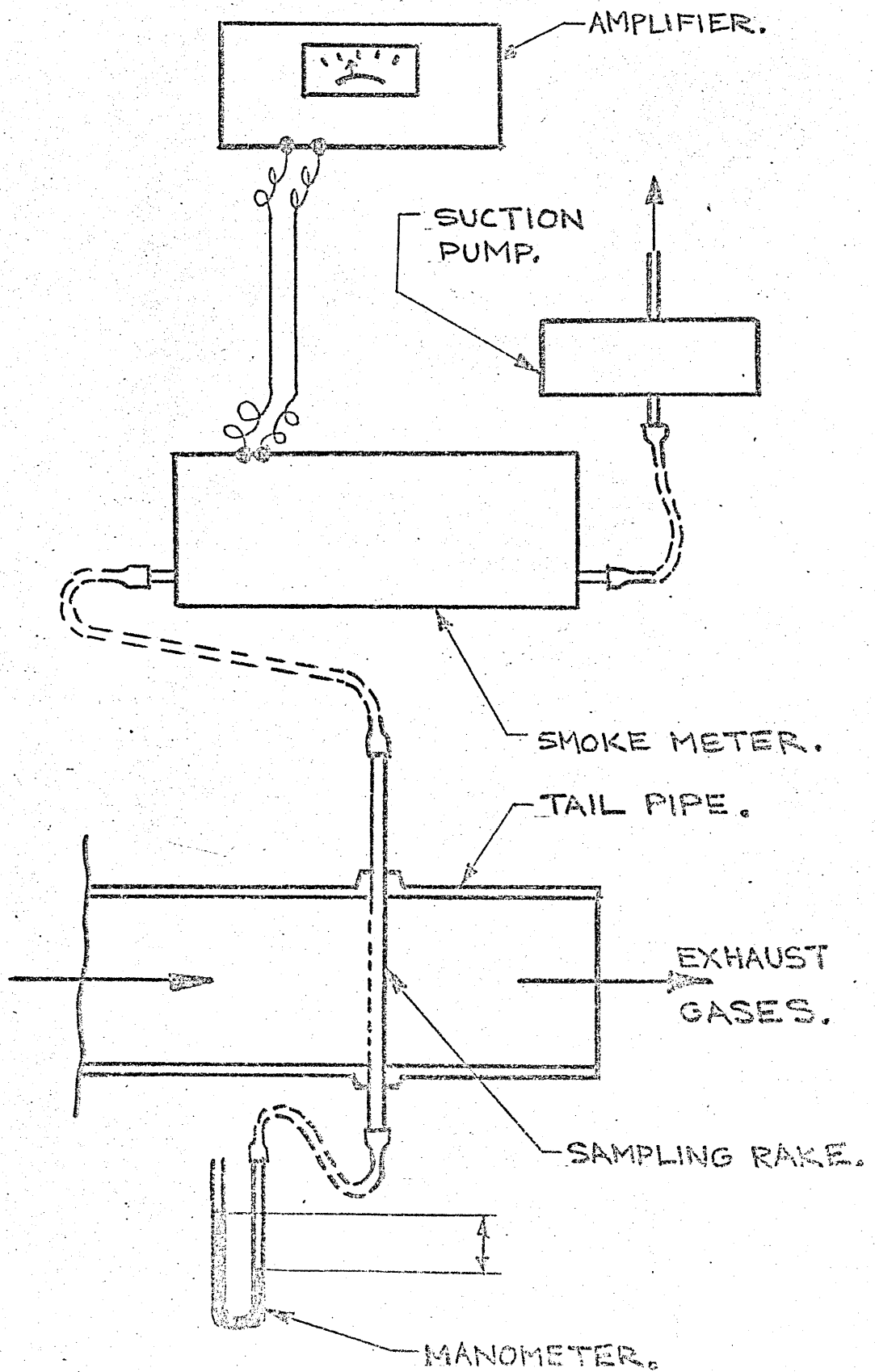


DIAGRAM OF SMOKE METER AND SAMPLING RAKE.

FIG. 24

WINDOW NITROGEN PURGE SYSTEM

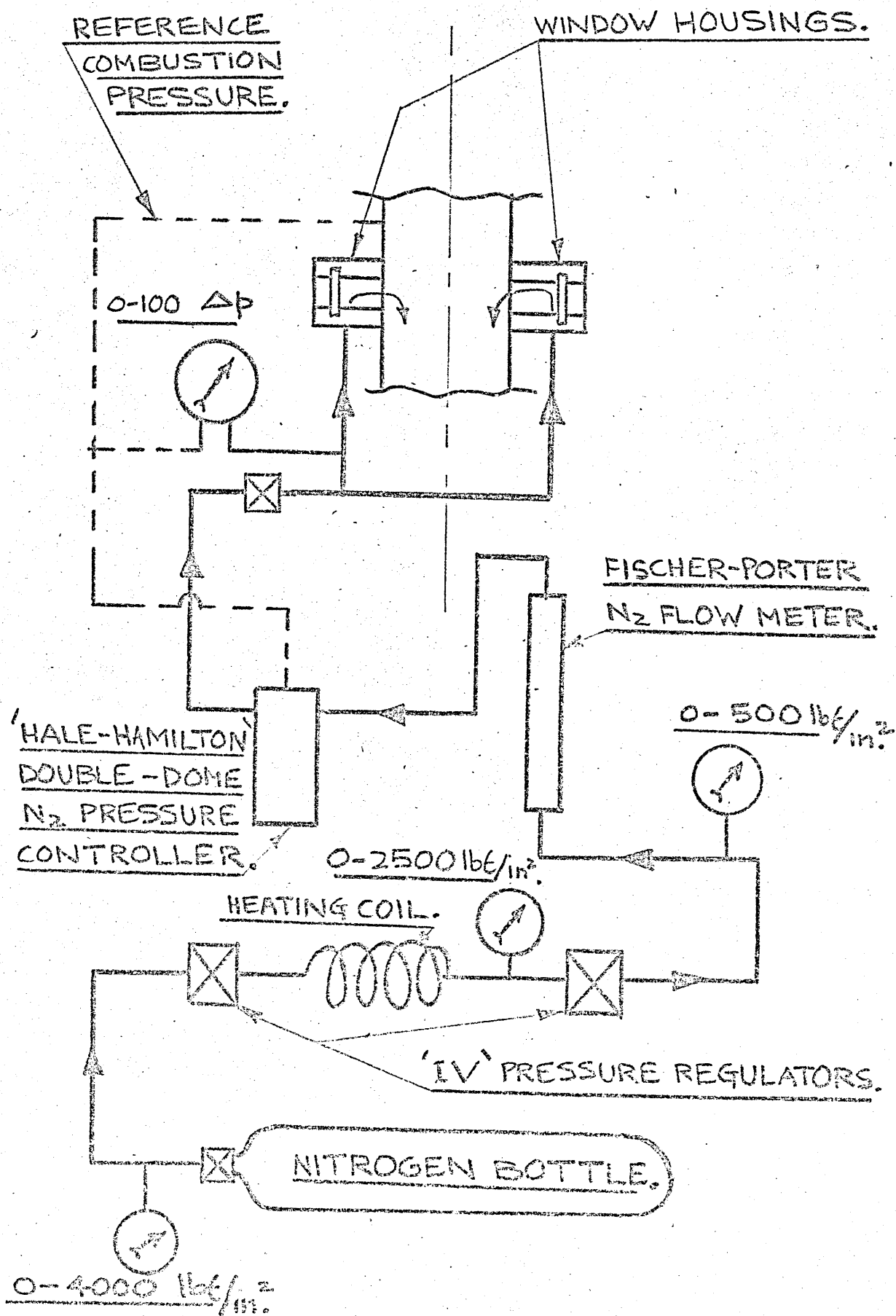


FIG. 25

FUEL SUPPLY SYSTEM

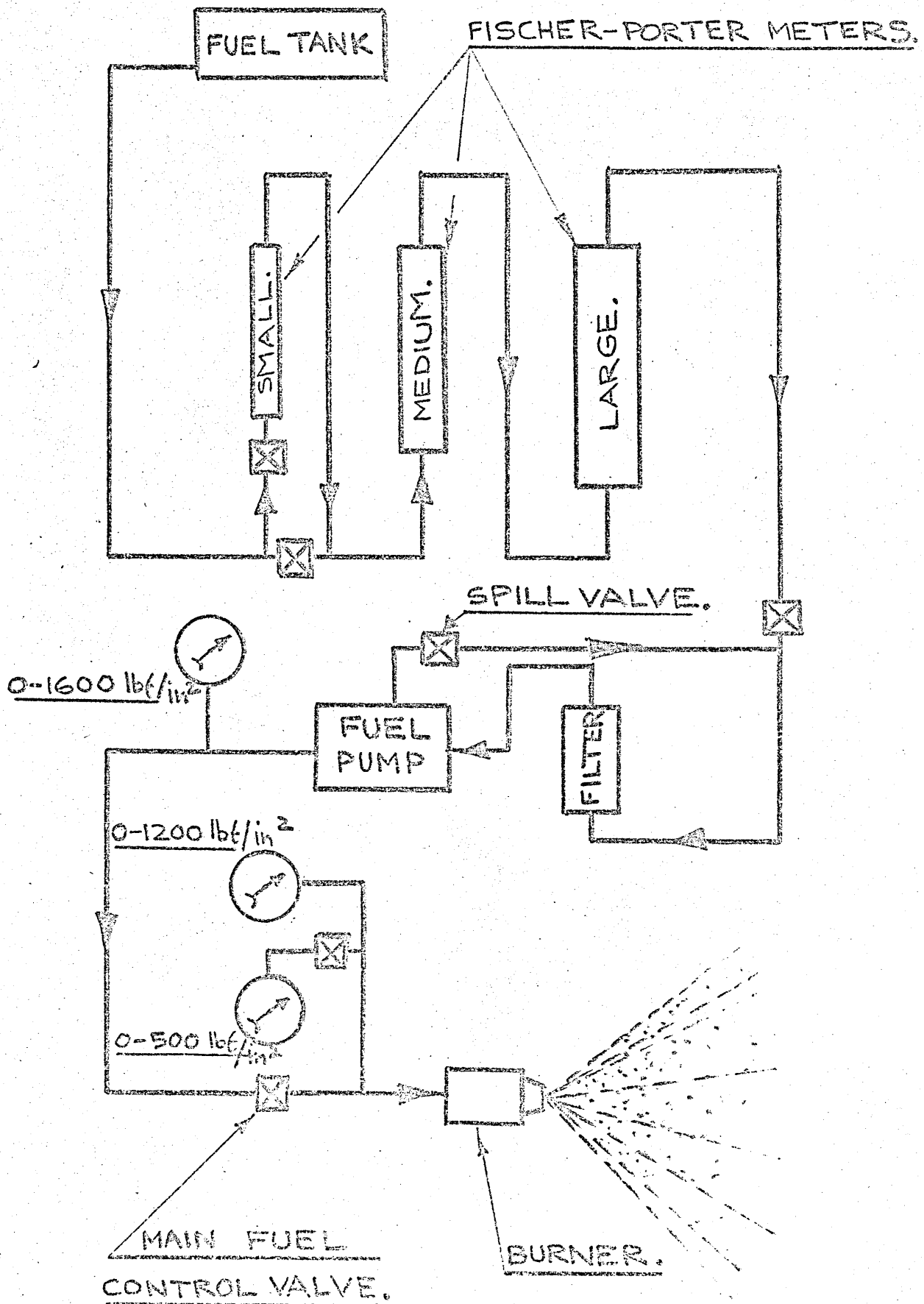
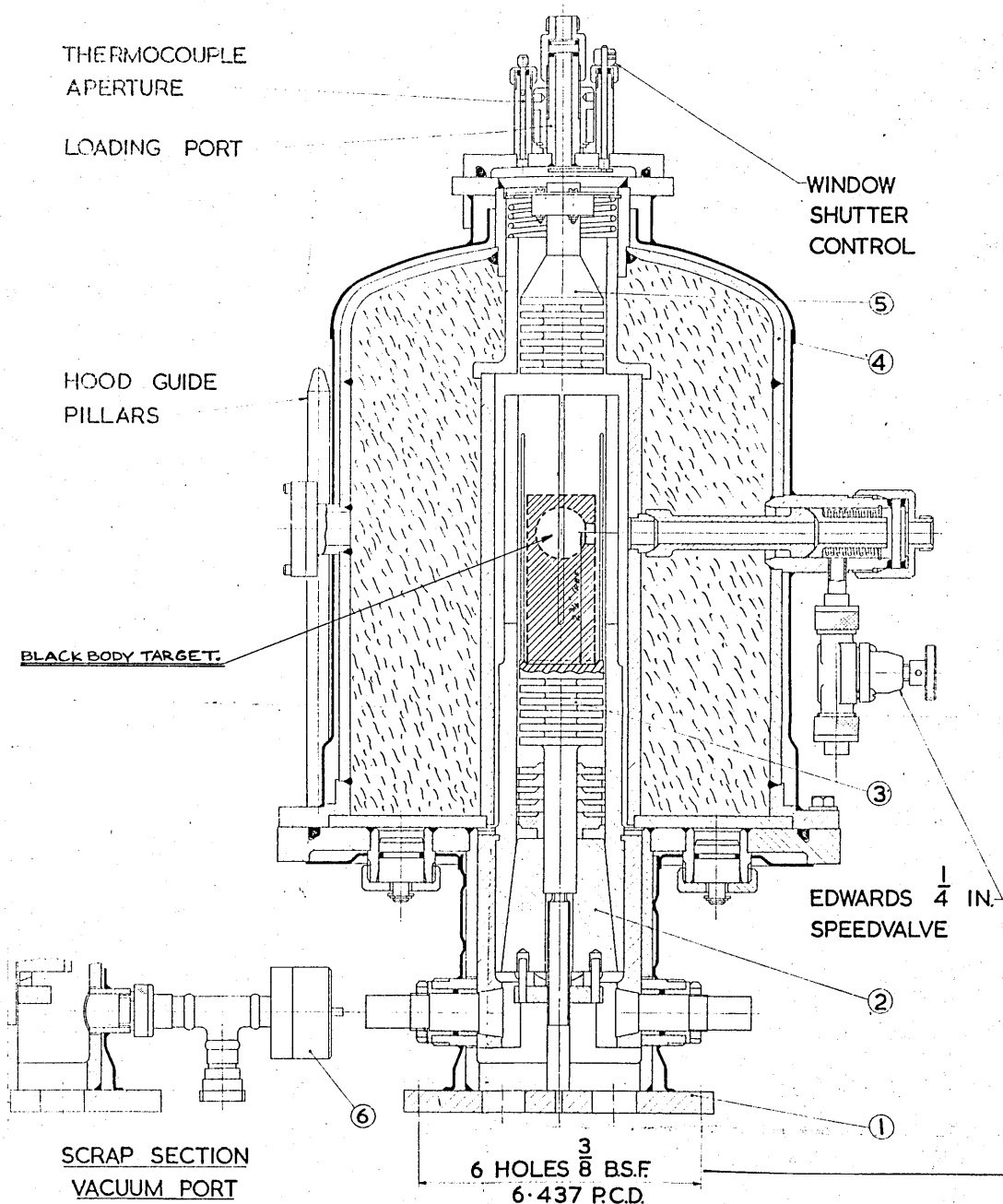


FIG. 26



ALL WATER CONNECTIONS
 $\frac{1}{2}$ IN. FLEXIBLE TUBING

10 K.V.A. VERTICAL FURNACE TYPE I

SPEMBLY TECHNICAL PRODUCTS LTD
 CHATHAM KENT

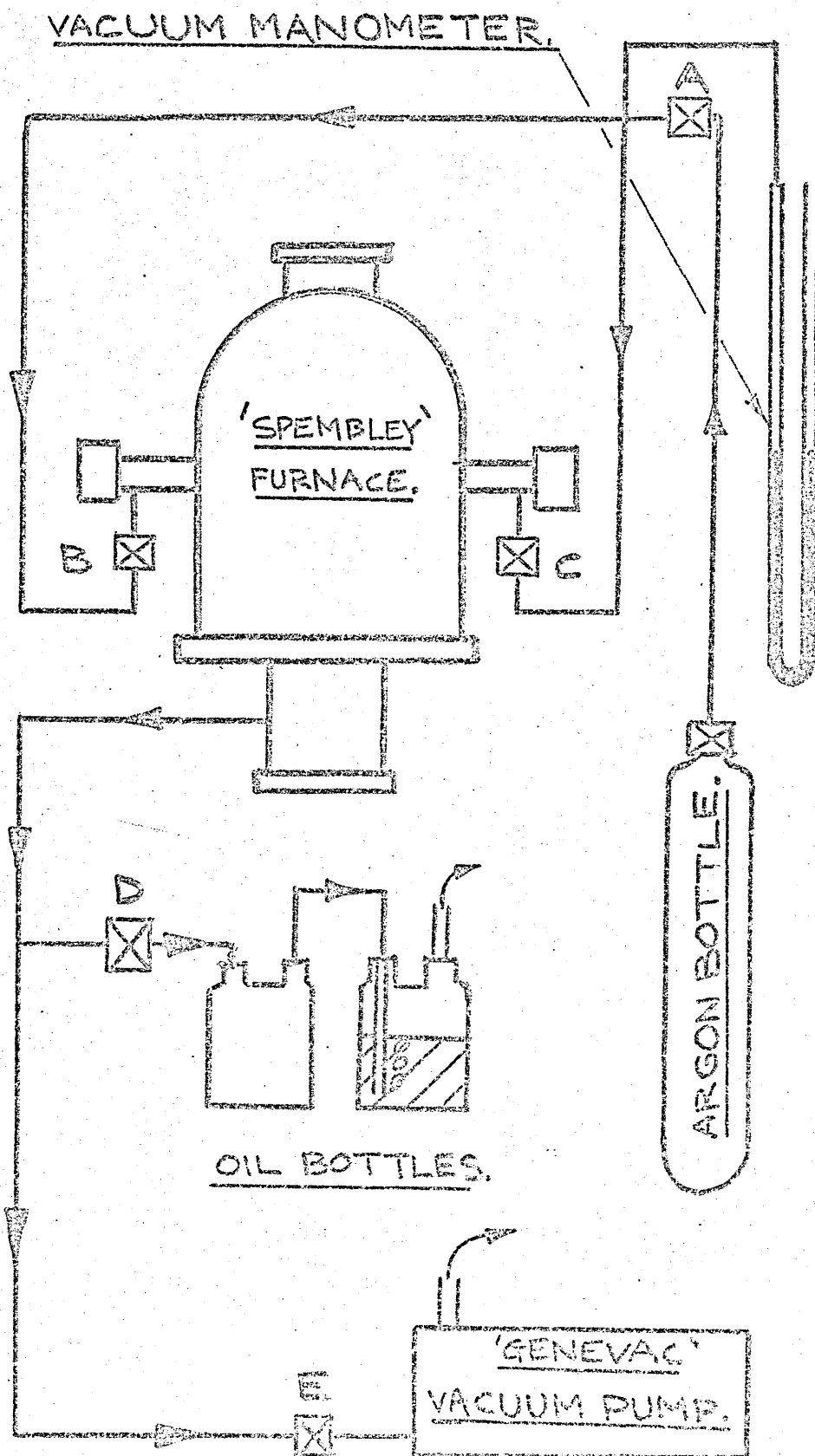
DRG N°

D24425

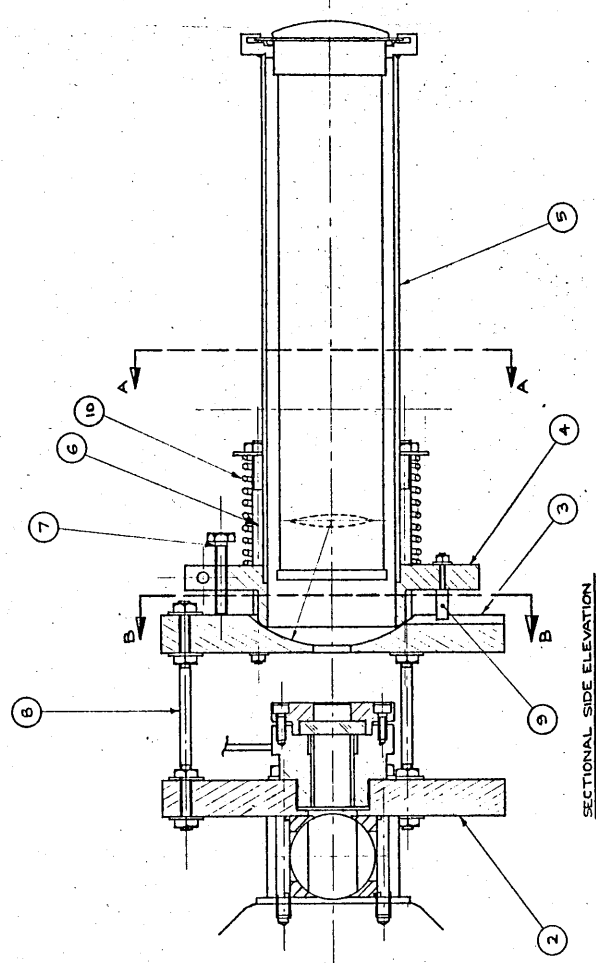
INTERNAL DETAILS OF THE SPEMBLY BLACK-BODY FURNACE.

FIG. 27

BLACK-BODY FURNACE VACUUM-
ARGON SYSTEM.

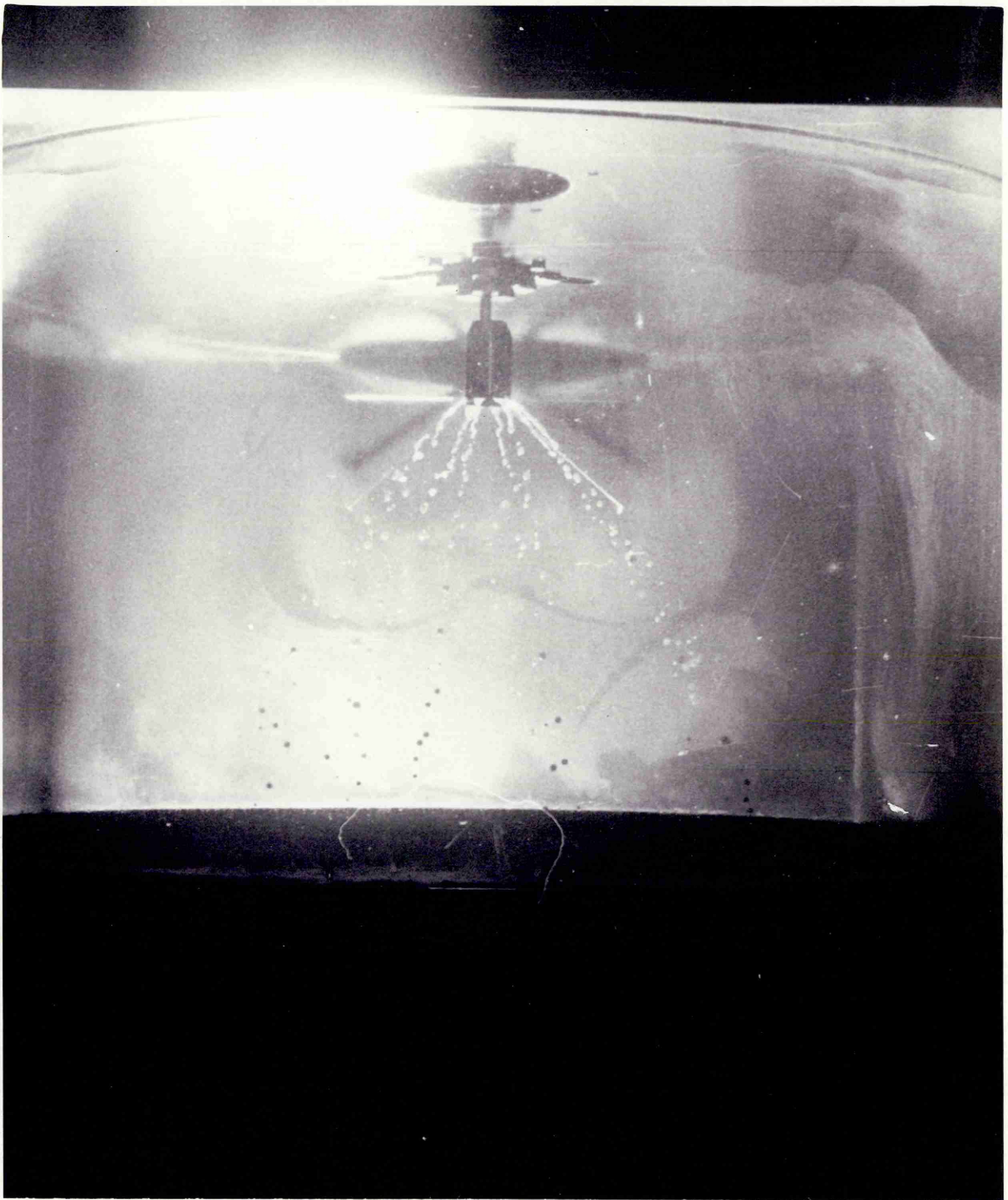


DRAWING NO. FD 300	ISSUE MODIFICATION	A
-----------------------	-----------------------	---



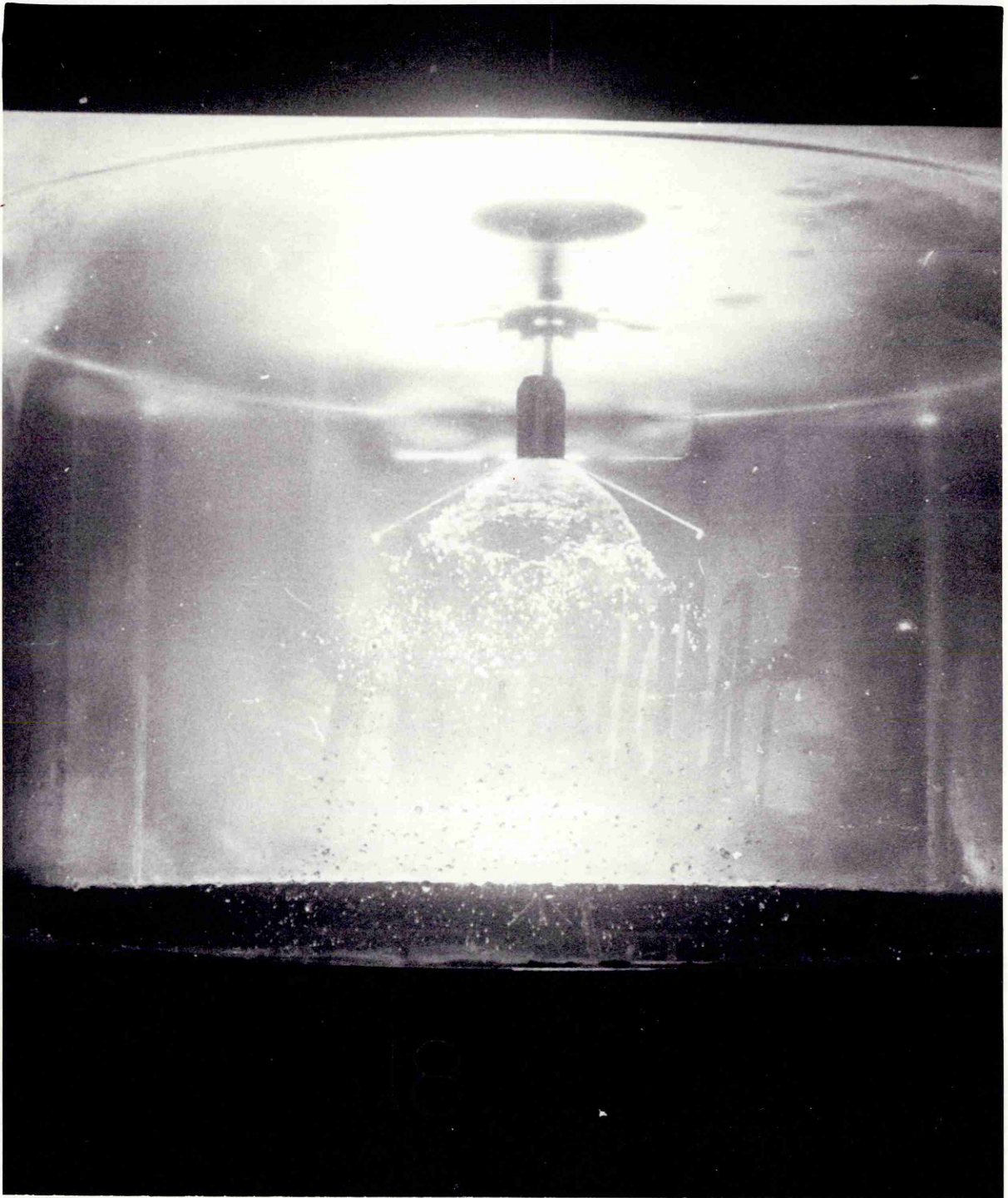
THIRD ANGLE PROJECTION				GENERAL TOLERANCE ON DIMENSIONS			
MACHINED		OTHER DIMENSIONS AS STATED		MACHINED		OTHER DIMENSIONS AS STATED	
FINISH		SEE		FINISH		SEE	
DETAILS		DETAILS		DETAILS		DETAILS	
12	—	LOCKING BOLT.	3	MS			
11	—	CLAMPING BOLT.	3	—			WASSE 1/4 LONGS TO SUIT.
10	—	SPRING PEG	3	—			
9	—	PD B3005	3	—			
8	—	POTANCE STUDS	3	—			
7	—	PD B3011	3	—			
6	—	ADJUSTING SCREW.	3	1 MS			WASSE 1/2 LONG.
5	—	PD B3027 SPRING RETAINING STUD	3	—			
4	—	PC B3003 PYROMETER TUBE.	1	—			
3	—	PC B3004 ADJUSTING PLATE.	1	—			
2	—	PC B3002 SEATING PLATE.	1	—			
1	—	PC B3000 MOUNTING BLOCK.	1	—			
ITEM	PART	DESCRIPTION	QTY	UNIT	OFF MAT.	1/2	FINISH.
DRAWN				CHECK APPROVED			
TITLE				HIGH PREASURE FLAME PROXIMITY.			
ISSUED BY				G.A. OF LAND PYROMETER MOUNTING.			
DRAWING No.				PB 8300			
THE COLLEGE OF AERONAUTICS				SHEET OF 1 SHEETS			
CRAMFIELD							

FIG.30



KEROSENE SPRAY FROM THE AIRBLAST ATOMISER
WITHOUT AIR ASSISTANCE AT FUEL PRESSURE
20 lbf./in². (Flow Number = 2.0).

FIG. 31



KEROSENE SPRAY FROM THE AIRBLAST ATOMISER
WITHOUT AIR ASSISTANCE AT FUEL PRESSURE
100 lbf./in². (Flow Number = 2.0)

FIG. 32



KEROSENE SPRAY FROM THE AIRBLAST ATOMISER
WITHOUT AIR ASSISTANCE AT FUEL PRESSURE
300 lbf./in². (Flow Number = 2.0)

OPTICAL SIGHT PATH FOR THE SCHMIDT METHOD.

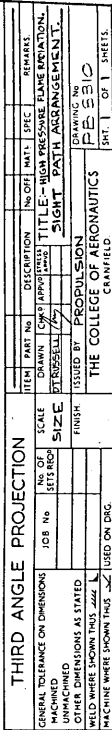


FIG. 34

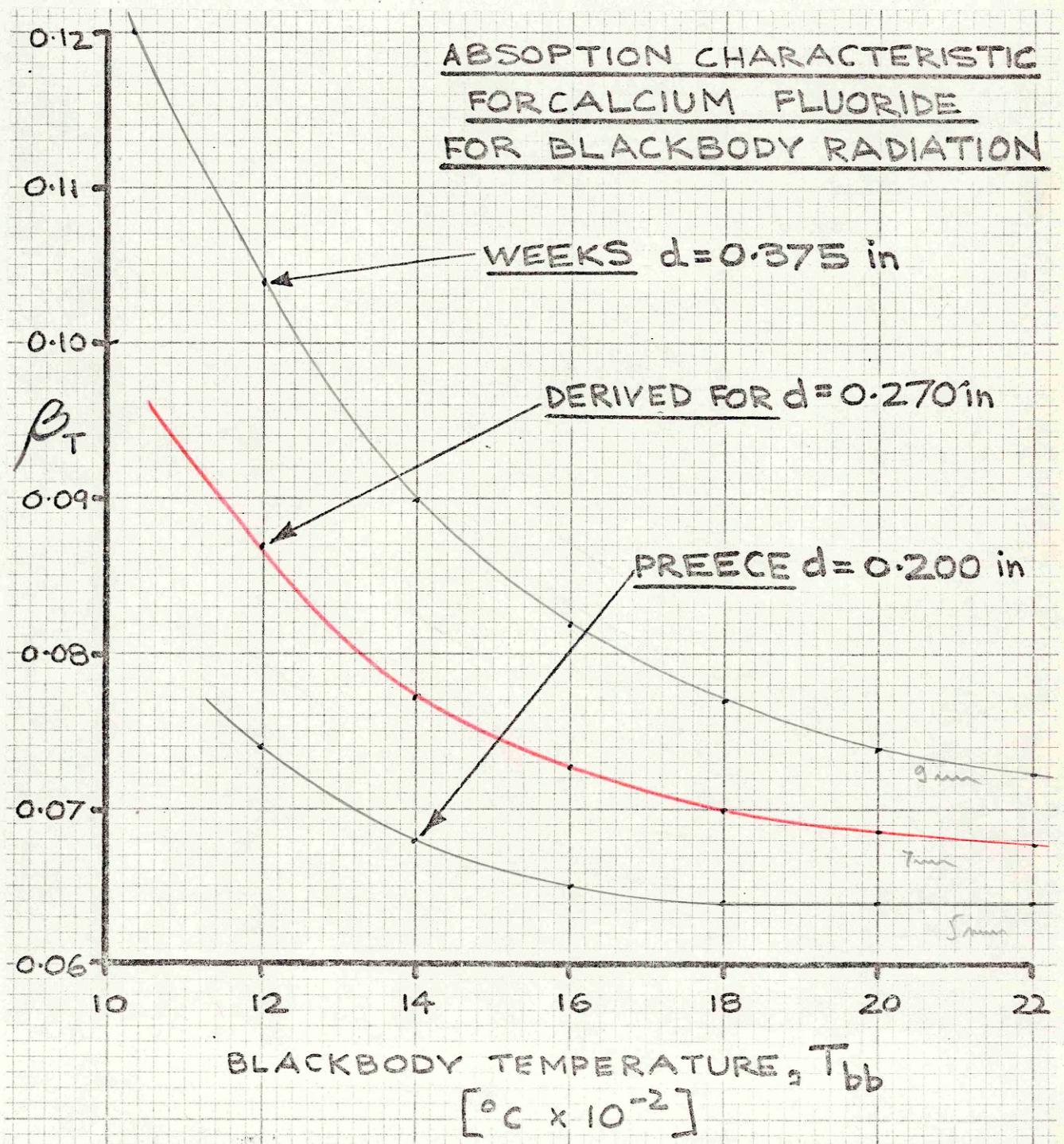


FIG. 35

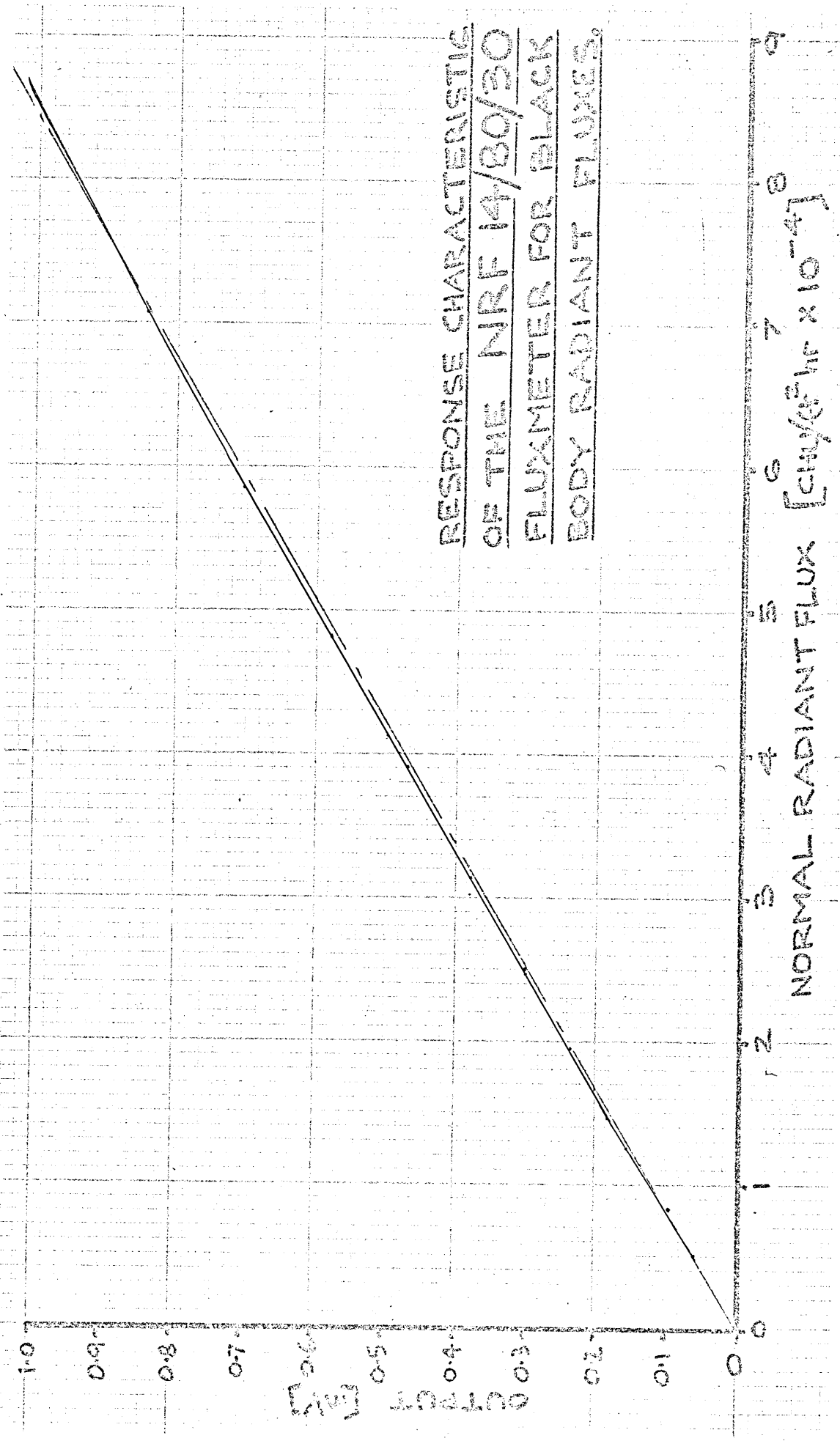


FIG. 36

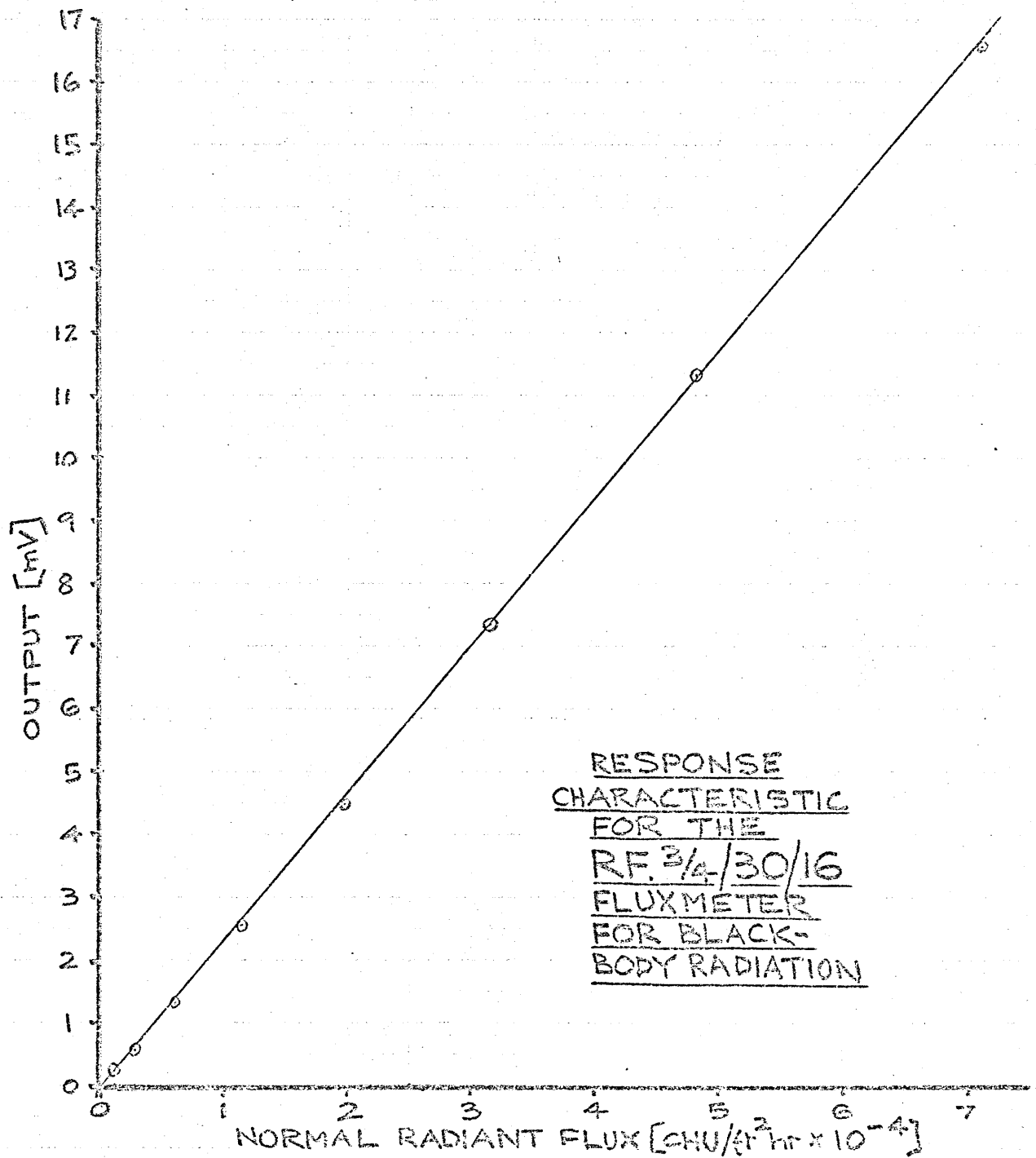


FIG. 37

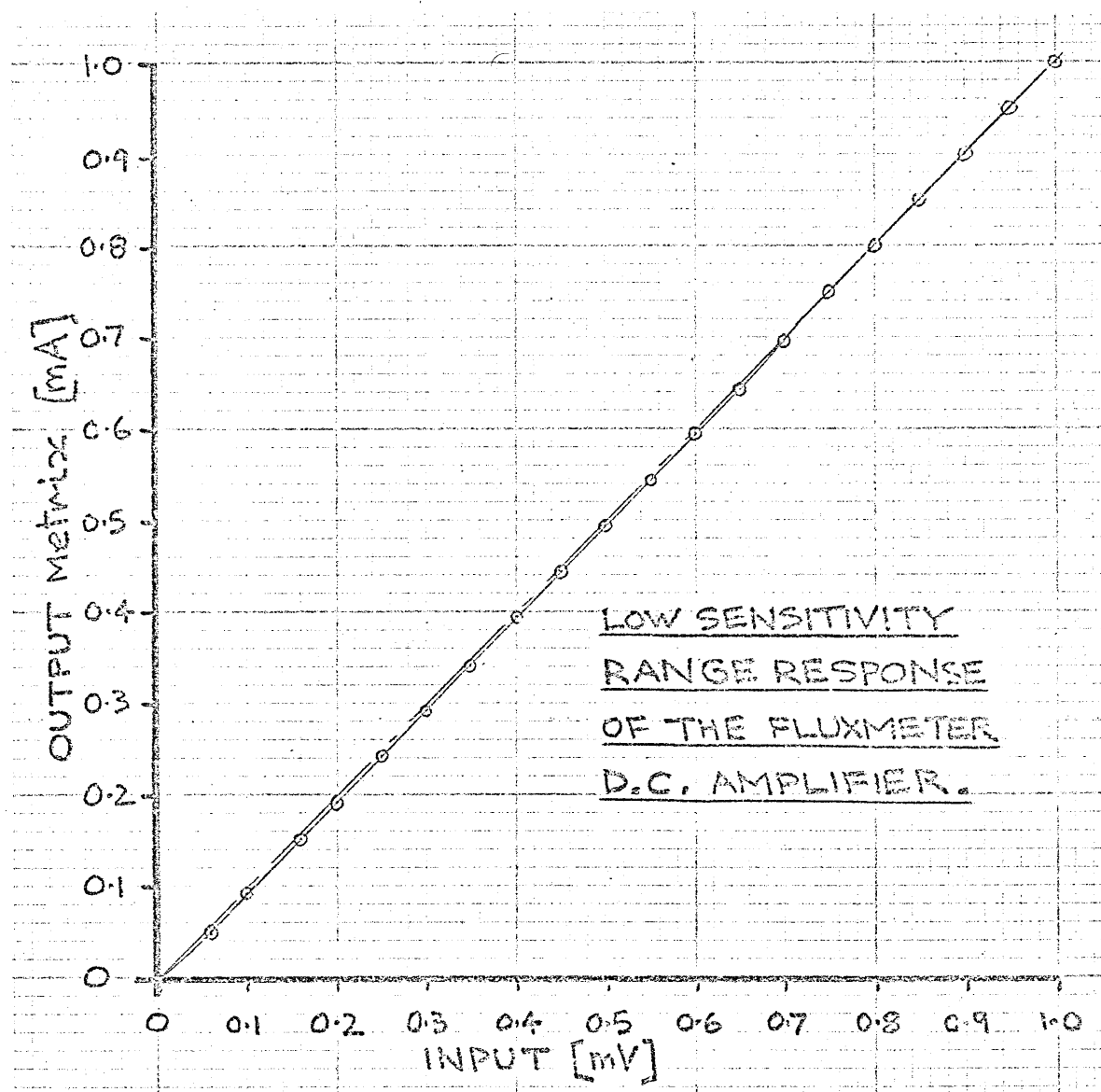


FIG. 38

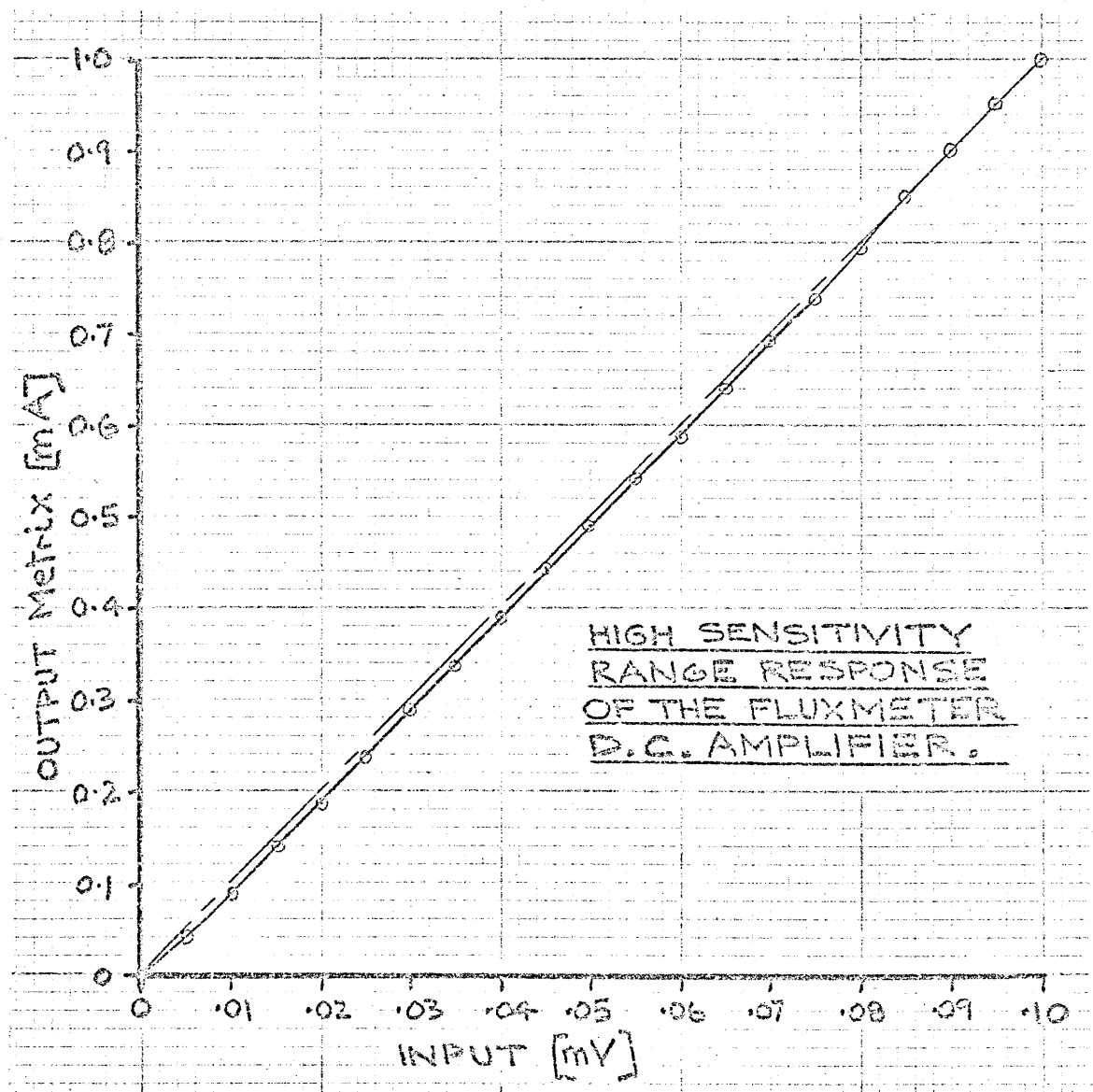


FIG. 39

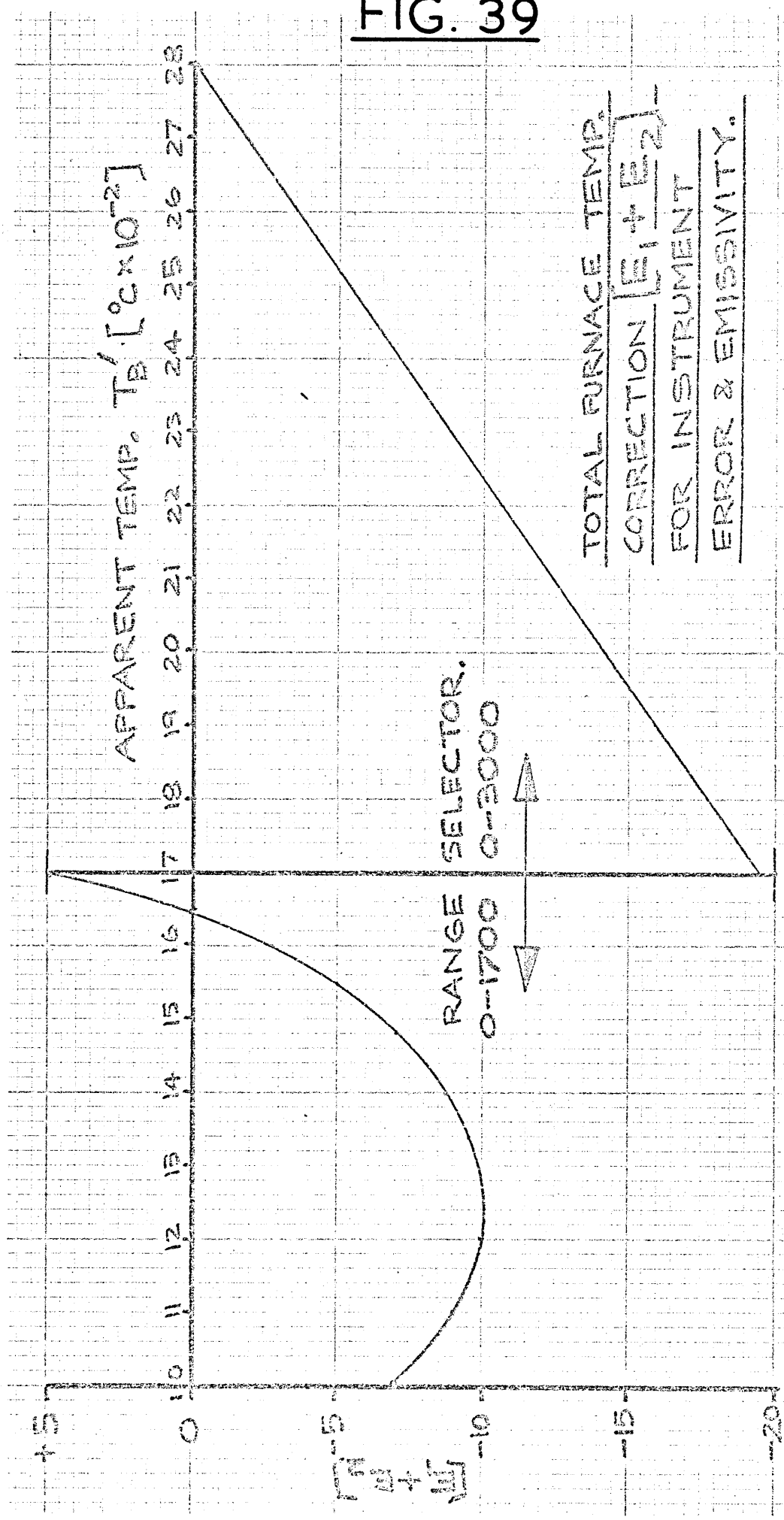
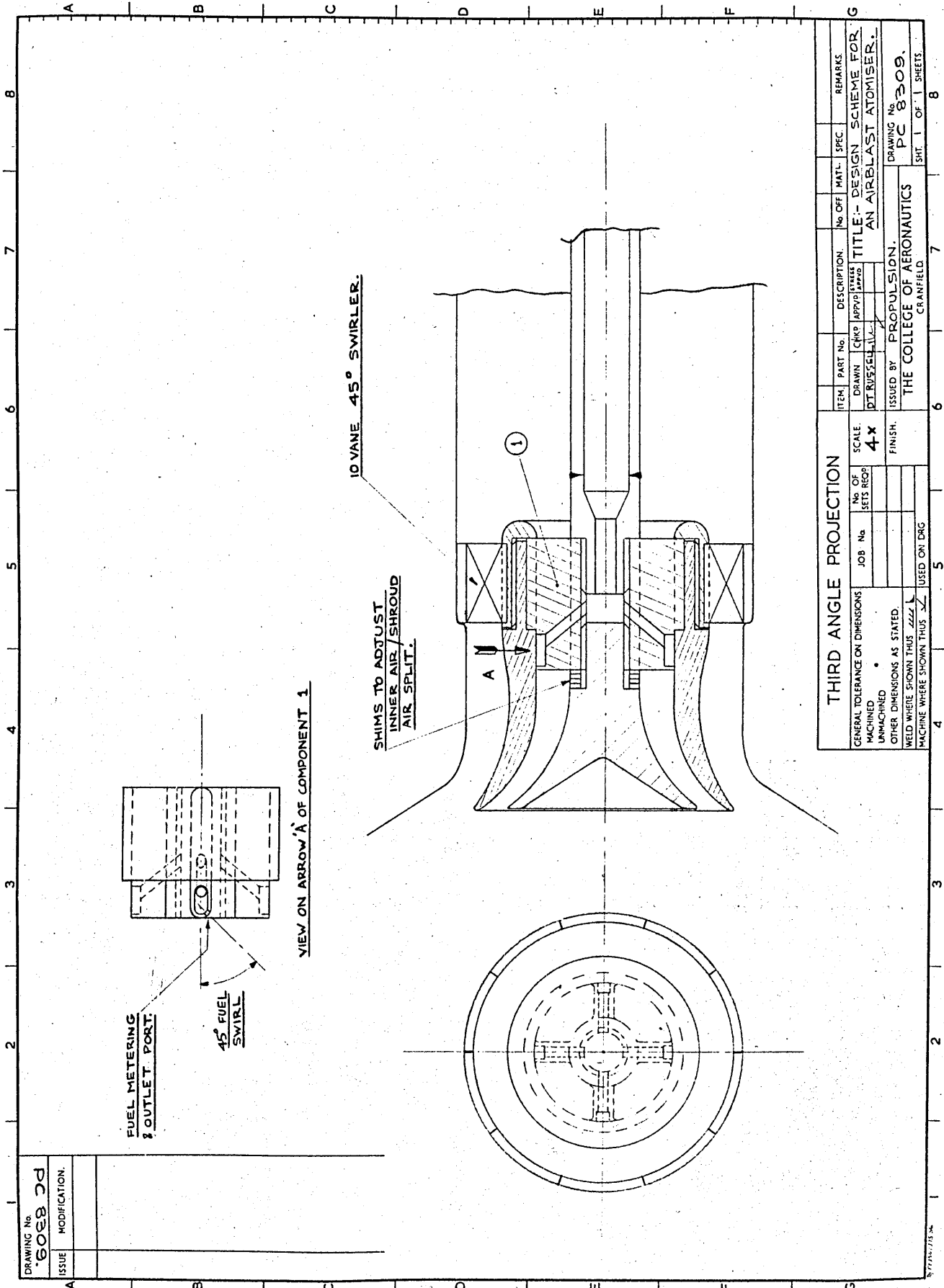
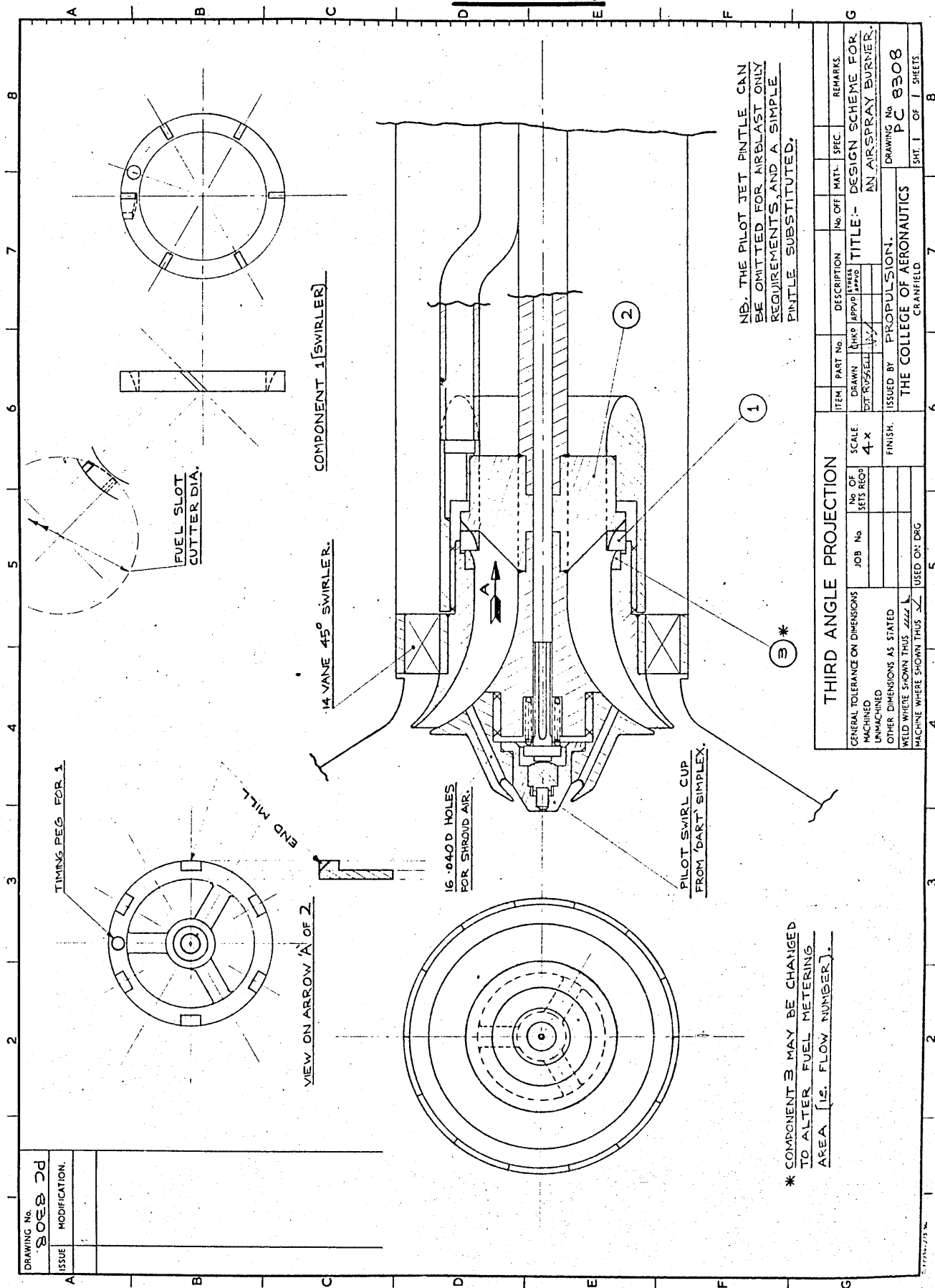


FIG. 40



THE SIMPLEX AIRBLAST ATOMISER.

FIG. 41

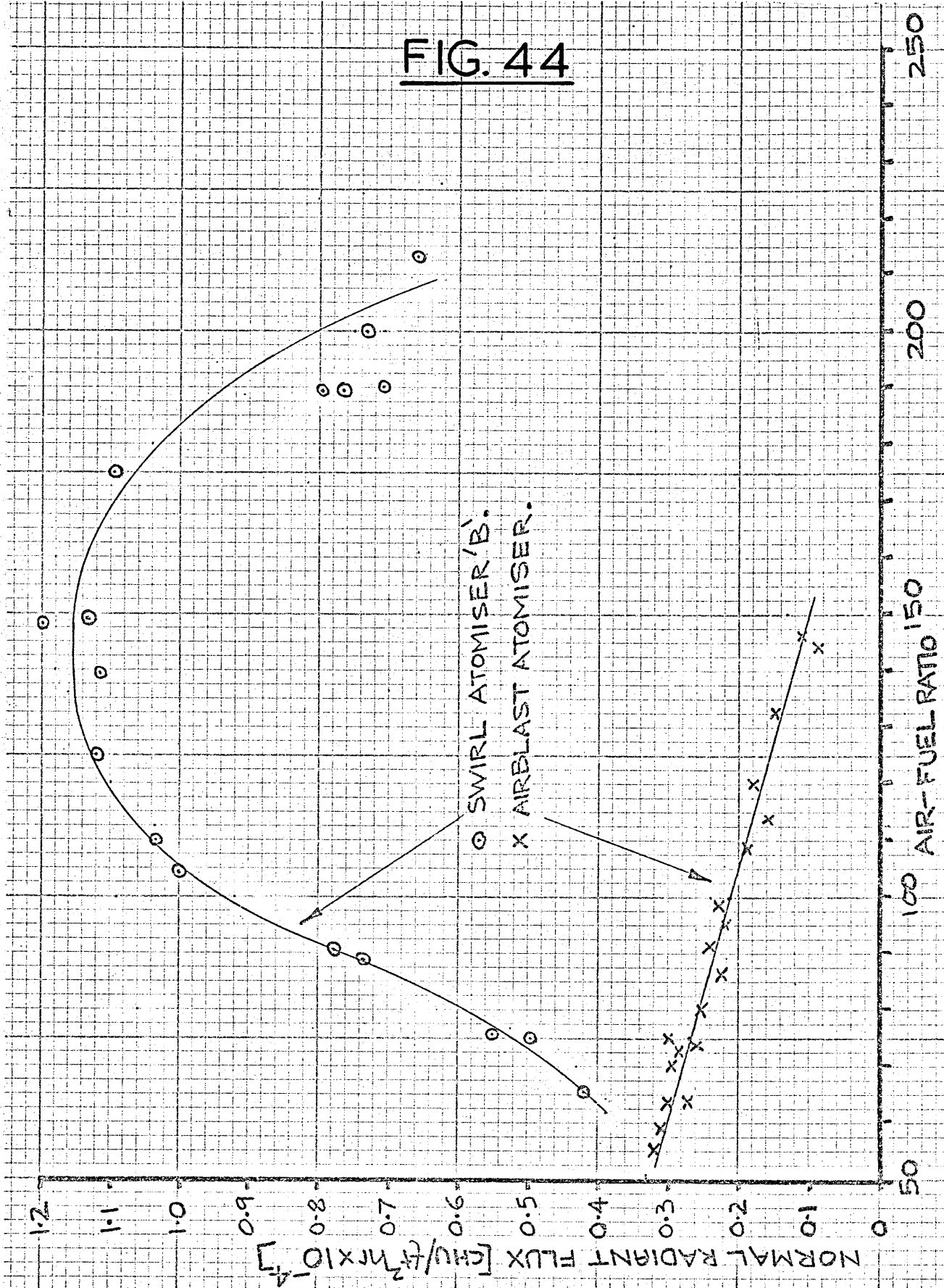


THE DUPLEX AIRBLAST/SWIRL ATOMISER.

FIGS. 42 & 43

THESE APPEAR ON
THE FRONTISPIECE.

FIG. 44

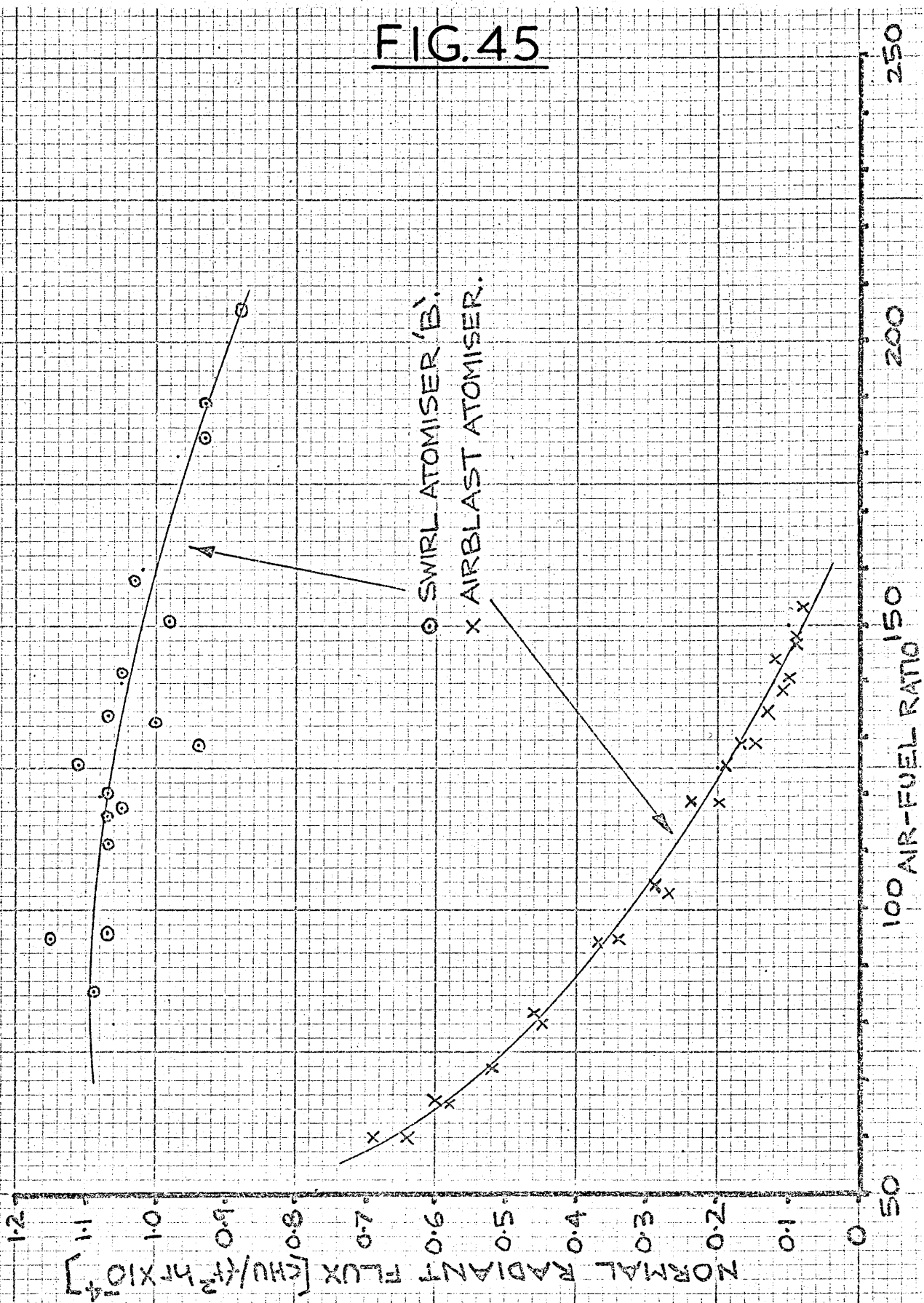


TOTAL FLAME RADIATION FOR AIRBLAST AND SWIRL ATOMISERS:-

COMBUSTION PRESSURE	=	70 lbf./in ² .
AIR MASS FLOW RATE	=	2.1 lb./sec.
AIR INLET TEMPERATURE	=	287° K.
(nominal conditions).		

From Tables 1 and 2.

FIG.45



TOTAL FLAME RADIATION FOR AIRBLAST AND SWIRL ATOMISERS:-

COMBUSTION PRESSURE = 135 lbf./in².
 AIR MASS FLOW RATE = 4.44 lb./sec.
 AIR INLET TEMPERATURE = 293° K.
 (nominal conditions).

From Tables 3 and 4.

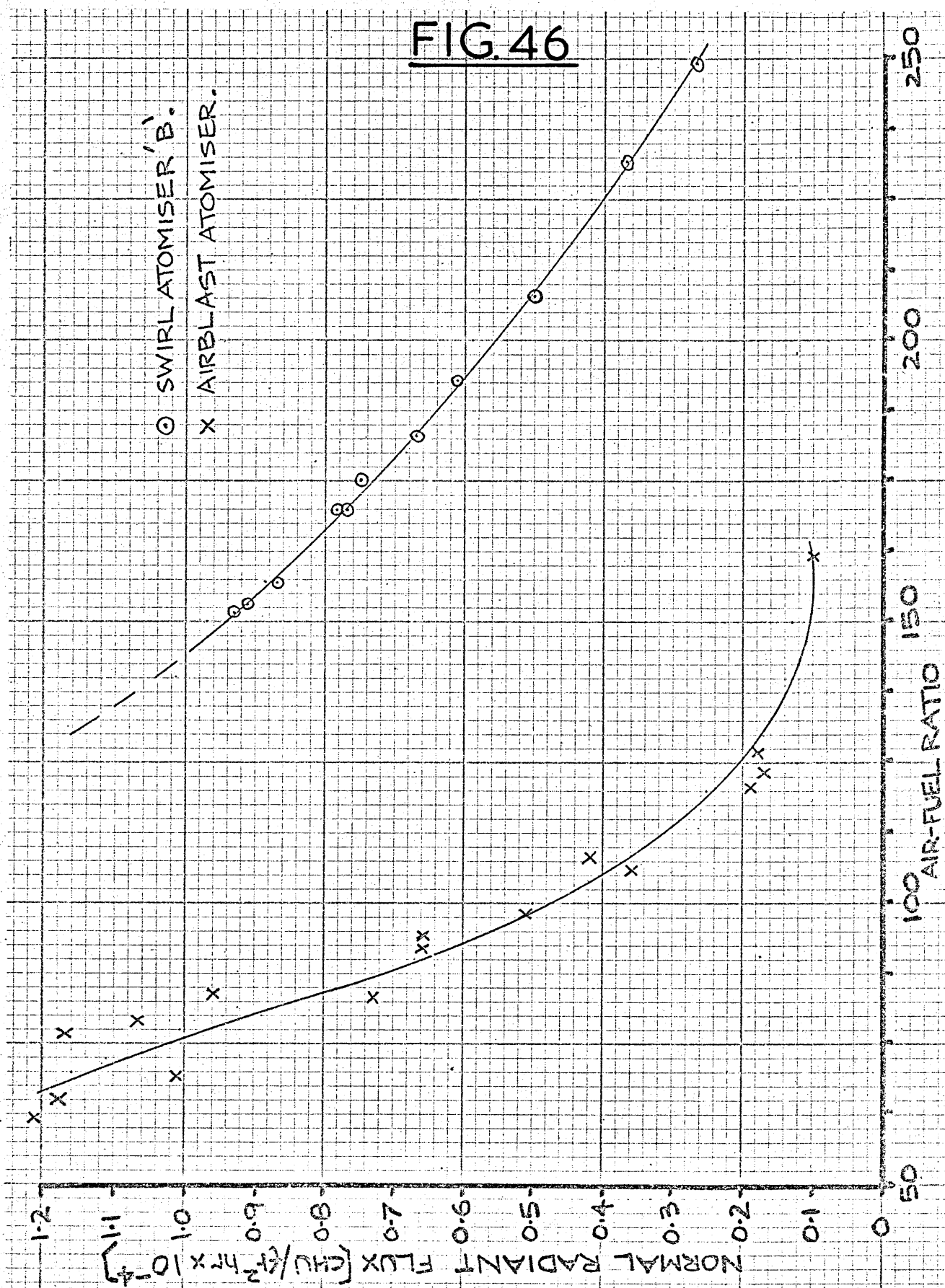
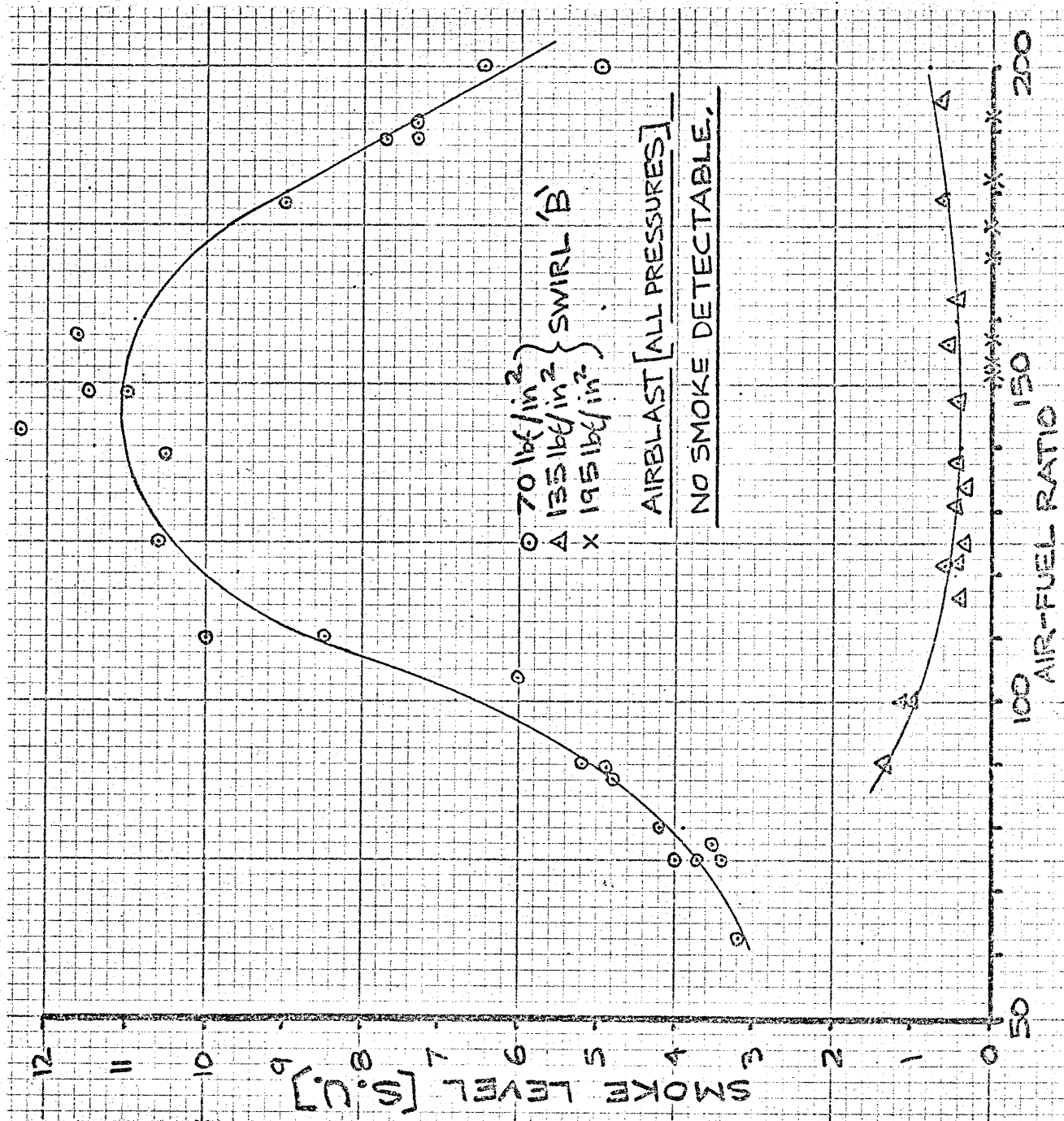


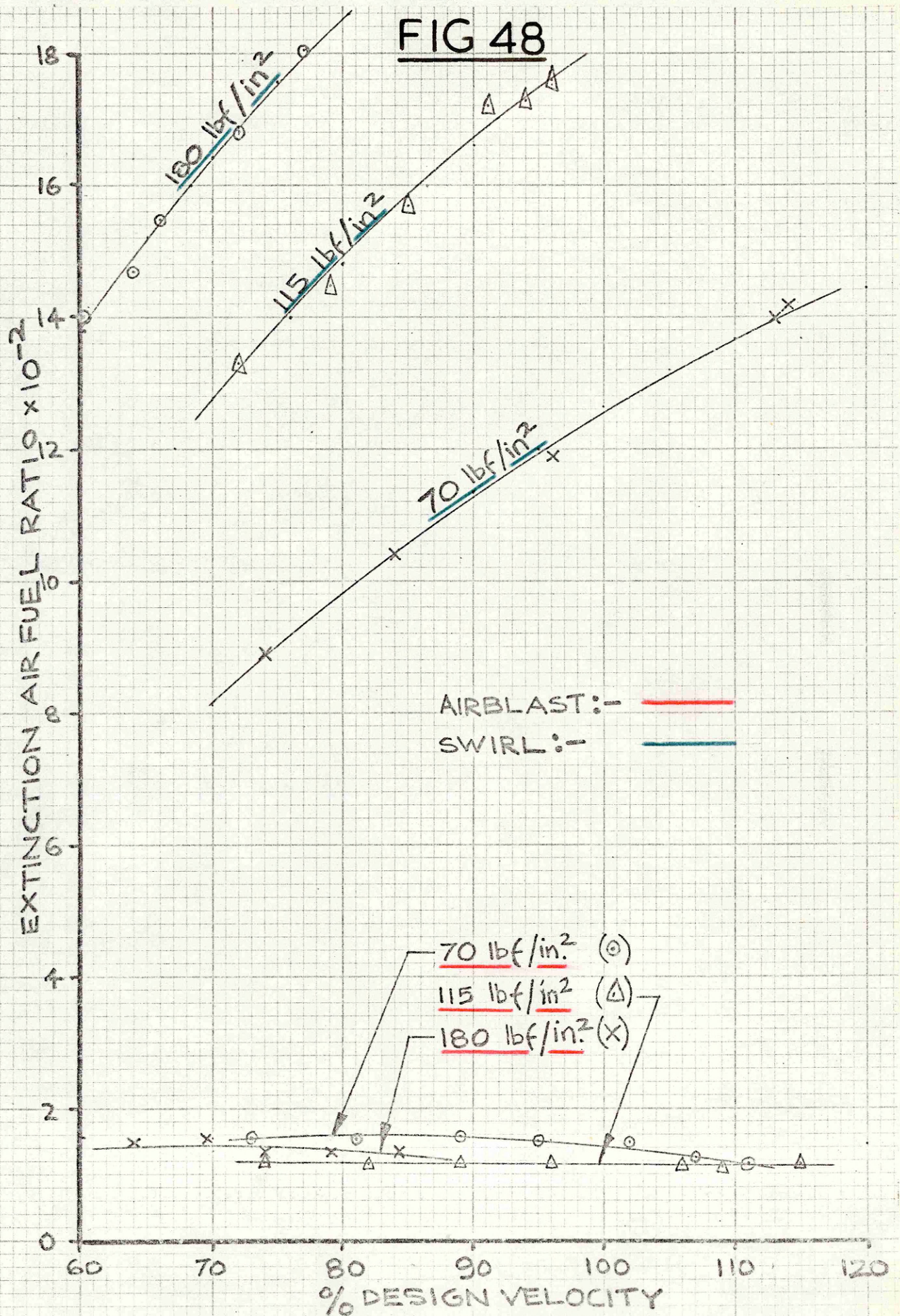
FIG. 47



EXHAUST SMOKE LEVELS FOR AIRBLAST AND SWIRL ATOMISERS.

From Tables 1 to 6.

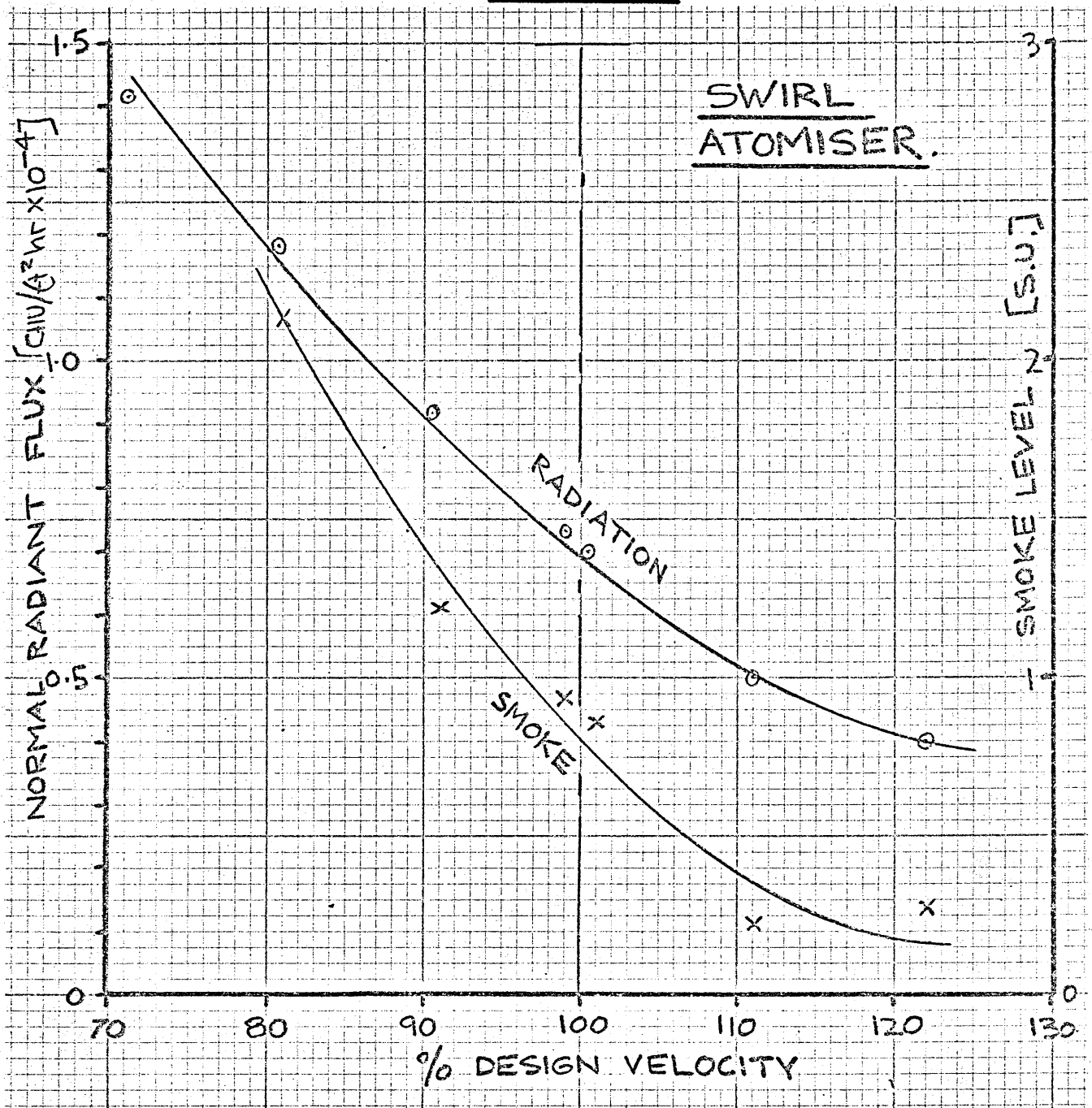
FIG 48



WEAK STABILITY LIMITS FOR AIRBLAST AND SWIRL ATOMISERS.

From Tables 9 to 14.

FIG. 49

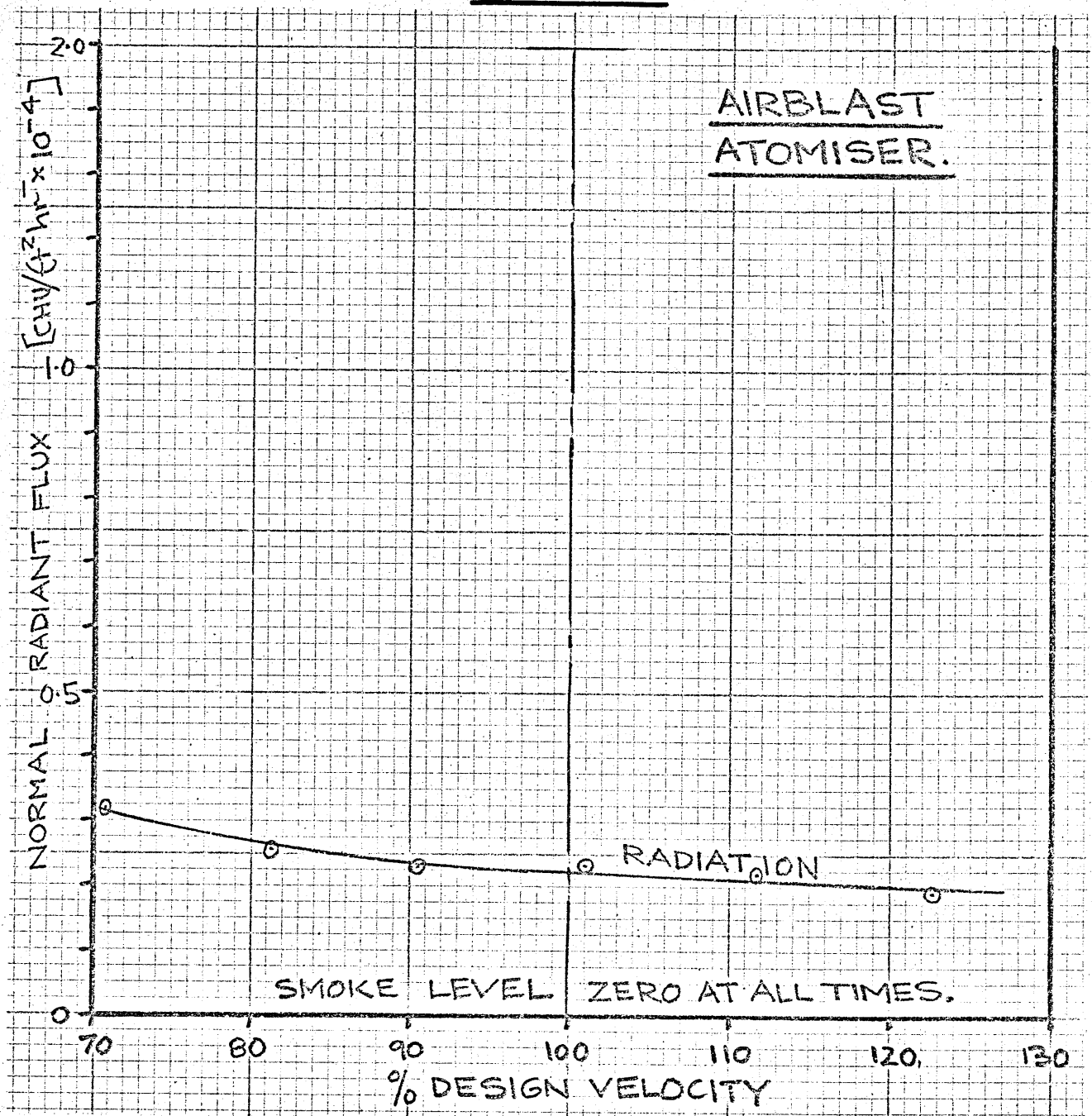


EFFECT OF VELOCITY ON FLAME TOTAL RADIATION AND
EXHAUST SMOKE LEVEL FOR SWIRL ATOMISER B (FN = .77).

COMBUSTION PRESSURE = 79 lbf./in².
AIR FUEL RATIO = 131.

From Table 7.

FIG. 50

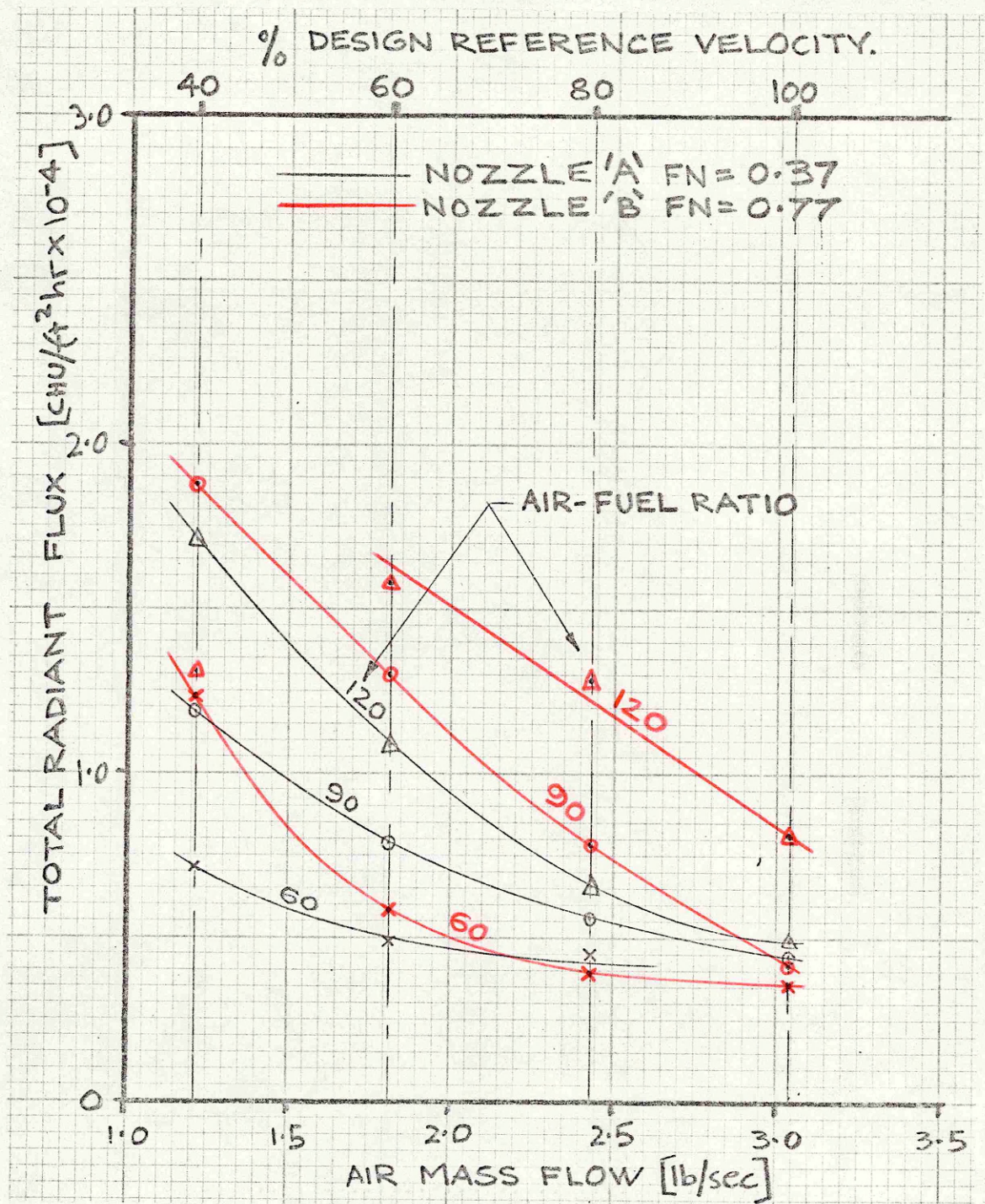


EFFECT OF VELOCITY ON FLAME RADIATION AND EXHAUST
SMOKE LEVEL FOR THE AIRBLAST ATOMISER.

COMBUSTION PRESSURE = 78 lbf./in².
AIR FUEL RATIO = 83

From Table 8.

FIG. 51



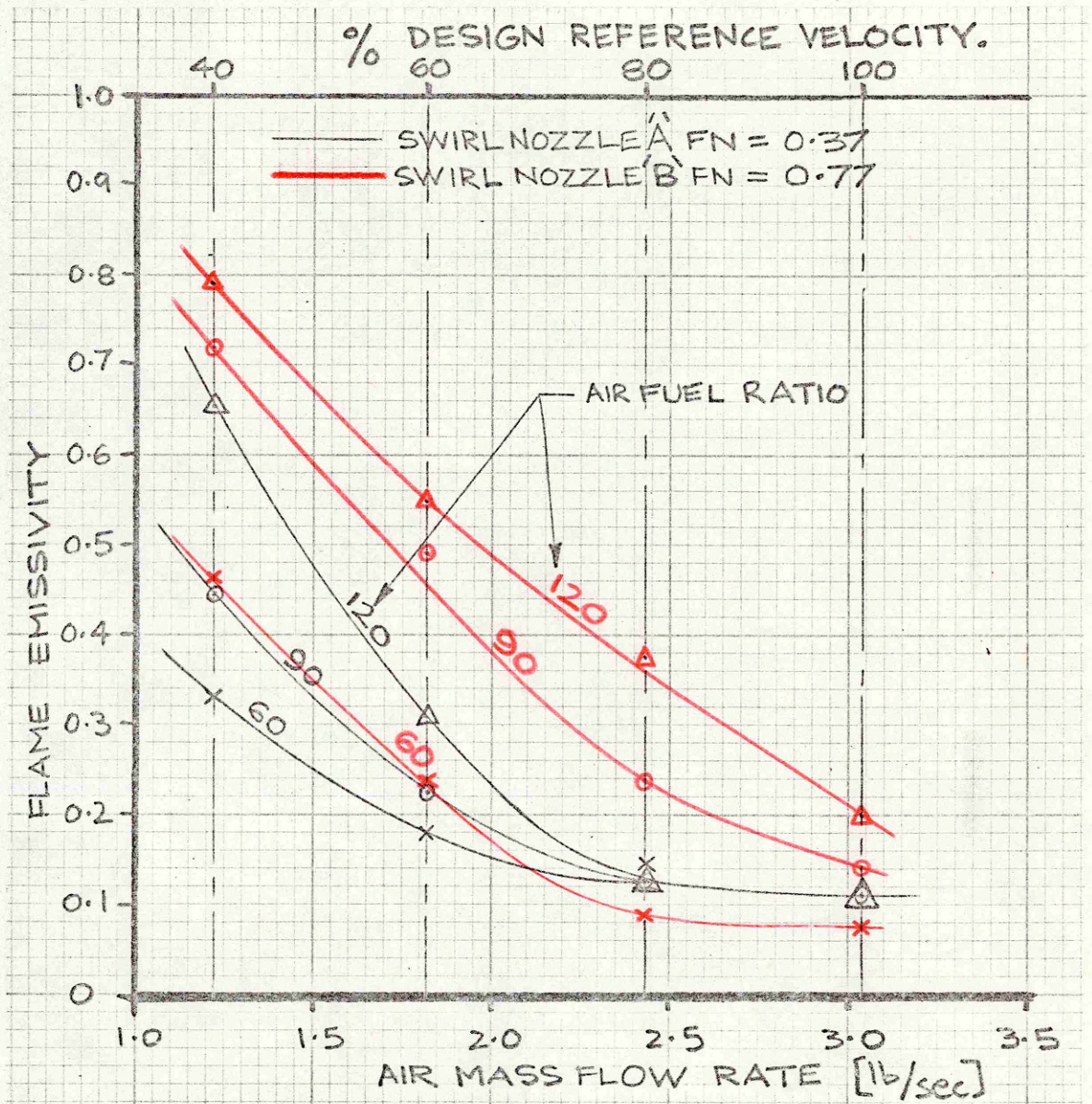
EFFECT OF SWIRL ATOMISER FLOW NUMBER ON FLAME
TOTAL RADIATION:

COMBUSTION PRESSURE = 60 lbf./in².

AIR INLET TEMPERATURE = 300°K.
(nominal conditions).

From Tables 15 and 16.

FIG. 52

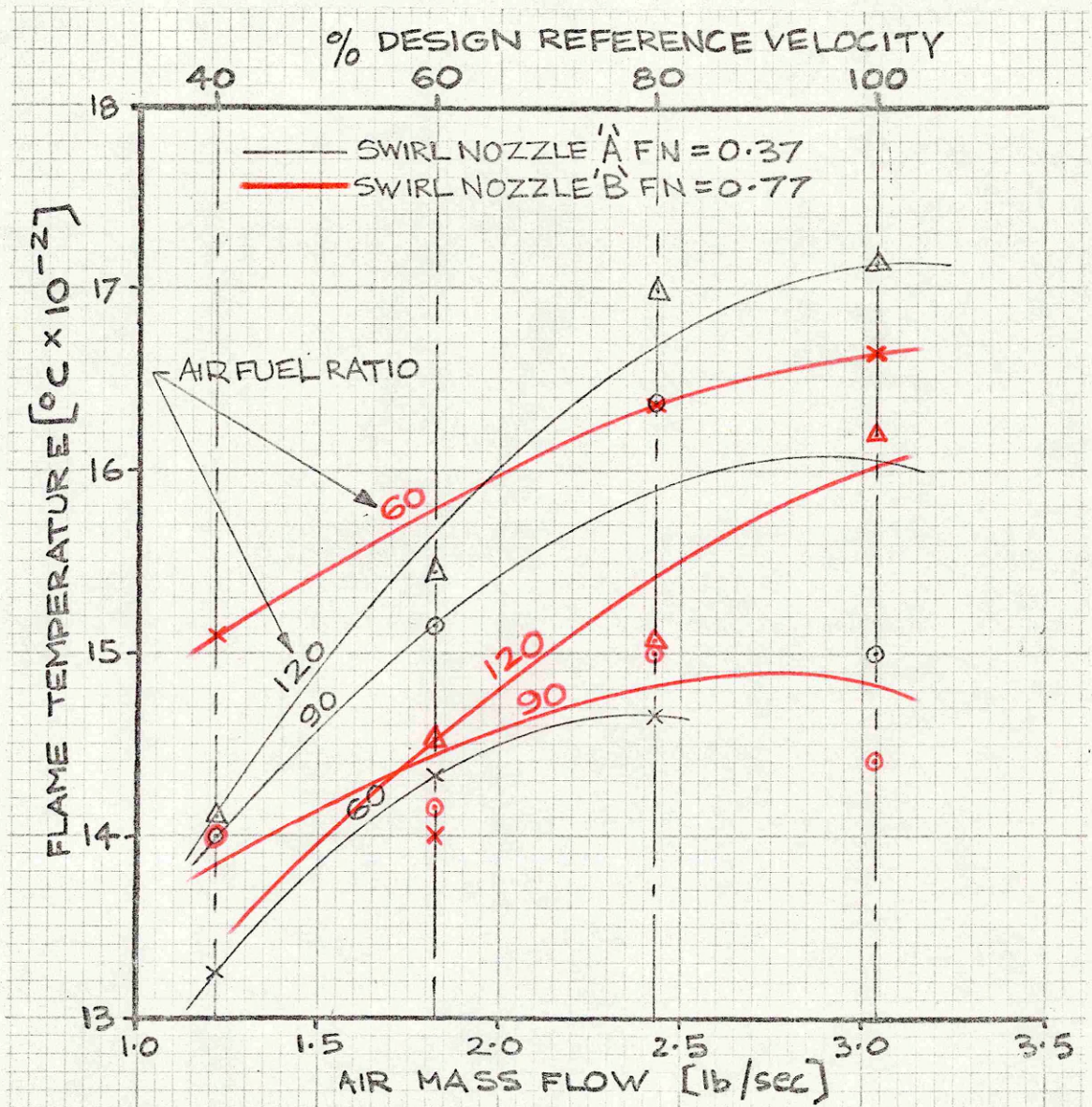


EFFECT OF SWIRL ATOMISER FLOW NUMBER ON FLAME
TOTAL EMISSIVITY:

COMBUSTION PRESSURE = 60 lbf./in².
AIR INLET TEMPERATURE = 3000° K.
(nominal conditions).

From Tables 15 and 16.

FIG. 53

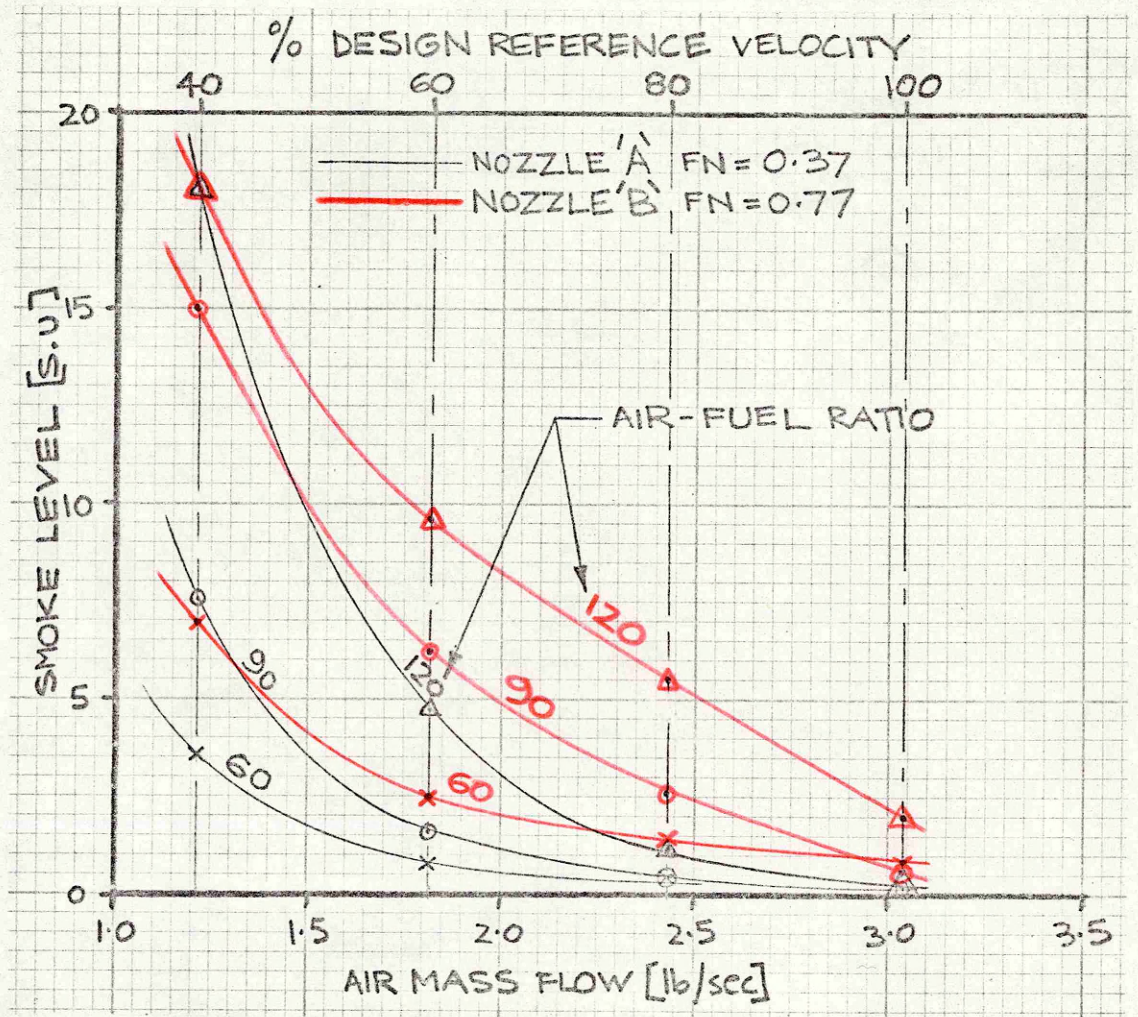


EFFECT OF SWIRL ATOMISER FLOW NUMBER ON FLAME TEMPERATURE:

COMBUSTION PRESSURE = 60 lbf./in².
 AIR INLET TEMPERATURE = 300° K.
 (nominal conditions).

From Tables 15 and 16.

FIG. 54

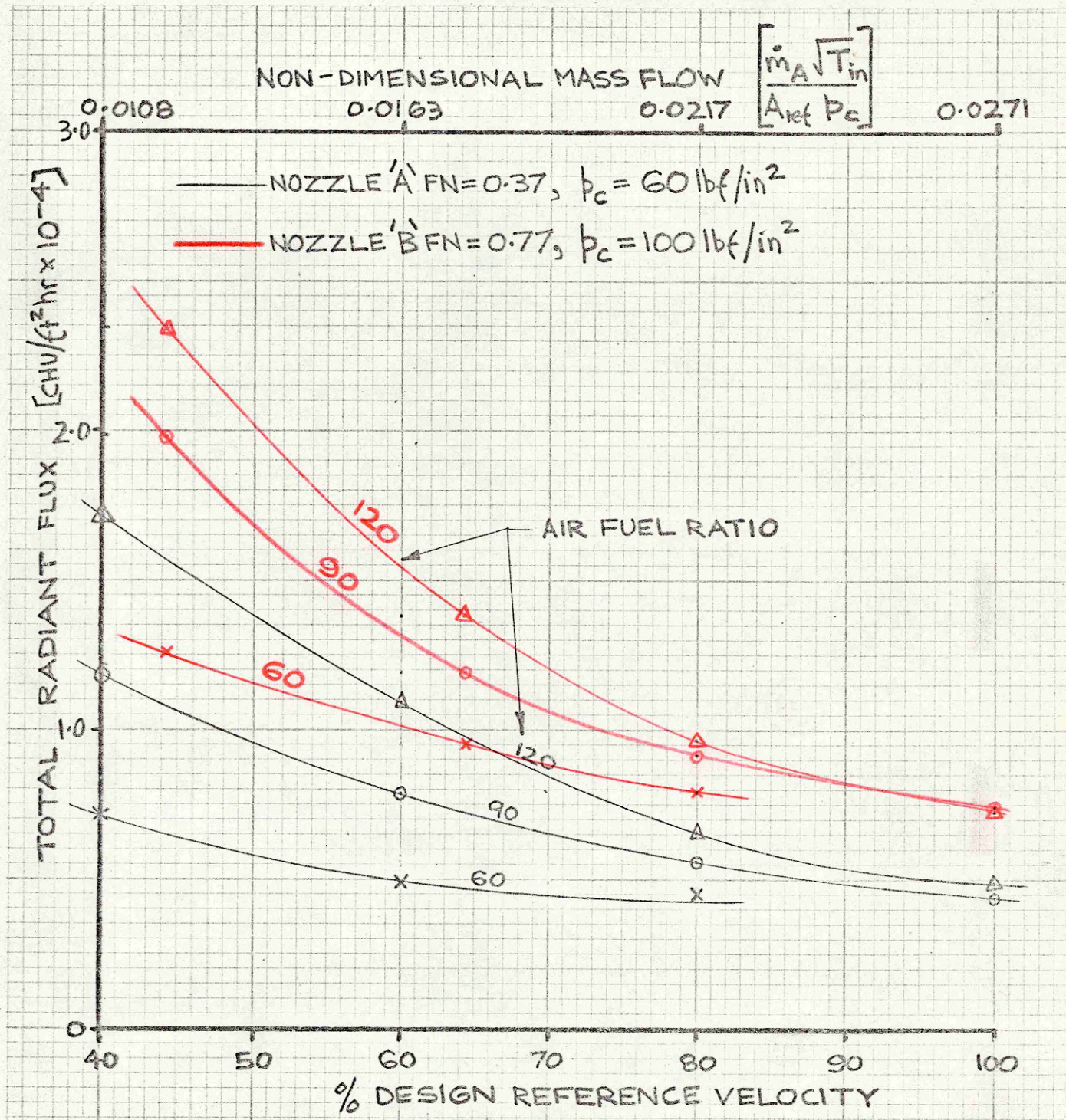


EFFECT OF SWIRL ATOMISER FLOW NUMBER ON EXHAUST SMOKE LEVEL:

COMBUSTION PRESSURE = 60 lbf./in².
 AIR INLET TEMPERATURE = 300° K.
 (nominal conditions).

From Tables 15 and 16.

FIG. 55



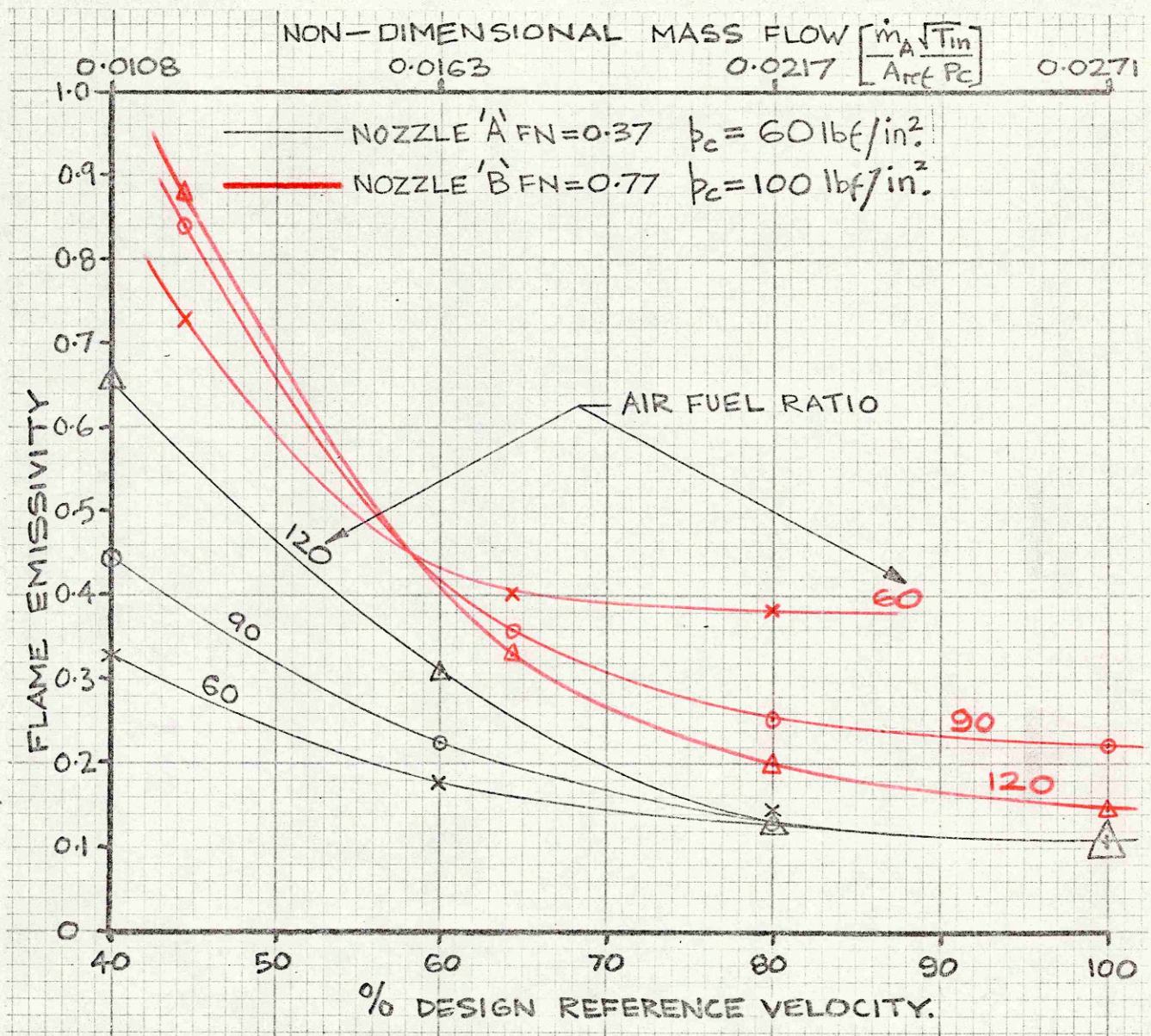
EFFECT OF COMBUSTION PRESSURE ON FLAME TOTAL RADIATION.

(with corresponding conditions at the same fuel injector pressure differential).

AIR INLET TEMPERATURE = 298° K.

From Tables 16 and 17.

FIG. 56



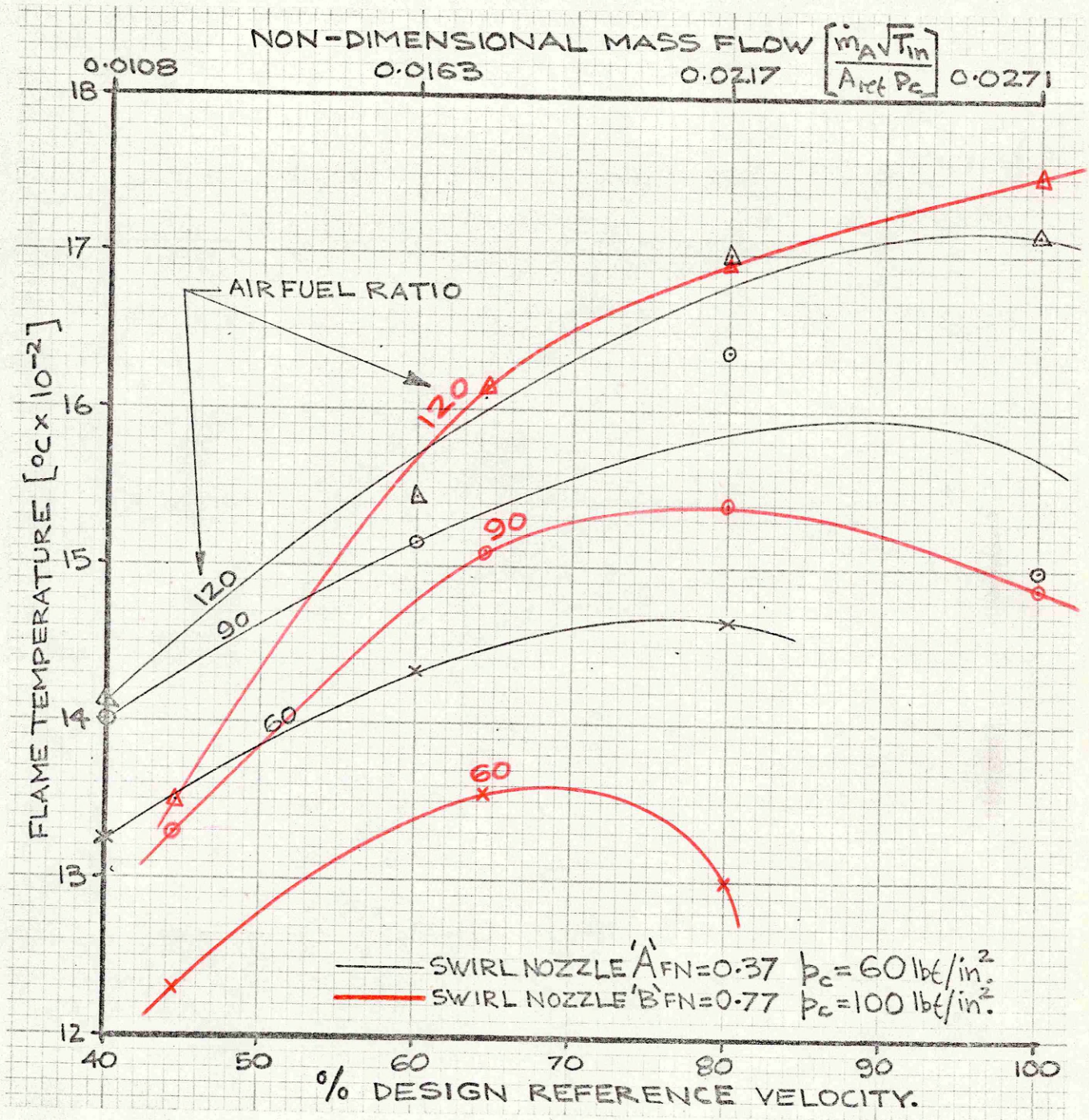
EFFECT OF COMBUSTION PRESSURE ON FLAME TOTAL EMISSIVITY.

(with corresponding conditions at the same fuel injector pressure differential).

AIR INLET TEMPERATURE = 298° K.

From Tables 16 and 17.

FIG. 57



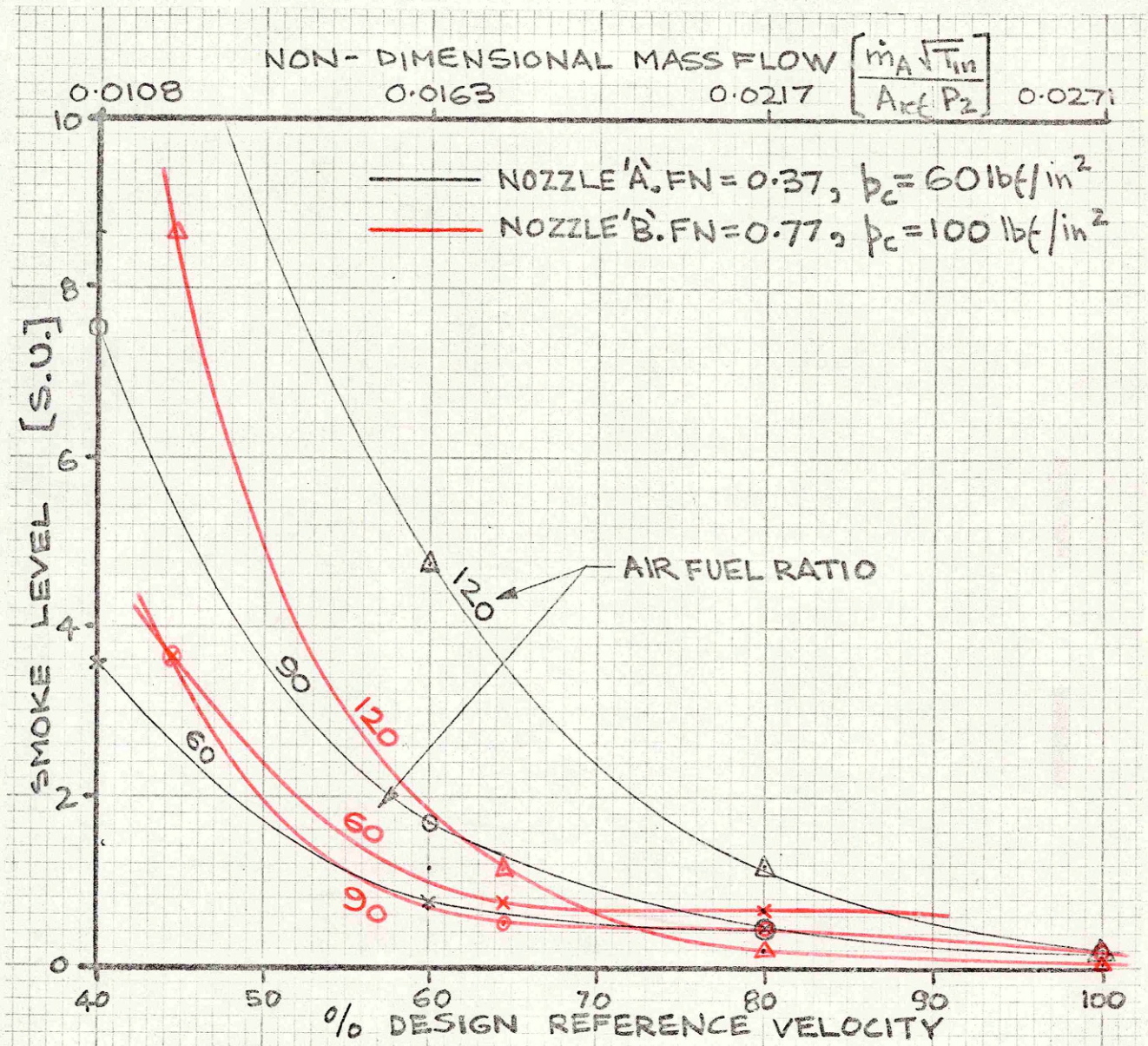
EFFECT OF COMBUSTION PRESSURE ON FLAME TEMPERATURE.

(with corresponding conditions at the same fuel injector pressure differential).

AIR INLET TEMPERATURE = 298° K.

From Tables 16 and 17.

FIG. 58



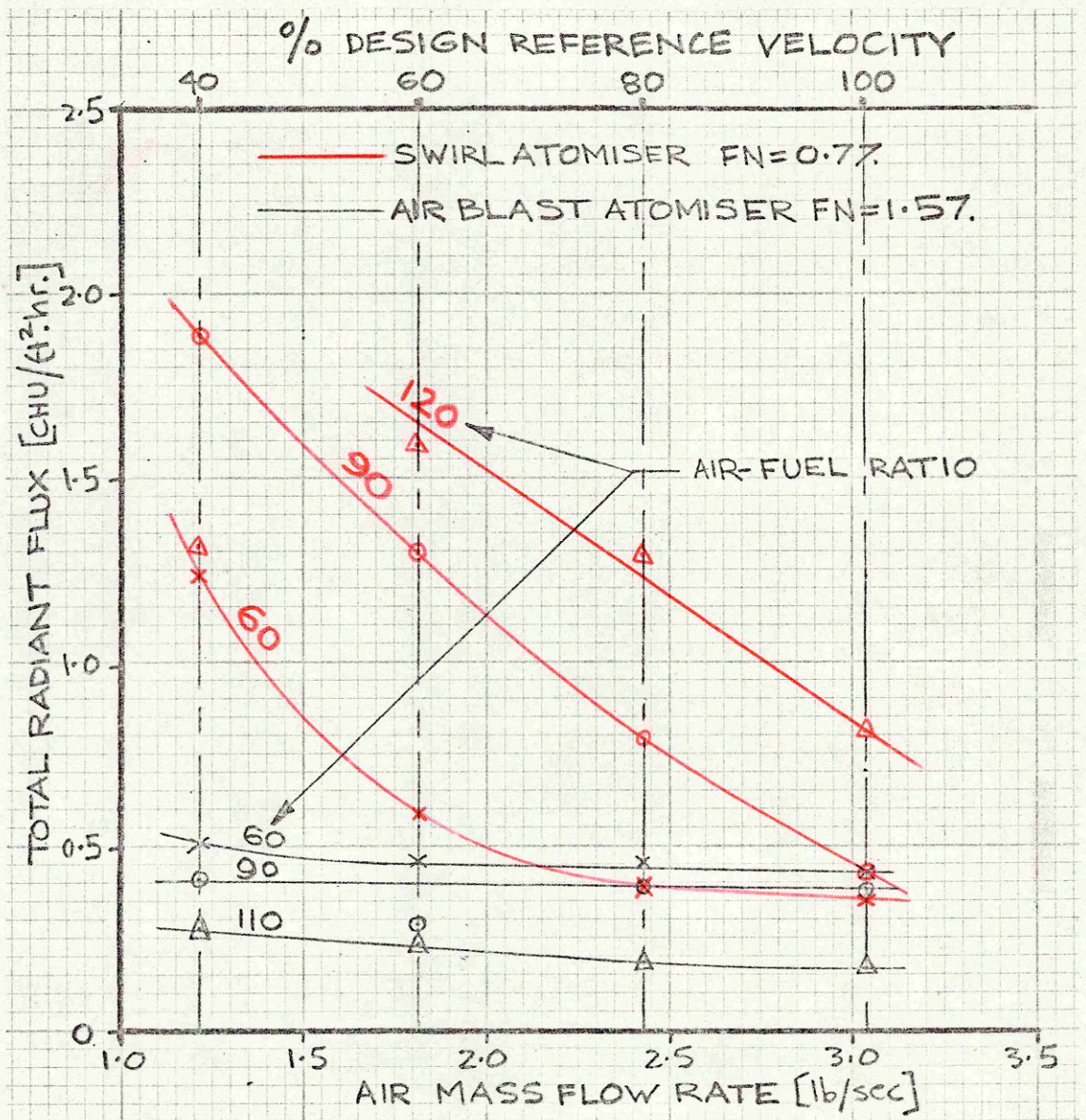
EFFECT OF COMBUSTION PRESSURE ON EXHAUST SMOKE LEVEL.

(with corresponding conditions at the same fuel injector pressure differential).

AIR INLET TEMPERATURE = 298° K.

From Tables 16 and 17.

FIG. 59

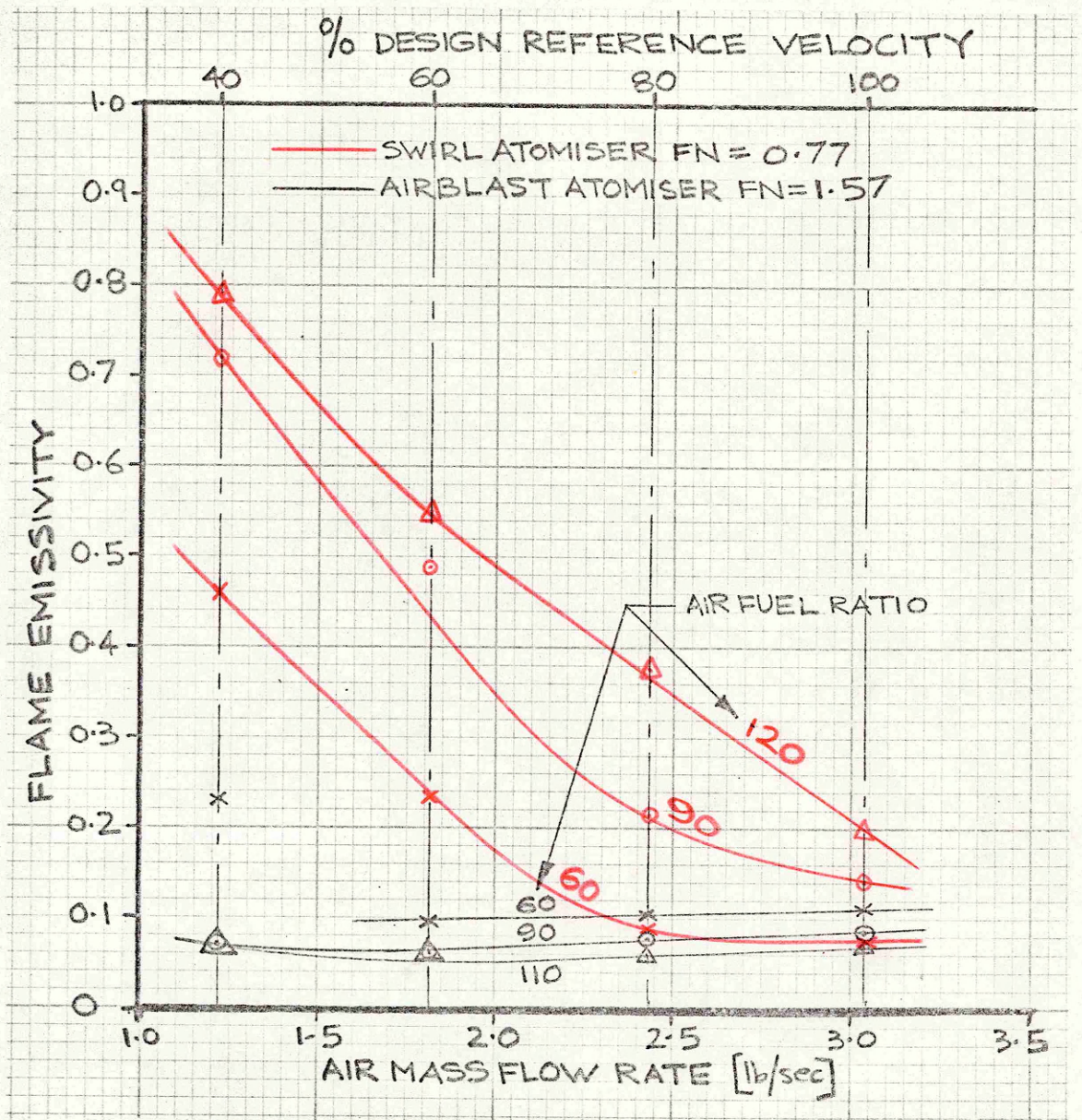


TOTAL RADIATION FOR AIRBLAST AND SWIRL ATOMISERS:-

COMBUSTION PRESSURE = 60 lbf./in².
 AIR INLET TEMPERATURE = 305° K.

From Tables 15 and 18.

FIG. 60



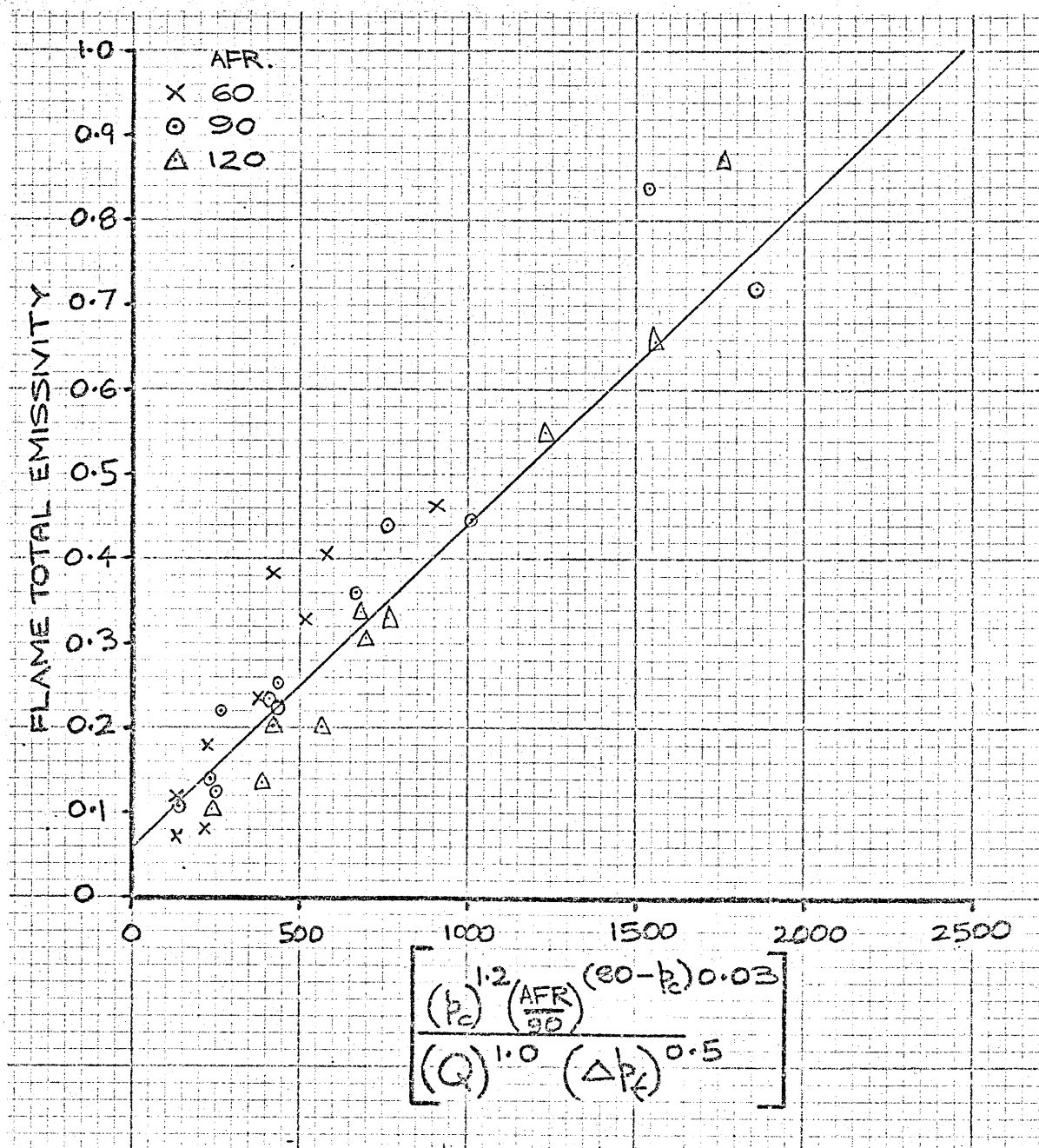
FLAME EMISSIVITY FOR AIRBLAST AND SWIRL ATOMISERS:-

COMBUSTION PRESSURE = 60 lbf./in².
 AIR INLET TEMPERATURE = 305° K.

(The airblast atomiser emissivities are apparent values at a black body background temperature of 1825° C).

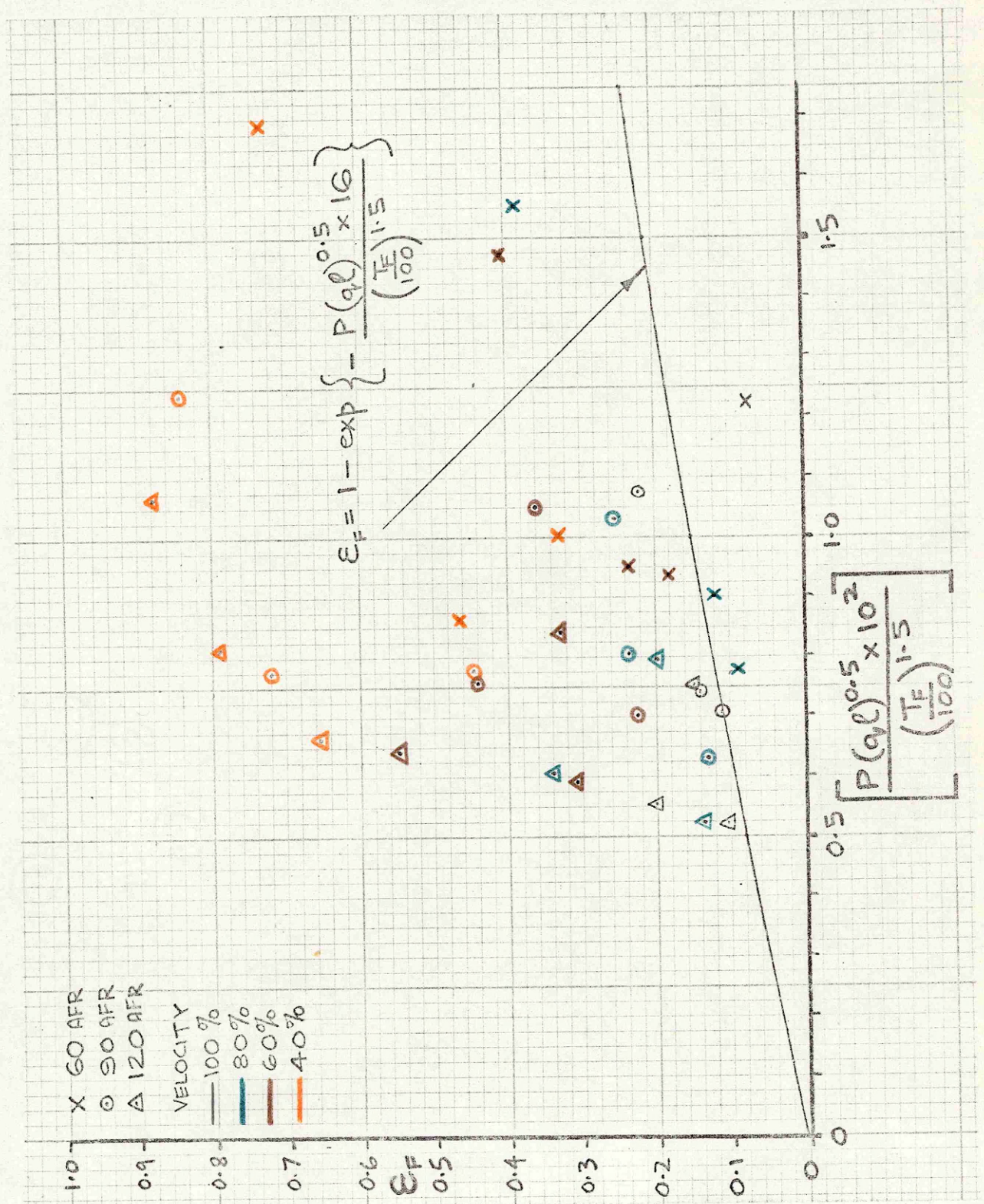
From Tables 15 and 18.

FIG. 61



CORRELATION OF THE TEST FLAME TOTAL EMISSIVITY DATA.

FIG. 62



COMPARISON OF THE TEST FLAME TOTAL EMISSIVITY
 RESULTS WITH THE CORRESPONDING NON-LUMINOUS
 EMISSIVITIES AS GIVEN BY THE REEVES EQUATION.

SCHMIDT METHOD INSTRUMENTATION.

FIG. 63

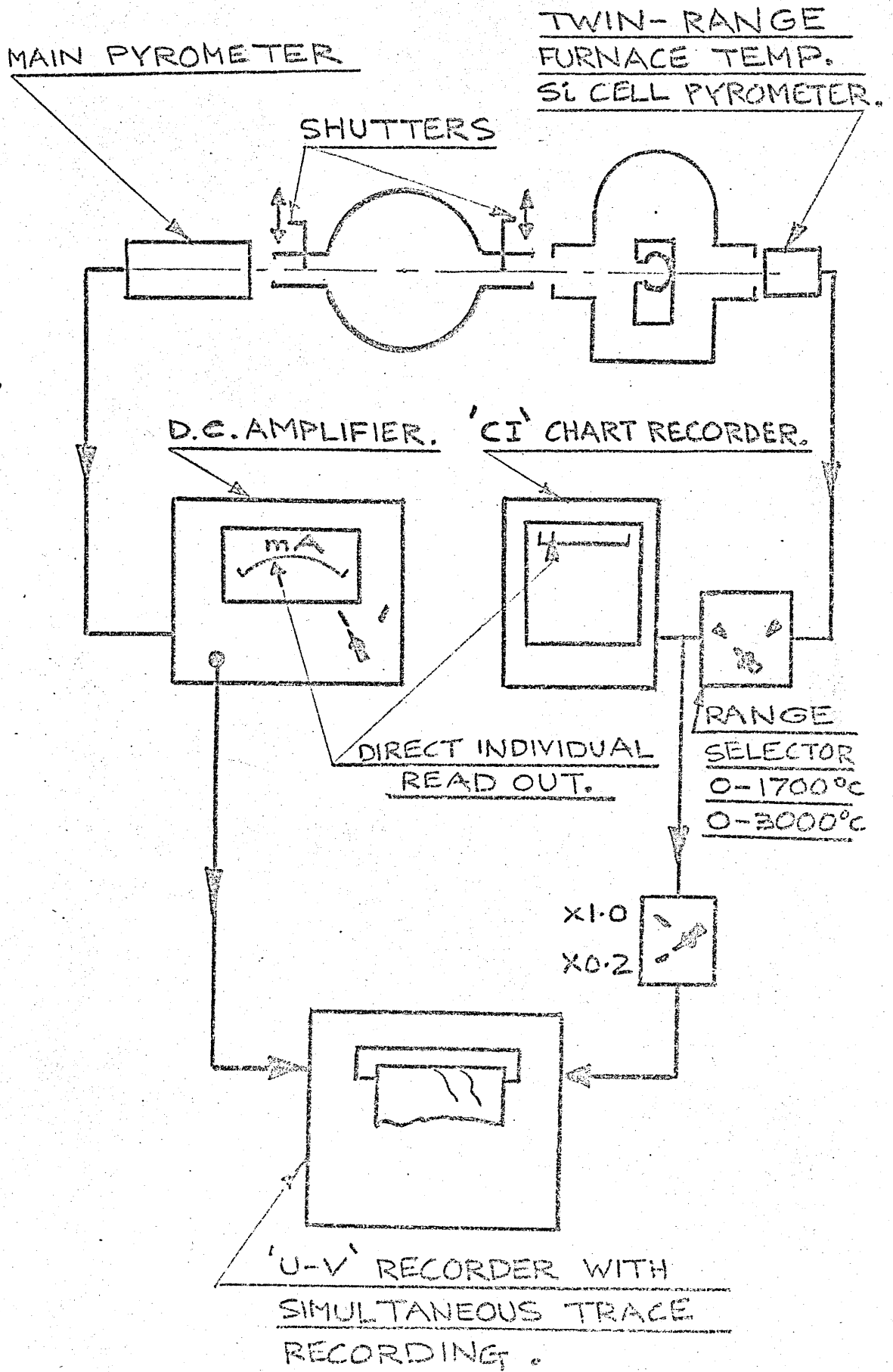
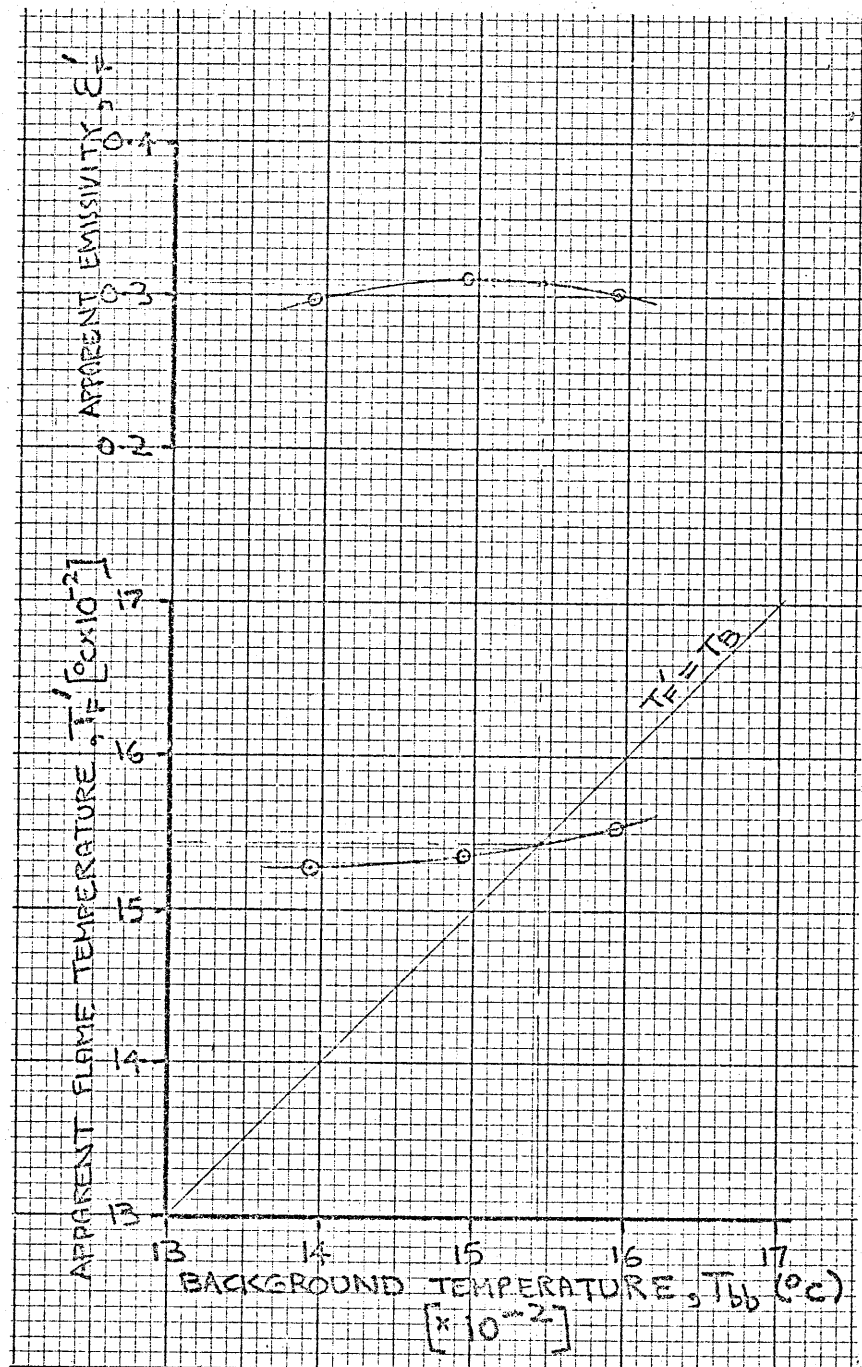


FIG. 64



GRAPHICAL SOLUTION FOR FLAME TEMPERATURE
AND EMISSIVITY.

(see Appendix IV).