INSTRUMENTATION FOR FLAME TEMPERATURE DETERMINATION

by

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LIST OF SYMBOLS

P	Radiation flux; radiant energy per unit of time for a given area A for a given small solid angle ω in a given mean direction θ
$T\,^\circ C$	Temperature in degrees Centigrade
$\nabla T\,C^\circ$	Temperature difference in Centigrade degrees
$T\,^\circ K$	Temperature in degrees Kelvin ($T\,^\circ C + 273\ C^\circ$)
c	Concentration of molecules
e	Base of Naperian logarithms
ℓ	Depth of flame in direction of axis of radiation system
α	Absorptance
β	Specific absorption coefficient
ϵ	Emittance
ρ	Reflectance
τ	Transmittance
$\lambda\mathring{A}$	Wavelength in Ångstroms ($1\ \mathring{A} = 10^{-8}$ cm.)
$\lambda\mu$	Wavelength in microns ($1\mu = 10^{-4}$ cm.)

SUBSCRIPTS

λ	Refers to a narrow wavelength region in vicinity of λ
B	Refers to a blackbody
F	Refers to a flame
M	Refers to a mirror
R	Refers to a receiver
S	Refers to a comparison source
BS	Refers to a blackbody at the temperature of the comparison source
BF	Refers to a blackbody at the temperature of the flame
Au	Refers to the gold point (1063 °C)
O	Refers to the ice point (0 °C)

SUMMARY

The concept of the temperature of a flame is considered.

A brief review of the literature on flame temperature determination by methods based on the use of the thermal radiation laws is presented.

The method of spectral-line reversal is discussed in detail, and its application, using the sodium D lines, to temperature determinations on an open flame rig and on a small tubular combustion rig is described. The problem of the loss of transparency of quartz in contact with flames containing sodium vapour is examined in some detail. The apparent difficulty in determining temperatures below about 1400 °K by the sodium-line reversal method is considered.

INTRODUCTION

The work described in this thesis has formed the initial stages of a programme of development of instrumentation and measurement techniques directed towards the determination of the temperature of gases under study on the spontaneous ignition rig at the Gas Dynamics Laboratory.

The objective is the determination of the axial temperature gradient of a hot gas stream in a divergent duct, a sketch of which appears in Fig. 1.

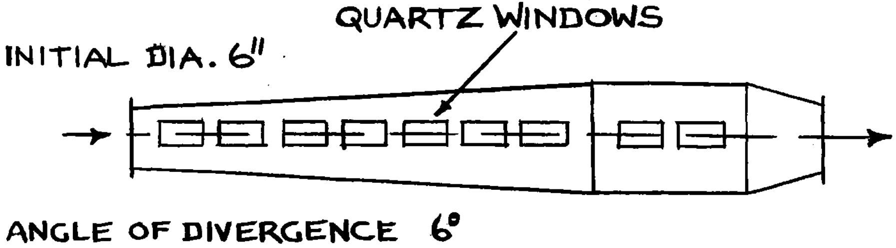

FIG 1 : SPONTANEOUS IGNITION RIG DUCT

The gas is composed of air contaminated with the products of combustion of hydrocarbon fuels, and in some regions combustion is in progress following the spontaneous ignition of injected fuel. The stream may be viewed through diametrically opposed quartz windows in the duct wall, and in general is seen to be uncoloured by the yellow associated with glowing carbon particles.

The temperatures encountered lie within the range 1100°K to 1900°K. This range could be covered with a platinum platinum-rhodium thermocouple, but it is considered that the insertion of a solid body into the stream might influence the stream conditions to an indeterminate degree. It is particularly feared that such a body would act as a flame stabilizer. Care has been taken in the design of the rig to control the degree of turbulence present, and attention is therefore concentrated on methods of temperature determination which may be considered to influence only slightly the process under analysis.

The objective outlined above has yet to be achieved, although some useful experience has been obtained. This experience has consisted of an appreciation of the general problem of flame temperature determination, of a literary survey of various types of instrumentation, and of trials on three different combustion rigs. The material thus gathered is given in the following presentation in the above sequence.

THE GENERAL PROBLEM

It is desirable at the outset that some consideration be given to clarification of the concept of the temperature of a flame.

Ribaud, Laure and Gaudry(27)* define a flame in terms similar to the following: A flame is a gaseous mixture in which composition changes occur accompanied by heat release. The definition may be extended to cover the period of recombination of dissociated molecules, and the period of cooling to the temperature of the surroundings. A significant characteristic of a flame as far as this study is concerned is that it is not, in general, a system in equilibrium, even when the flame as a whole is in equilibrium with its surroundings.

Qualitatively, temperature has been defined by Preston(25) as the degree of hotness. Quantitatively, temperature, according to Lewis and von Elbe(18)(19), defines a state of statistical equilibrium. According to statistical mechanics, the temperature of a body is defined by the molar content of translational energy of a perfect gas in energy equilibrium with it. On the basis of these definitions it should be possible to assign a temperature to any gas in which the translational energy distribution is

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* Numbers in parentheses apply to references grouped separately at the end of the thesis.

an equilibrium distribution. Lewis and von Elbe emphasize that this condition is likely to be closely approximated even under rapidly varying conditions. The determination of the "gas law" parameters, pressure and molar volume, would thus be sufficient for temperature determination. Such determinations would be difficult to make, although in the so-called "thermodynamic methods" the principle is used indirectly.

Molecules of a gas may possess energy of translation, rotation, vibration, and electronic excitation. The energy of electronic excitation corresponds to the possession of energy in excess of that in which the electrons are in their lowest energy states. The energy of translation is practically unquantized, but the other forms are quantized. There will be a definite distribution of the energy of a gas among these different degrees of freedom when the gas is in a state of internal equilibrium, and parameters of any of the energy states may, in theory, be used for temperature determination. In view of the difficulty in determining the gas law parameters, this is a considerable advantage. It makes possible, in particular, the use of methods based on thermal radiation.

In the case of a gas in which internal equilibrium between the various energy states does not exist, temperature determinations based on the parameters of any one of the energy states should not be regarded as a determination of the gas temperature unless a close approximation to equilibrium between that state and the translational state can be established.

The determination of the gas temperature defined by statistical mechanics is of interest in studies in gas dynamics, for it is one of the basic parameters used in flow analysis. It is evident, however, that in certain problems, notably those involving chemical reaction, droplet evaporation, and the physical strength of adjacent solid boundaries, knowledge is also required of the energy distributed among the degrees of freedom other than the translational. In this connection, if an equilibrium distribution exists within a given degree of freedom, a corresponding temperature may be assigned to the gas equal to the temperature at which the particular equilibrium energy distribution found in that state would be found in the same state in a gas which, as a whole, was in a state of internal equilibrium. This has led to the use of such terms as "rotational temperature", which would apply to the rotational energy distribution. In cases where an equilibrium energy distribution does not exist within a given energy state, a temperature may not be assigned to that state. Further complications arise from the fact that a flame consists of a gaseous mixture, and a temperature determination is therefore associated with the particular molecules under study. Hence the use of terms such as "rotational temperature of CH".

The term "flame temperature" therefore generally requires qualification. It is clear that considerable variation may be found experimentally between temperature values associated with the different energy states of a given constituent of a flame, and between the various constituents. The significance of any determination will depend on the purpose for which it is made.

There appear to be two alternative methods of approach:

1. Formulate new concepts to replace the temperature concept, and seek to determine their values rather than supposed temperature values.

2. Determine the degree of departure from equilibrium conditions, and use this in assessing the significance of any supposed temperature determination.

The first method does not appear to have been explored. The second method is commonly tackled in either or both of the following ways:

1. Make temperature determinations by different methods, or by variations of the same method.

2. Study the probability of the process being in equilibrium.

Where experimentation is relatively straightforward, the first approach is adopted. Under more difficult conditions, recourse may be made to the second approach.

SCALES OF TEMPERATURE

It is important to refer a temperature determination to an acceptable reference scale, for, as discussed by Obert,(22) temperature is often regarded as a fundamental dimension.

The Thermodynamic Scale of temperature is generally recognised as the fundamental scale. It was proposed by Lord Kelvin in the following terms - "The absolute values of two temperatures are to one another in the proportion of the heat taken in to the heat rejected in a reversible thermodynamic engine working with a source and refrigerator at the higher and lower of the temperatures respectively".

The practical establishment of the scale is effected by determining the Gas Scale, which is based on the supposed behaviour of a perfect monatomic gas. Experimental work on monatomic gases at low pressure is carried out, and corrections are applied to approximate as closely as possible to the Thermodynamic Scale.

As described by Weber(32), difficulty in measuring temperatures on these scales has led to the establishment of the International Temperature Scale. This scale is intended to agree with the thermodynamic scale as closely as most practical purposes require. It is based on fixed and reproducible equilibrium temperatures such as the gold point (the temperature of equilibrium between solid and liquid gold) to which numerical values are assigned, and upon empirical formulae for the relations between temperature and the indications of specified instruments calibrated at these points.

Temperatures are designated as °C, the ice-water equilibrium temperature being taken as 0°C and the water-steam equilibrium temperature as 100°C.

Above the gold point (1063°C), the temperature is defined by Planck's relation, giving the following equation for the ratio between the radiation flux produced by a blackbody at a temperature T°C to that produced at the gold point:

$$\frac{P_B}{P_{B(Au)}} = \frac{e^{\frac{C_2}{\lambda(T_{Au} + T_0)}} - 1}{e^{\frac{C_2}{\lambda(T + T_0)}} - 1} \qquad (1)$$

The value of the constant, C_2, is taken as 14380μ K°, and the temperatures $(T_{Au} + T_0)$ and $(T + T_0)$ are in degrees Kelvin.

The Planck formula is consistent with the thermodynamic scale, and thus affords an opportunity of determining temperatures on the thermodynamic scale by suitable handling of the variables P_B and λ. Unfortunately, the postulated blackbody is a concept, although close approximations to it in practice are obtained with a small opening in a relatively large cavity.

SOME PRACTICAL CONSIDERATIONS

Static and total temperatures

The gas in a flame will generally possess energy of directed motion, and in consequence it is necessary to distinguish between static and total temperatures. The static temperature of the gas is the temperature considered above, and the total temperature is the temperature of the gas if brought isentropically to rest. The static temperature is connected with the density of the gas and with the intensity of thermal radiation from the gas. The total temperature is connected with the total energy per unit mass of the gas. The temperature of an object in the gas stream is sometimes estimated from empirical relationships giving a result intermediate between the static and total temperatures. Depending on the problem, either or both temperature values may be required.

Point and mean temperatures

In general, it is desired to determine the variation of temperature with position in a region in which it varies significantly, owing to the fact that many important variables, such as thermal radiation and the creep strength of materials, show marked variations for comparatively small variations in temperature.

It is sometimes expedient, however, to determine "mean" values and seek to interpret the significance of such values from qualitative considerations.

Steady and fluctuating temperatures

The determination of the steady temperatures of gases has received considerable attention, and permits the use of a wide range of instrument types, based largely on visual methods. Combustion is essentially a fluctuating process, however, and electronic equipment is often employed in order to follow the fluctuations. This poses more difficult instrumentation problems.

METHODS OF TEMPERATURE MEASUREMENT

Any property varying in a known manner with temperature may, in theory, be used in temperature determination. Freeze(8) lists about four hundred references covering a great variety of methods and types of instrumentation.

For tackling the problems on the spontaneous ignition rig in the Laboratory, it was decided that instrumentation based on radiation methods should be developed. For this reason, the following literature survey covers this field alone.

RADIATION FROM FLAMES

According to Finkelnburg(5), all thermally excited gases radiate continuously over the entire electromagnetic spectrum. This radiation is generally weak, but in the case of carbonaceous flames (which contain minute carbon particles) the continuous radiation may be strong enough for measurement purposes.

The thermal radiation from flames not containing free carbon occurs largely in discrete spectral regions, and is the result of quantum energy changes in states other than that of translation. Changes in the energy of electronic excitation produce line spectra, and changes in the energy of rotation or vibration produce band spectra, a band being a series of related lines. Line spectra are associated with atoms, and band spectra are associated with polyatomic molecules.

A sketch of the electromagnetic spectrum in the visible radiation region is given in Fig. 2, and the regions of some representative hydrocarbon flame spectra are indicated for illustrative purposes. Elements radiating in the visible region are sometimes added to the flame. The positions of the lines emitted by sodium and lithium vapour, commonly used as additives, are shown.

In addition to thermal radiation, flames may emit chemiluminescent radiation resulting from the formation, in a chemical reaction, of molecules in an excited electronic state.

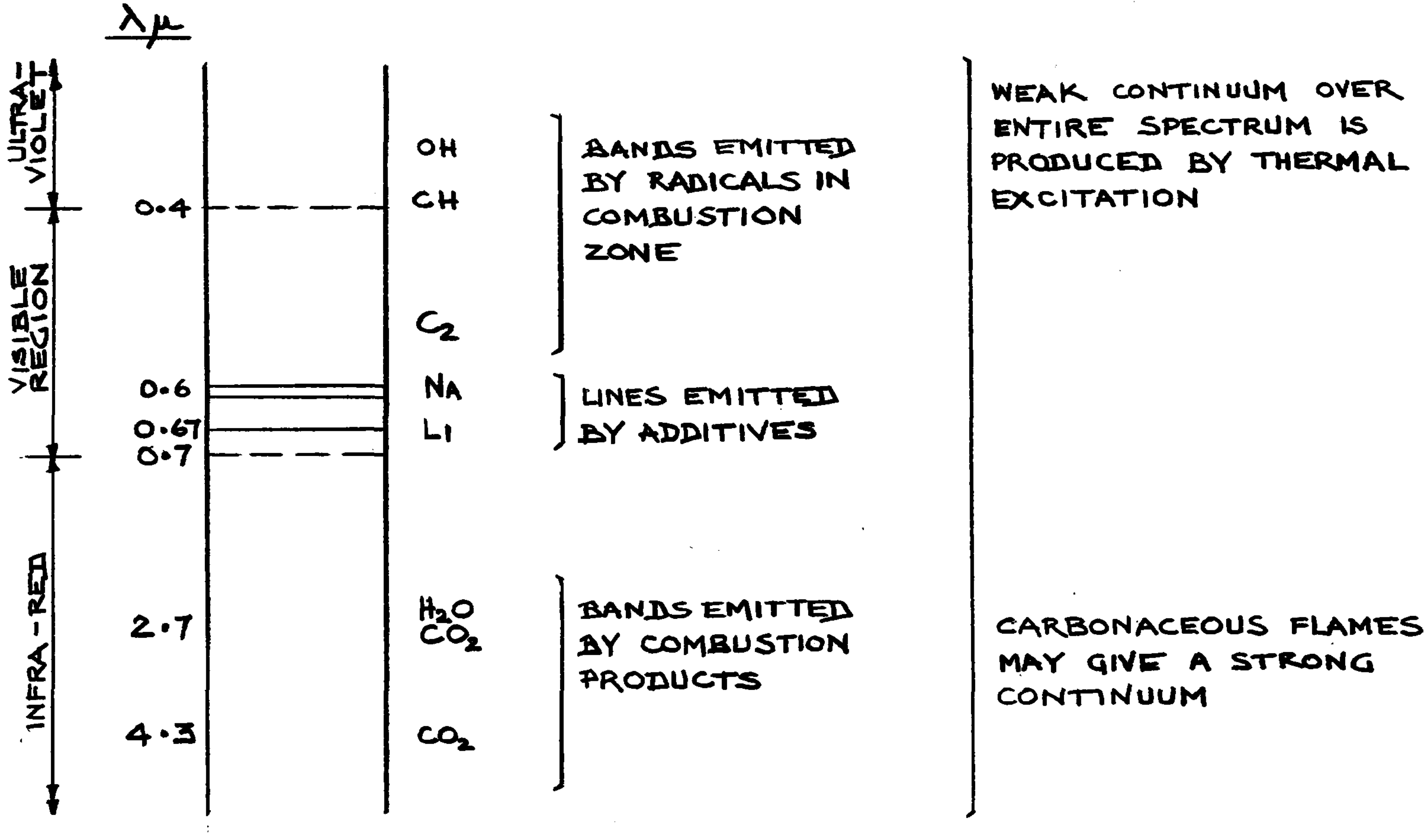


FIG 2: REGIONS OF HYDROCARBON FLAME SPECTRA

THE LAWS OF THERMAL RADIATION

Kirchoff's law and the blackbody concept

If the processes occurring when radiation is incident upon a body are considered, it will be apparent that some radiation may be absorbed, some reflected and some transmitted.

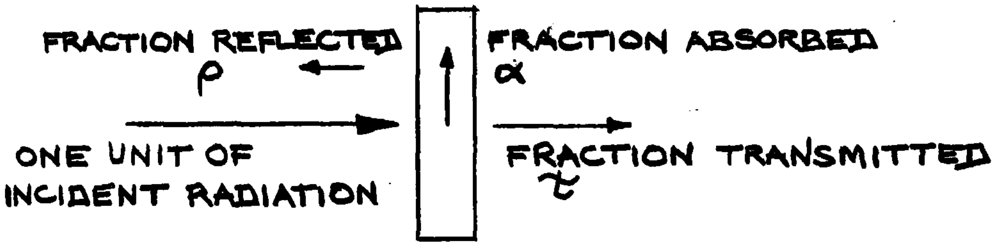


FIG 3 : PARTITION OF RADIATION FLUX BY A BODY

From the principle of the conservation of energy, the parameters shown in Fig. 3 may be related by the equation

$$\alpha + \rho + \tau = 1 \qquad (2)$$

If the body is considered to be situated in an enclosure held at a uniform temperature, application of the same principle leads to the result

$$\epsilon = \alpha \qquad (3)$$

where ϵ is the emittance of the body. The emittance is the ratio of the thermal radiation flux emitted by the body to the thermal radiation flux that would be emitted by a blackbody at the same temperature. Equation 3 is one form of Kirchoff's law. It is associated with the concept of a blackbody, for which

$$\epsilon_B = \alpha_B = 1 \qquad (4)$$

and

$$\rho_B = \tau_B = 0 \qquad (5)$$

Reference has already been made to the fact that the closest approximation in practice to a blackbody is a small hole in a relatively large cavity. The blackbody concept is a mathematical convenience. Actual bodies are referred to the blackbody by means of the parameters α, ρ and τ.

It may be noted that these parameters generally vary with the mean direction of observation, and the angle of inclination of the mean direction of observation to the normal to the surface of the body should be specified when giving data on the values of the parameters. In general, also, the parameters will be a function of temperature.

The application of Kirchoff's law to radiation studies on flames requires further consideration. If a continuum produced by thermal excitation of the gas or by radiation from carbon particles alone is considered, then the law may be applied either to the total radiation over the entire spectrum, or to radiation in a narrow spectral region, as desired. In some cases, however, a gas may emit radiation in different spectral regions from those in which it absorbs radiation. From the principle of the conservation of energy, Kirchoff's law will always hold when the complete spectrum is considered, but in a given narrow spectral region the relationship

$$\epsilon_\lambda \neq \alpha_\lambda \qquad (6)$$

should be assumed, unless an experimental check has proved otherwise.

The Stefan - Boltzmann law

One form of the law is the statement that the total thermal radiation flux produced by a blackbody is proportional to the fourth power of the absolute temperature, or that

$$P_B \propto T^4 \qquad (7)$$

It is evident that large variations in thermal radiation flux result from small changes in temperature.

Planck's formula

Planck's formula relates the thermal radiation flux produced by a blackbody over a given narrow wavelength interval to the absolute temperature. The formula may be written

$$P_{B\lambda} \propto \lambda^{-5}\left(e^{\frac{C_2}{\lambda T}} - 1\right)^{-1} \qquad (8)$$

where C_2 is a constant equal to 14380μK°.

Equation 7 may be obtained by integrating Equation 8 from $\lambda = 0$ to $\lambda = \infty$.

Wien's formula

Wien's formula is an approximate form of Planck's formula, and may be used with great accuracy in the visible region of the spectrum and for temperatures below about 3500°K. It is therefore widely used in radiation pyrometry.

One form of the formula is

$$P_{B\lambda} \propto \lambda^{-5} e^{-\frac{C_3}{\lambda T}} \qquad (9)$$

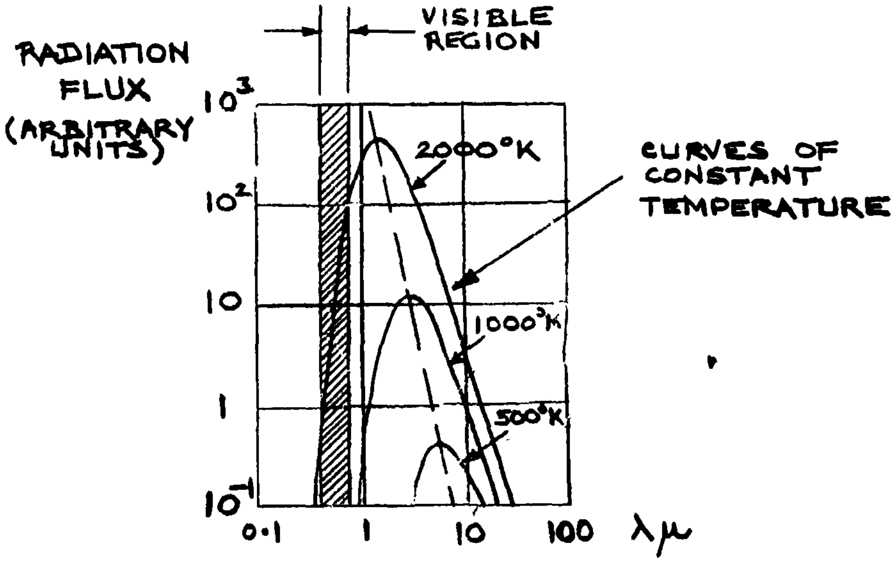
where C_3 is taken as 14350μK°.

Graphical representation of radiation formulae

The variations of $P_{B\lambda}$ with λ for given values of T, and of $P_{B\lambda}$ with T for given values of λ, are given in Figs. 4 and 5 respectively. Fig. 4 is a representation of Planck's formula, and demonstrates the manner in which $P_{B\lambda}$ increases with increase in T at fixed λ, and also the shift of the peaks of the curves of constant T towards the shorter wavelengths as T is increased. In fact,

$$\lambda_{MAX.} \propto \frac{1}{T} \qquad (10)$$

This is one form of a relationship known as Wien's law.



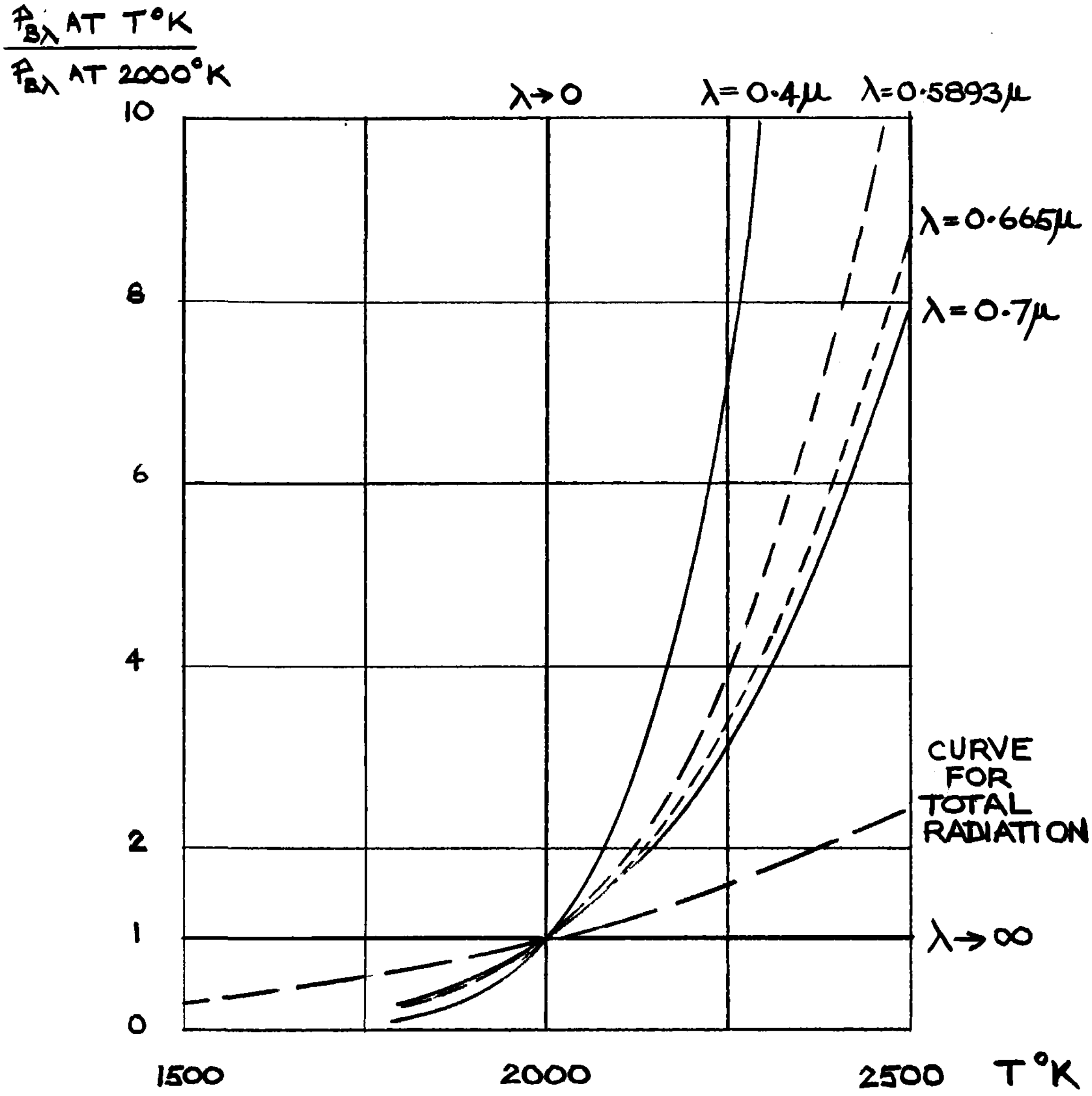
[CURVES FROM SEARS, "PRINCIPLES OF PHYSICS", VOL III, ADDISON WESLEY PRESS, 1948]

FIG 4: GRAPHICAL REPRESENTATION OF PLANCK'S FORMULA

Fig. 5 is based on calculations by the author from Wien's formula in the form

$$\frac{P_{B\lambda} \text{ AT } T°K}{P_{B\lambda} \text{ AT } 2000°K} = e^{\frac{c_2}{\lambda}\left(\frac{1}{2000} - \frac{1}{T}\right)} \qquad (11)$$

and is intended to illustrate the thermal radiation flux versus temperature relationships for various wavelength regions in the visible spectrum at temperatures in the vicinity of 2000°K, chosen as a representative flame temperature. It is clear that the curves are much steeper for spectral radiation than for total radiation, in the temperature range shown. The considerable sensitivity of spectral radiation flux to temperature variation is noteworthy.



λ = 0·4 μ	BLUE "LIMIT" OF VISIBLE SPECTRUM
λ = 0·7 μ	RED " " " "
λ = 0·5893 μ	MEAN WAVELENGTH OF SODIUM D LINES
λ = 0·665 μ	MEAN WAVELENGTH OF OPTICAL PYROMETER TRANSMISSION

FIG 5: GRAPHICAL REPRESENTATION OF WIEN'S FORMULA AND THE STEFAN-BOLTZMANN LAW

Definition of brightness temperature

The brightness temperature of a body is the temperature of a blackbody emitting the same thermal radiation flux as the body, in a given narrow spectral region. The parameter is a useful one when a body is being used as a source of radiation, and when the property of interest is its equivalence to a blackbody.

GENERAL CONSIDERATIONS OF RADIATION SYSTEM

The radiation system shown in Fig. 6 is used as a basis for a discussion of general considerations.

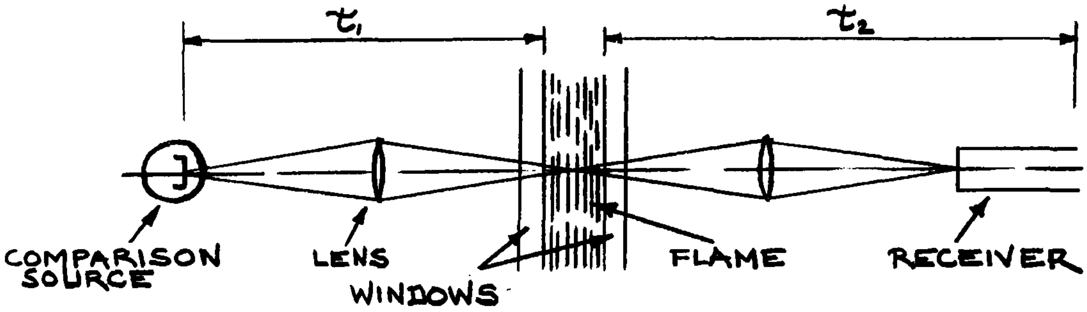


FIG 6 : EXAMPLE OF RADIATION SYSTEM

Thermal radiation from a comparison source is focused in the flame under study and also on a receiver. An alternative arrangement is to place the comparison source and receiver in the focal planes of the respective lenses so that a "bundle of rays" from a point on the comparison source would be rendered parallel by the nearer lens, and focused on the receiver by the second lens.

The comparison source is, preferably, an experimental blackbody, and Quinn(26) used this type of source. Practical difficulties, notably loss of strength at high temperatures, limit the usefulness of such sources, and a non-blackbody comparison source may be used if the degree of departure from blackbody conditions is known. The tungsten ribbon filament lamp is a particularly useful comparison source owing to the fact that the properties of tungsten are well established, thus facilitating wide use of this element in radiation pyrometry.

Radiation from the comparison source traverses a longer path than that from the flame, and in effecting comparisons of radiation flux it is clear that the flux from the comparison source must be multiplied by τ_1 to give the equivalent flux at the flame.

If the rays travelling from points to one side of the centre of the comparison source are drawn through the nearer lens, it will be seen that, unless this lens is larger than the one nearer the receiver, some of the radiation from the comparison source transmitted by the first lens will not be received by the second lens. To ensure that equivalent "bundles of rays" from the comparison source and from the flame reach the receiver, a screen with a small hole may be placed over the lens nearer the receiver, if the lenses are equal in size. In general, optical arrangements should be carefully examined, preferably by setting them out on a full scale drawing, before proceeding with experimental studies.

In visual methods, comparisons are not made of radiation flux directly, but of radiation flux per unit area. The term "radiation intensity" is applied to this parameter.

It is important to realise that, though the images of the comparison source and of the receiver may be focused at any desired point in the flame, the radiation from the flame may not thus be exclusively observed originating from selected regions along the axis of the radiation system. If the flame is of uniform concentration and temperature along this axis, the radiation may be regarded as coming from a series of thin layers of flame, each of which is capable of making an equivalent contribution to the total radiation. This point is emphasised by Hett and Gilstein (14), and may be demonstrated by a consideration of the amount of radiation flux from any given layer that would be transmitted by the focusing system to the receiver.

This constitutes a severe limitation, and has led Pavia(23) to conclude that radiation methods are useless for a temperature traverse across a flame. Various techniques have been developed in an attempt to determine the temperature variation along the axis of the radiation system, such as the line contour studies of Strong, Bundy and Larson(30) and the examination of radiation from different emitters by Silverman(28). Localization of additive injection may be employed on a laboratory scale in special instances, but it is not a generally applicable technique, due to the rapid diffusion of the additive in a direction perpendicular to the direction of flow. If certain assumptions are acceptable regarding the concentration and distribution of emitters, varying the position of the axis of the radiation system may give information regarding the temperature distribution, but such methods are in the early stages of development, and are clearly of limited application.

THE EMITTANCE OF A FLAME

An important characteristic of flames is that the equation

$$\rho_F = 0 \qquad (12)$$

may be assumed with high accuracy. This assumption is made by Worthing and Halliday(33) for carbonaceous flames, and has been verified for alkali metal vapours in the range 900°C to 1800°C by Kohn(16). The assumption is implicit in the relationship

$$\tau_F = 1 - \epsilon_F \qquad (13)$$

which can be derived from equations 2, 3 and 12. Equation 13 is used by many workers without reference to the assumption of zero reflectance. This practice is followed below, although in general the assumption should be borne in mind.

The spectral absorptance of a flame which has uniform properties along the radiation path will be a function of the concentration of the absorbing molecules, the specific absorption coefficient and the depth of flame observed. The relationship

$$\alpha_{F\lambda} = 1 - e^{-c\beta_\lambda l} \qquad (14)$$

is readily derived. The product $c\beta_\lambda$ is the spectral absorptance per unit depth of flame.

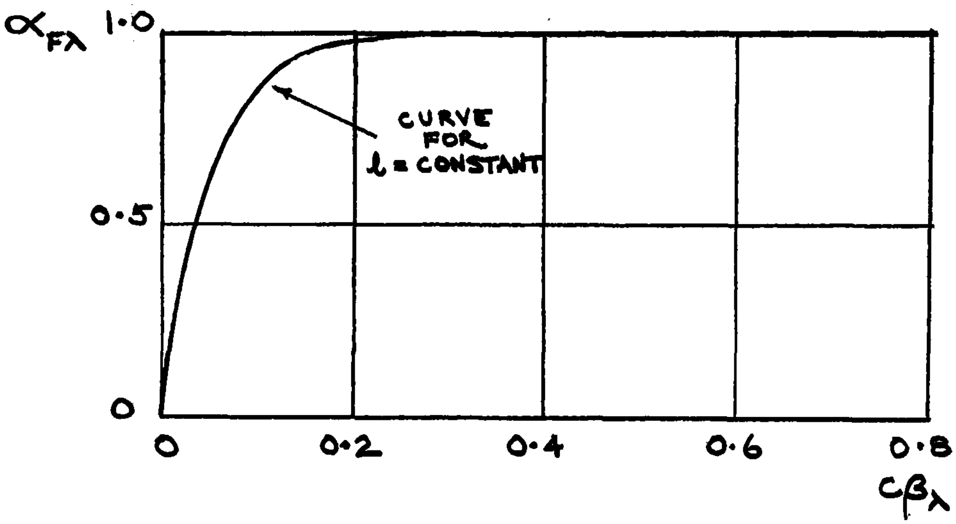


FIG 7 : VARIATION OF SPECTRAL ABSORPTANCE OF A FLAME WITH ABSORPTANCE PER UNIT DEPTH

Fig. 7 illustrates the manner in which the spectral absorptance of a flame of given depth increases asymptotically to unity as the concentration of the absorbing molecules is increased. A similar curve is obtained if $c\beta_\lambda$ is given a fixed value, and l is plotted as abscissa.

If the receiver used in the radiation system produces a distributed spectrum, the spectral radiation intensity versus wavelength distribution from the comparison source and from the flame may be observed.

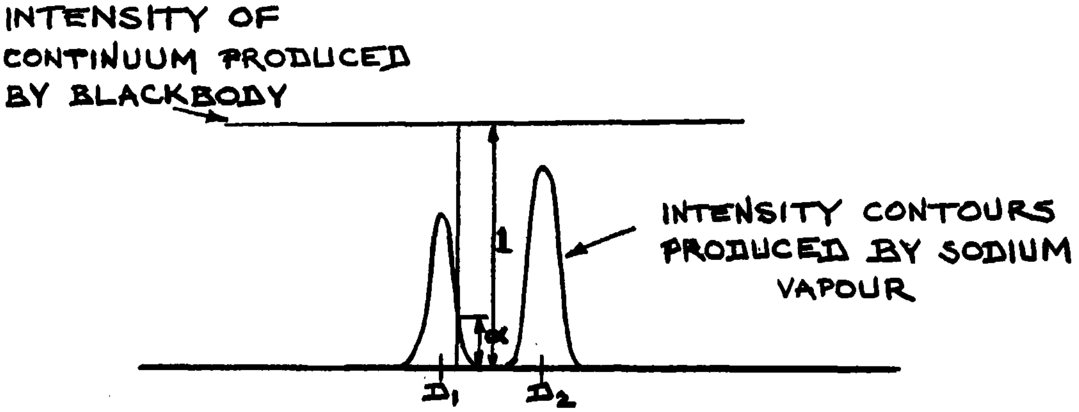


FIG 8 : INTENSITY CONTOURS

Fig. 8 is a diagrammatic representation of such distributions for a blackbody and for sodium vapour respectively, both being at the same temperature. The blackbody spectral radiation intensity is substantially constant over the small spectral region considered, and the sodium vapour spectral radiation intensity is a marked function of wavelength. At any wavelength, the value of $\alpha_{F\lambda}$ is given by the ratio of the height of the sodium vapour curve to the height of the blackbody curve, for $\alpha_{F\lambda}$ and $\epsilon_{F\lambda}$ are equal in the case of sodium vapour, as discussed below. The shapes of the lines depend on several factors, as described by Strong, Bundy and Larson$^{(30)}$, the most important being the process of self-absorption.

RADIATION METHODS OF TEMPERATURE MEASUREMENT

Three methods of handling the thermal radiation equations indicate the following methods of tackling the problem of temperature measurement in practice:

1) If the gas is a blackbody, measure the spectral or total radiation flux.

2) If the gas is not a blackbody, measure the spectral radiation

flux and the spectral emittance.

3) Determine the distribution of spectral radiation flux between the various energy states of the gas.

A considerable variety of techniques within the above framework has been developed during the past fifty years. The following summary briefly outlines some of the most commonly used techniques.

For simplicity, the transmittance of all parts of the optical system is taken equal to unity, and attention is thus centred on the radiation flux from the comparison source and from the flame.

The properties of the flame along the axis of the radiation system are considered constant.

It is assumed that, where the comparison source is not a blackbody, the apparatus would be set up so that the amount of radiation reflected by the comparison source through the radiation system may be neglected. This requirement is considered further in the appendix.

METHODS APPLICABLE TO CARBONACEOUS FLAMES

Carbonaceous flames contain minute carbon particles which radiate thermally, giving a continuous spectrum. The assumption that the radiation from these particles is exclusively thermal is usually made with confidence by experienced workers in the field, and reference to this is made by Hett and Gilstein(14).

Kurlbaum's method

The method developed by Kurlbaum(17) is the one most widely used for carbonaceous flame temperature determination. It is described by Lewis and von Elbe(19), and consists of observing a comparison source with an optical pyrometer first directly and then with the flame interposed. The temperature of the comparison source is controlled to give the same

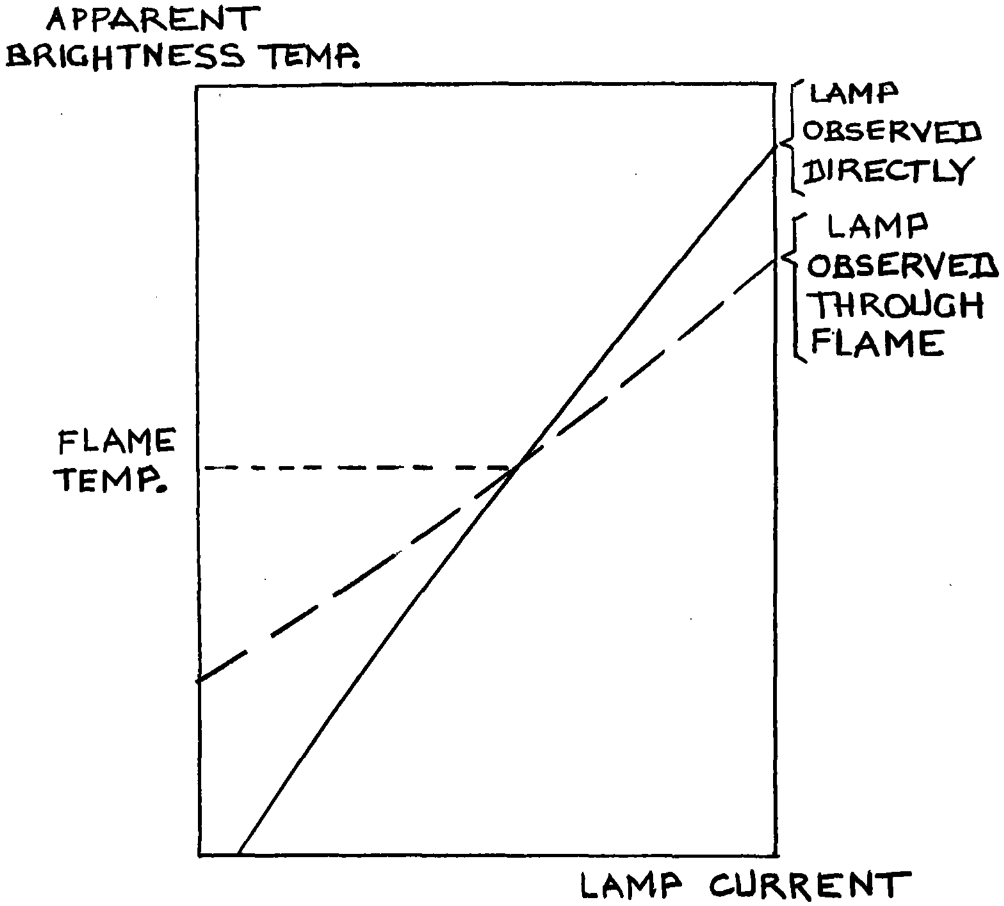


FIG 9 : CURVES PLOTTED IN KURLBAUM'S METHOD

pyrometer reading in each case. The brightness temperature of the comparison source, given by the optical pyrometer reading, is then equal to the temperature of the flame.

The curves shown in Fig. 9 illustrate the manner in which the match may be effected. The point of intersection of the curve of lamp brightness temperature versus lamp current and the curve of apparent brightness temperature versus lamp current with the flame interposed gives the flame temperature.

The radiation flux equations are:

$$P_{s\lambda} = \epsilon_{s\lambda} P_{(BS)\lambda} \qquad (15)$$

$$P_{F\lambda} = \epsilon_{F\lambda} P_{(BF)\lambda} \tag{16}$$

For the lamp observed directly,

$$P_{R\lambda} = \epsilon_{S\lambda} P_{(BS)\lambda} \tag{17}$$

For the lamp observed through the flame,

$$P'_{R\lambda} = \epsilon_{S\lambda} P_{(BS)\lambda} (1 - \epsilon_{F\lambda}) + \epsilon_{F\lambda} P_{(BF)\lambda} \tag{18}$$

If

$$P_{R\lambda} = P'_{R\lambda} \tag{19}$$

then

$$P_{(BF)\lambda} = \epsilon_{S\lambda} P_{(BS)\lambda} \tag{20}$$

It is noteworthy that the result is independent of $\epsilon_{F\lambda}$, although the point of intersection of the curves of Fig. 9 is more clearly defined at higher values of the emittance. This method has been widely used on a laboratory scale for the study of diffusion flames of hydrocarbon gases burning slowly in air.

The method may be modified to permit the use of a comparison source at a fixed brightness temperature. In this case, the flame must be observed directly, to obtain an extra relationship.

<u>The mirror method</u>

In this method, a receiver measures first the radiation flux from the flame, and then the same flux augmented by flame radiation reflected from a mirror placed behind the flame, as illustrated in Fig. 10.

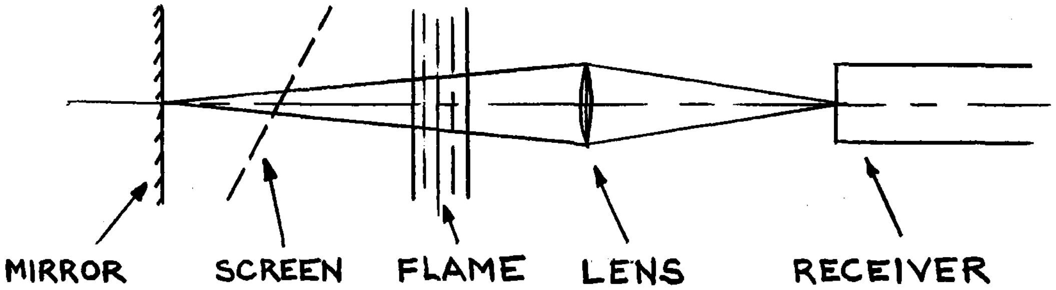


FIG 10: RADIATION SYSTEM FOR MIRROR METHOD

For the flame observed directly,

$$P_{R\lambda} = \epsilon_{F\lambda} P_{(BF)\lambda} \qquad (21)$$

For the mirror observed through the flame,

$$P'_{R\lambda} = \epsilon_{F\lambda} P_{(BF)\lambda} + \epsilon_{F\lambda} P_{(BF)\lambda} \rho_{M\lambda} (1 - \epsilon_{F\lambda}) \qquad (22)$$

Equations 21 and 22 may be combined to give

$$\frac{P'_{R\lambda}}{P_{R\lambda}} = 1 + \rho_{M\lambda} (1 - \epsilon_{F\lambda}) \qquad (23)$$

$$\text{if} \quad \epsilon_{F\lambda} \neq 0 \qquad (24)$$

Equations 21 and 23 provide the basis for the temperature determination.

The maximum possible value of $\frac{P'_{R\lambda}}{P_{R\lambda}}$ from equation 23 tends to 2 when $\rho_{M\lambda} \rightarrow 1$ and $\epsilon_{F\lambda} \rightarrow 0$. In general the value will lie between 1 and 2.

Hett and Gilstein$^{(14)}$ used this method to determine fluctuating temperatures by using two receivers for simultaneous measurement of $P'_{R\lambda}$ and $P_{R\lambda}$.

Continuum intensity distribution methods

These methods are based on the assumption that the ratio of the spectral radiation flux from the flame at one wavelength to that at another corresponds with the same ratio for a blackbody at the temperature of the flame. This is a satisfactory assumption, provided that the values of $\epsilon_{F\lambda}$ are equal at the two spectral regions examined. An example of the application of the principle is given by Hottel and Broughton$^{(15)}$.

METHODS APPLICABLE TO NON-CARBONACEOUS FLAMES

These methods utilise either radiation emitted by the flame or radiation from an additive introduced into the flame. The latter technique is most widely employed, and is treated first.

The spectral-line reversal method

This method was first proposed by Féry$^{(4)}$ and is described by Lewis and von Elbe$^{(18)(19)}$. It has been used extensively during the past half century for the determination of the temperatures of open flames, and less extensively for the determination of the temperatures occurring in the cylinders of reciprocating engines.

The additives used in this method are compounds containing an alkali metal which, when set free in the flame, emits radiation in a convenient spectral region. Atoms of alkali metals have a single electron in the outer "shell", and are thus listed in the first column of the Periodic Table. Experimentally, sodium, lithium and potassium are generally used. At the temperature levels commonly employed, the vapours of these elements satisfy the requirement that, for a given vapour, absorption and emission occur in the same spectral regions, and the relationship $\epsilon_\lambda = \alpha_\lambda$ may be applied.

With reference to a flame containing sodium vapour, observation of the flame spectrum in a spectroscope of average resolving power will show two sharply defined adjacent lines in the yellow region of the spectrum. These are produced by the sodium in the flame, and correspond with the dark absorption lines in the sun's spectrum known as the Fraunhofer D lines. If a comparison source is placed behind the flame, and its image is focused in the flame and refocused on the spectroscope slit, the observer may view the continuum produced by the comparison source simultaneously with the lines produced by the sodium. The combined spectrum will appear as shown in Fig. 11.

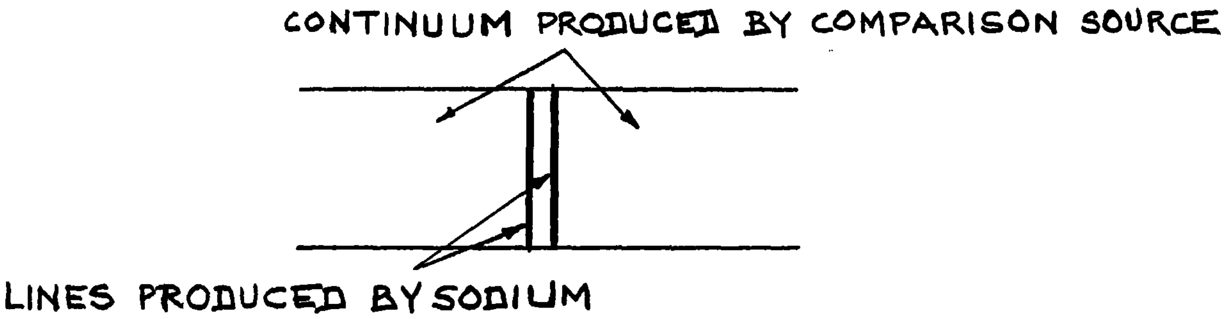


FIG 11 : COMBINED SPECTRUM IN LINE REVERSAL METHOD

The lines will appear bright or dark against the adjacent continuum according to whether the brightness temperature of the comparison source in the region of the D lines is lower or higher than the flame temperature. When the lines merge into the continuum and appear neither bright nor dark, the temperature of the flame is equal to the brightness temperature of the comparison source.

Expressed symbolically, at a given wavelength within one of the lines,

$$P_{R\lambda} = \epsilon_{S\lambda} P_{(BS)\lambda} (1 - \epsilon_{F\lambda}) + \epsilon_{F\lambda} P_{(BF)\lambda} \qquad (25)$$

and, adjacent to the lines,

$$P'_{R\lambda} = \epsilon_{S\lambda} P_{(BS)\lambda} \qquad (26)$$

If $P_{R\lambda} = P'_{R\lambda}$, then

$$P_{(BF)\lambda} = \epsilon_{S\lambda} P_{(BS)\lambda} \qquad (27)$$

and the flame temperature is equal to the brightness temperature of the comparison source in the region of the sodium D lines.

The equations are identical with those used in Kurlbaum's method, and the spectral-line reversal method is sometimes referred to as the Kurlbaum-Féry method. The term "reversal" arises from the experimental difficulty of effecting a close intensity balance. The technique followed when visual observation is employed is to vary the comparison source temperature until the point at which the sodium lines reverse from bright to dark is determined as closely as possible. As with Kurlbaum's method, the result is independent of $\epsilon_{F\lambda}$, although the sensitivity of effecting a reversal increases as $\epsilon_{F\lambda}$ increases. It may be shown that the method is independent of the existence of a continuum produced by radiation from carbon particles, although the sensitivity of the method is affected thereby, as discussed by Foote(6) and Perkins(24).

Griffiths and Awbery(12) and Strong, Bundy and Larson(30) discuss the effect of temperature variation along the axis of the radiation system. In general, observation of a hot region through a cooler fringe tends to give a result that is closer to the mean temperature than when a cool core is observed through a hotter fringe.

El Wakil, Myers and Uyehara(3) describe an electronic technique for determining flame temperatures by the sodium-line reversal method. Their paper contains a valuable commentary on the nature of the temperature measured. In the subsequent discussion, Hett expresses the belief that the chemical kinetics of sodium needs additional study before full confidence can be given to line reversal temperatures. A survey of the literature on the method indicates that unexpectedly high temperature values are sometimes obtained, and it is advisable to view critically any temperatures determined in regions in which combustion is taking place, for in such regions the thermal radiation may be augmented by chemiluminescence. Nevertheless, the method has been widely used and approved.

Methods using approximate continua.

Quinn(26) has developed a variation of the mirror method using a slit in the plane of the flame spectrum produced by a spectroscope to isolate the practically flat peak of the intensity distribution contour of sodium radiation from the flame. To ensure that the peak is being observed, sufficient sodium must be added to the flame to produce a value of $\epsilon_{F\lambda}$ equal to unity over the spectral region observed. By the use of electronic equipment, Quinn was able to measure fluctuating pulse-jet exhaust temperatures as low as 950°C.

Silverman(28) has applied the constant-temperature comparison source modification of Kurlbaum's method to the approximate continuum produced by carbon dioxide in the infra-red region of the spectrum.

Methods using intensity distribution in band spectra

These methods are discussed by Herzberg(13) and by Gaydon and Wolfhard(10). They have been applied to the rotational energy bands produced by flame radicals, and lead in many instances to such high temperature determinations that the radiation from such radicals could not have been exclusively thermal. Nevertheless, information thus obtained may be of interest in chemical reaction studies.

Spectrographs of high resolving power and long exposure times are required. The bands observed are useful only if self-absorption is known to be negligible. The methods appear to be applicable only to small flames under closely controlled conditions.

METHODS CHOSEN FOR STUDY

Following upon a consideration of the various radiation methods, it was decided that the sodium-line reversal method and Quinn's method would be applied to the spontaneous ignition rig in an attempt to determine the flame temperatures in the divergent duct. The sodium-line reversal method would be applied first to obtain mean values, and Quinn's method would be applied later to determine temperature fluctuations. Each method was to be examined on a small-scale rig prior to its use on the larger rig, for purposes of convenience and economy. Experiences with the sodium-line reversal method are described in this thesis. The second method is still under investigation.

OPEN FLAME RIG

In order to obtain experience prior to the construction of a temperature instrumentation rig, the open flame rig illustrated in Fig. 12 was constructed.

The method of salt aspiration and the optical arrangements corresponded closely with those used by Griffiths and Awbery(12).

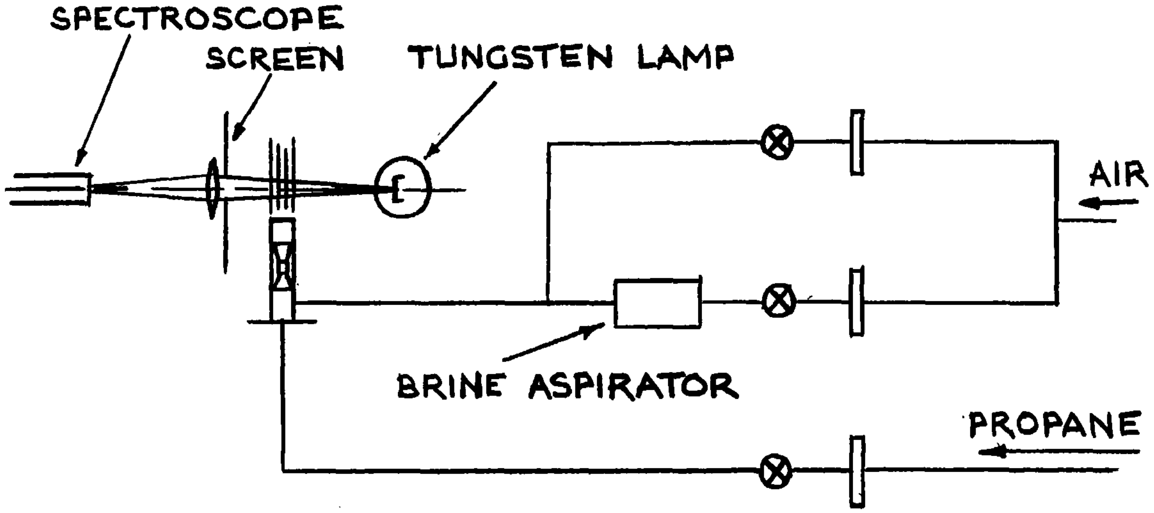


FIG 12: OPEN FLAME RIG

Propane-air mixtures were burned above the 1" diameter grid of a Fisher burner, in which gases are pre-mixed before combustion. The propane was commercially supplied, and had a minimum purity of 97%.

The propane and air flows were metered by small orifice plates in 1/4" pipe lines. The orifices were calibrated against Wet-Test Meters, as the pipe and orifice sizes were considerably below standard. Data for propane density calculations were taken from Deschner and Brown$^{(2)}$, based on a purity of 98.3%.

The introduction of sodium into the flame was effected by the use of a "scent-spray" type of brine atomizer, shown diagrammatically in Fig. 13. The by-pass in the air line, shown in Fig. 12, was an addition made in order to control the quality of the atomization independently of the total air

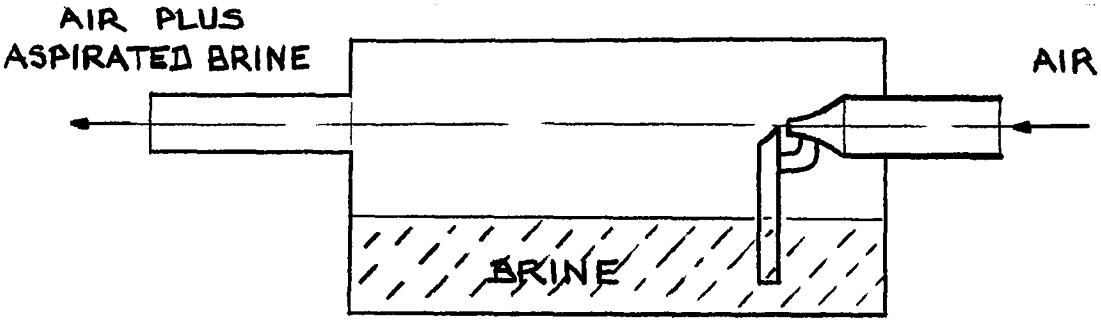


FIG 13: BRINE ASPIRATOR

flow, as it was found that the quality of the atomization deteriorated at the higher flows through the aspirator. The building-up of brine droplets in the lines downstream of the aspirator was a disadvantage in operation, and partial clogging of the burner grid by salt necessitated periodic washing of the burner.

The spectrum was observed in a Canadian Arsenals Type J.S. direct vision spectroscope. The two sodium D lines could be readily resolved when the slit was sufficiently narrow.

The tungsten ribbon filament lamp used as a comparison source was obtained from the Canadian General Electric Co.. It was calibrated for brightness temperature at $\lambda = 0.665\mu$, in the red spectral region, against lamp current by means of a Leeds and Northrup type 8622 optical pyrometer. It was found that a five minute interval was required for the establishment of steady conditions when lighting the lamp from cold, and care was taken to permit equilibrium conditions to be established before recording each temperature. The curve obtained is shown in Fig. 14. The correction curve for brightness temperatures at $\lambda = 0.5893\mu$, in the region of the

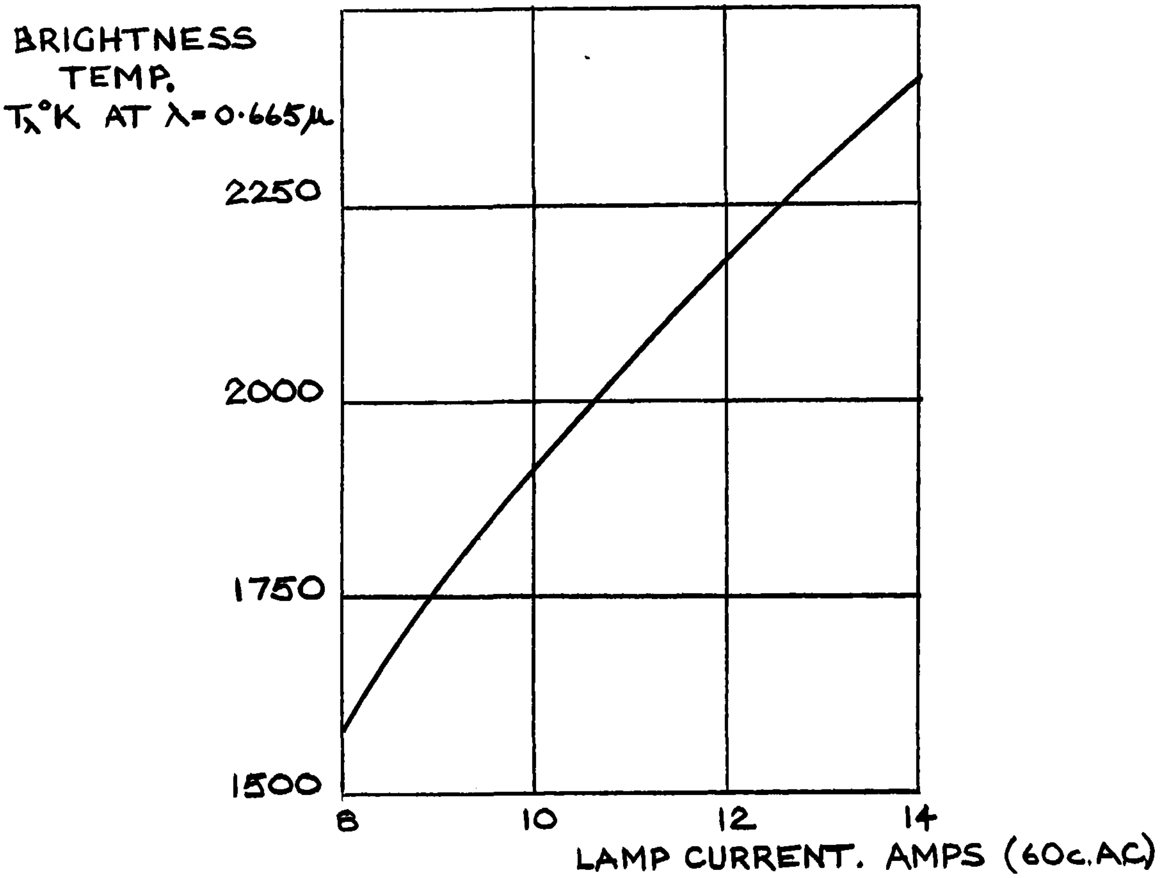


FIG 14: CALIBRATION CURVE FOR TUNGSTEN RIBBON FILAMENT LAMP

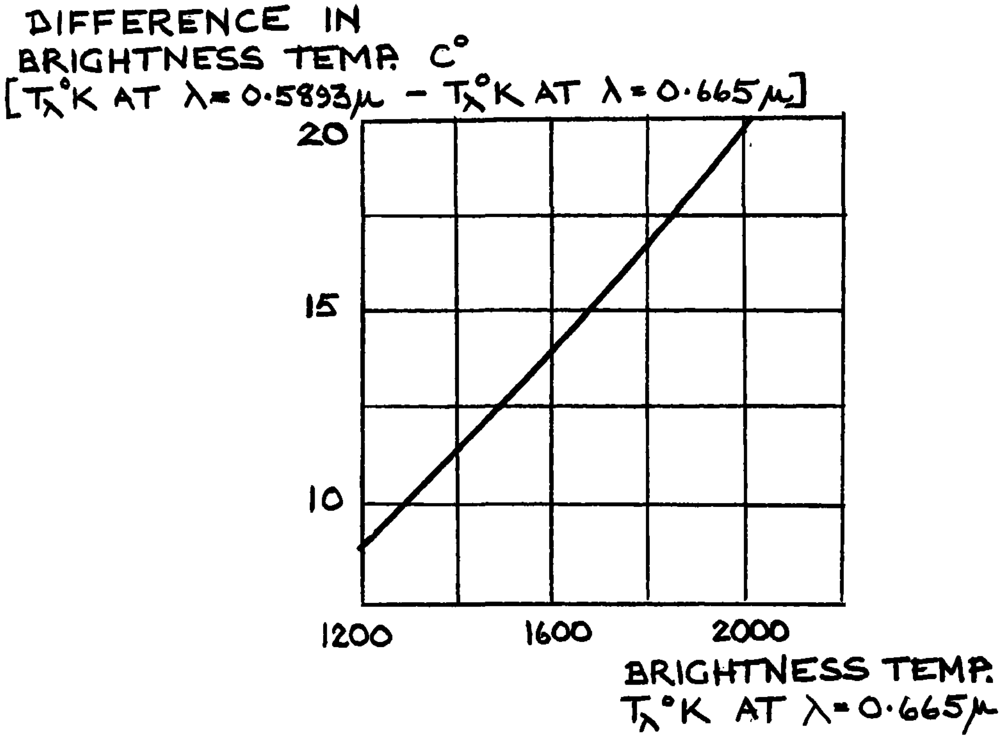


FIG 15: BRIGHTNESS TEMPERATURE CORRECTION

sodium D lines, is given in Fig. 15, and was calculated from data on the spectral emittance of tungsten given by Forsythe and Worthing(7). Lewis and von Elbe(18) describe the method of calculation in detail. The correction for lens transmittance was assumed to be equal in magnitude but opposite in sign to the correction of Fig. 15, and therefore the curve of Fig. 14 was taken to give brightness temperatures at the D lines directly.

Flame temperature determinations

Thirty reversals were obtained for different propane/air mass flow ratios within the range 0.05 to 0.11 and for air mass flows in the region of 2.5 to 3.5 lb/hr. The flame was observed in the region just above the bunsen cones attached to the grid. The mean curve which summarises the results is given in Fig. 16. The scatter was high, of the order of ± 50 C°. This was attributed partly to lack of experience in observation, and partly to the variations in setting.

For comparison, the results for propane-air mixtures given by Loomis and Perrott(20), obtained with apparatus similar to that used by the author, are presented. Conversion of the results to a propane/air mass flow ratio basis was effected by assuming that the specific gravity of the propane used, "of commercial grade", was 1.56 times that of air.

Results given by Blackshear(1) for sodium-line reversal determinations at a height of three inches above an opening on which an open flame of propane and air was stabilized are also plotted.

The author's results are displaced to the right of those of Loomis and Perrott, but agree quite closely with those of Blackshear.

For further comparison, a curve of maximum values of temperature obtained later by the author from the combustion of propane-air mixtures

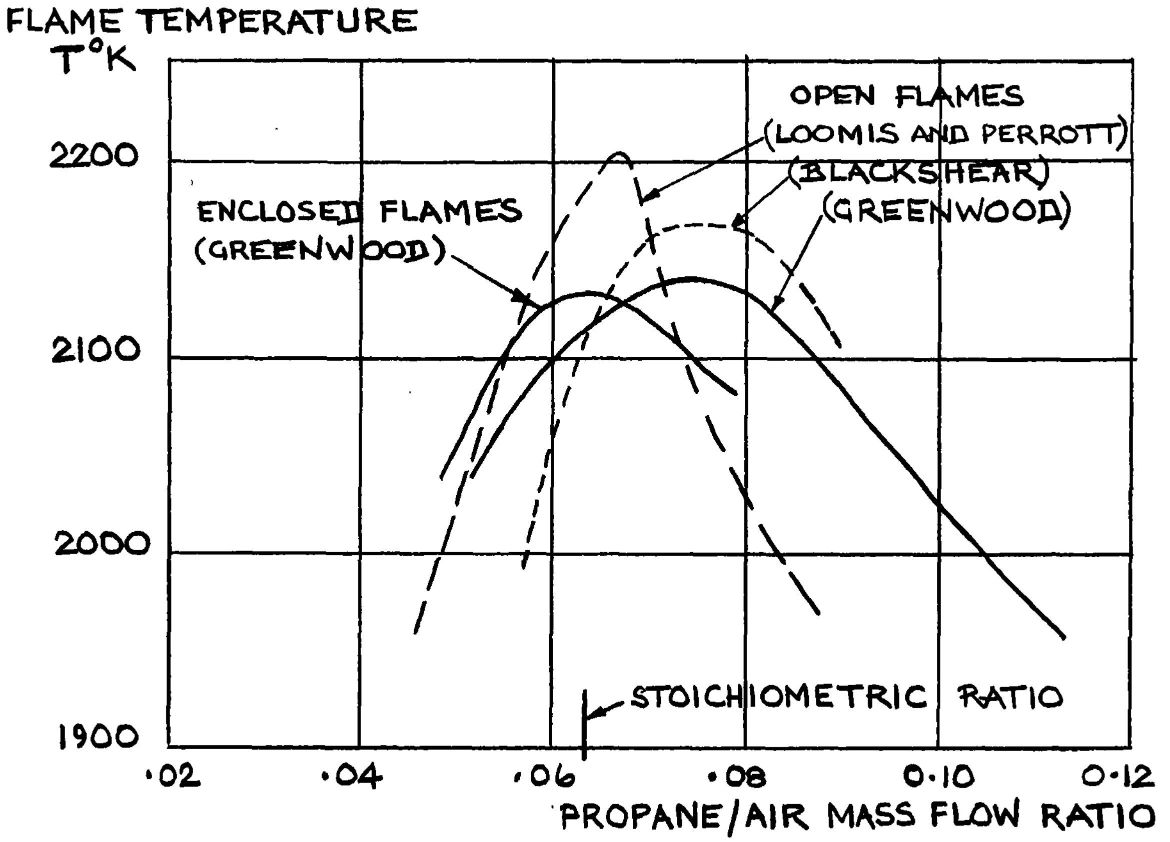


FIG 16: TEMPERATURE DETERMINATIONS ON OPEN FLAMES

in a quartz combustion tube on the temperature instrumentation rig is also shown in Fig. 16. It is debatable with which open flame curve it more closely corresponds, but general agreement in the stoichiometric region is evident.

The experiments on this rig served to acquaint the author with the method, and with the necessity for refining the experimental technique. It was apparent that temperatures of the right order of magnitude were being determined. Results obtained with open flames are of doubtful value, particularly at rich mixture strengths, for which the possibility of combustion occurring in the outer regions of the flames between unburnt hydrocarbons and the surrounding atmosphere must be considered.

TEMPERATURE INSTRUMENTATION RIG

The temperature instrumentation rig was constructed for the purpose of making temperature traverses along the axes of small-scale combustion tubes, thus carrying out work similar to that proposed for the spontaneous ignition rig.

The rig is shown diagrammatically in Fig. 17, and photographs are given in Figs. 18 - 21. The radiation system was stationary, and the combustion tube was carried on a sliding frame which could be moved in the direction of the axis of the tube. This arrangement permitted the radiation system to be more firmly mounted.

Several types of combustion tube were used, with internal diameters of approximately one inch, and with lengths of from two to three feet.

Propane-air mixtures were burned in the tubes. The burner consisted of a cylindrical plug containing four radially drilled holes from which propane issued into an air stream which had passed through swirl vanes to produce a vortex motion, in conventional manner.

The propane metering orifice consisted of a 0.06" diameter hole drilled in shim brass and located in 1/4" standard pipe. It was calibrated by a Wet-Test Meter.

The results were plotted on a practically dimensionless basis. Mass flow was plotted as ordinate, and the product of the pressure drop across the orifice, expressed as a head, and the ratio of the absolute pressure to the absolute temperature measured upstream of the orifice, was plotted as abscissa. The points fell on a straight line, within the limits of experimental error, and provided a calibration curve.

The air metering orifice consisted of a 0.25" hole drilled in a thin brass plate and located in 2" standard pipe. It was calibrated by standard orifices. The results were plotted in the same manner as described above for the propane orifice.

It was considered desirable to use dry-salt aspiration on this rig to avoid the practical difficulties and some of the theoretical objections

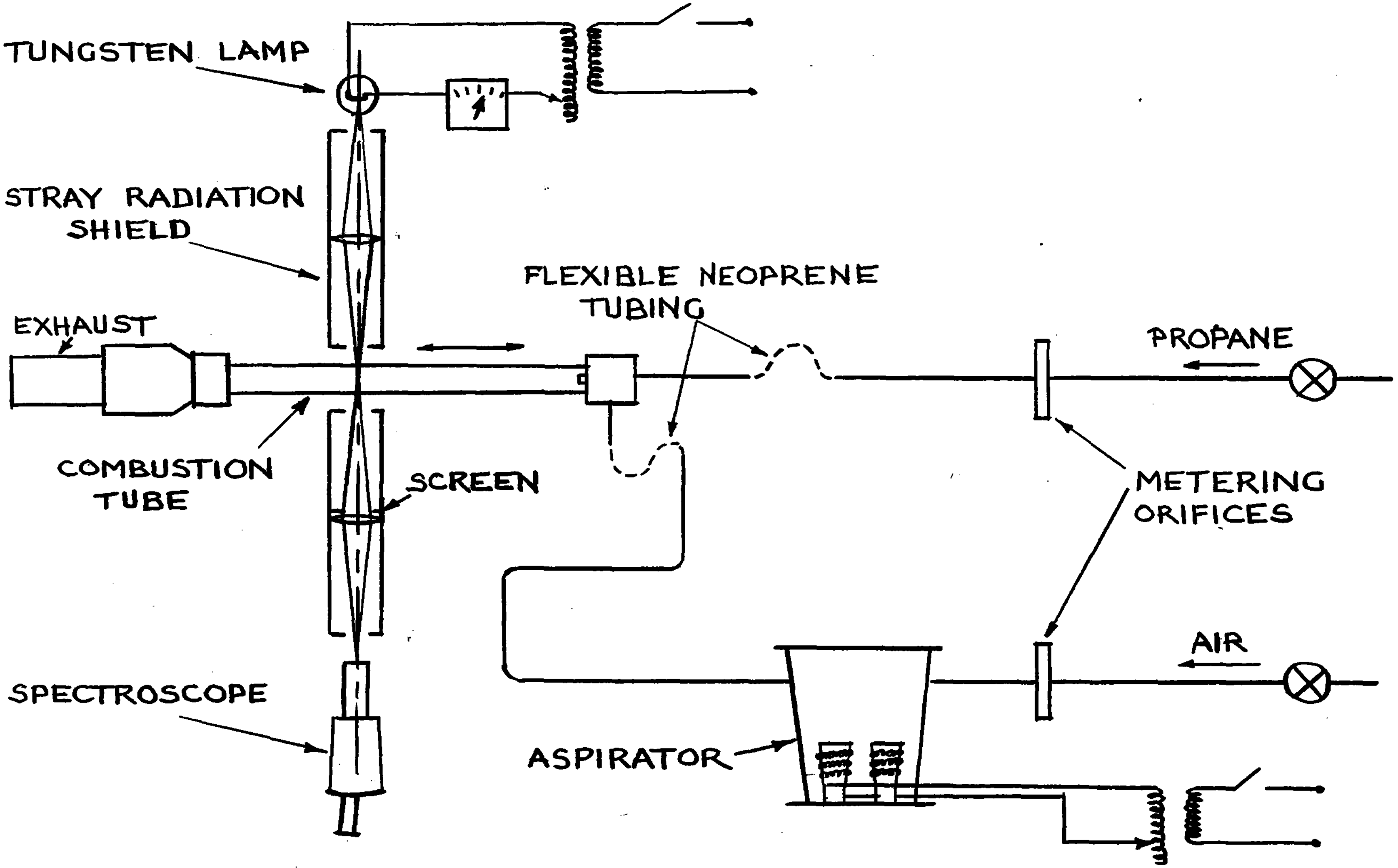


FIG 17: TEMPERATURE INSTRUMENTATION RIG

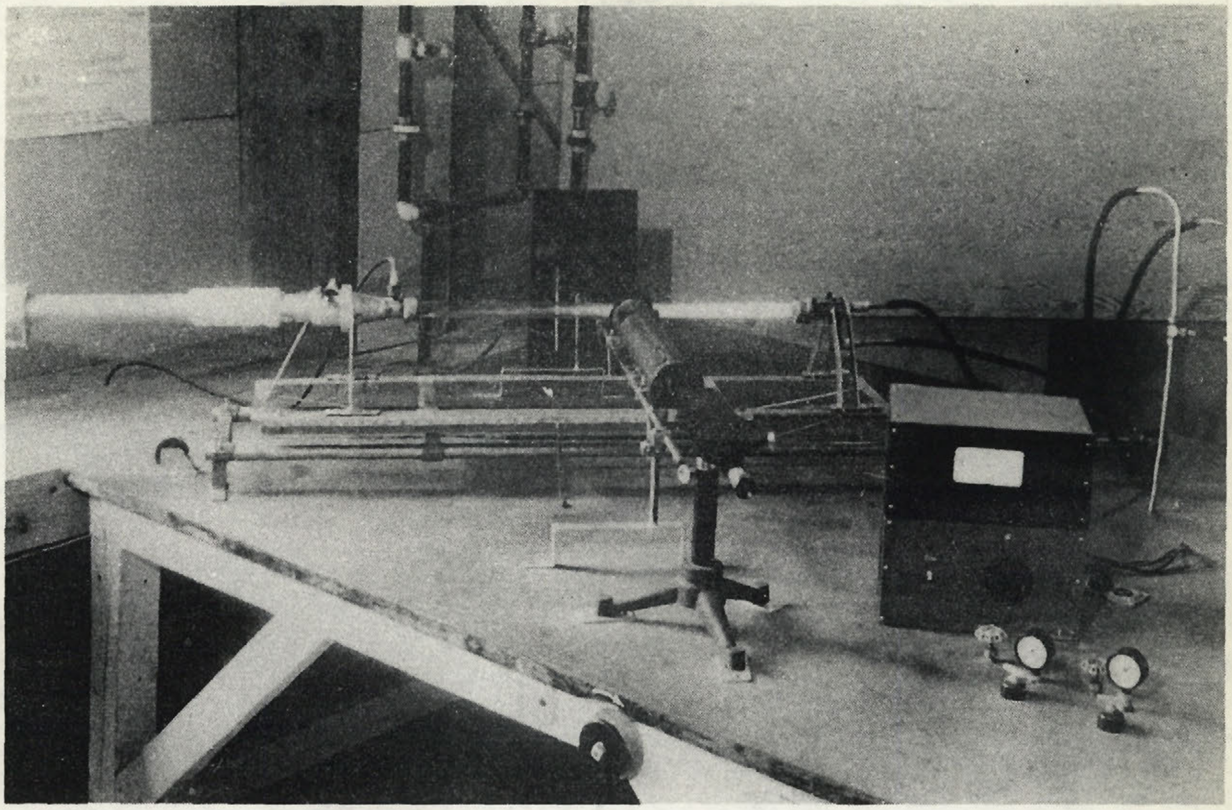


FIG.18 TEMPERATURE INSTRUMENTATION RIG

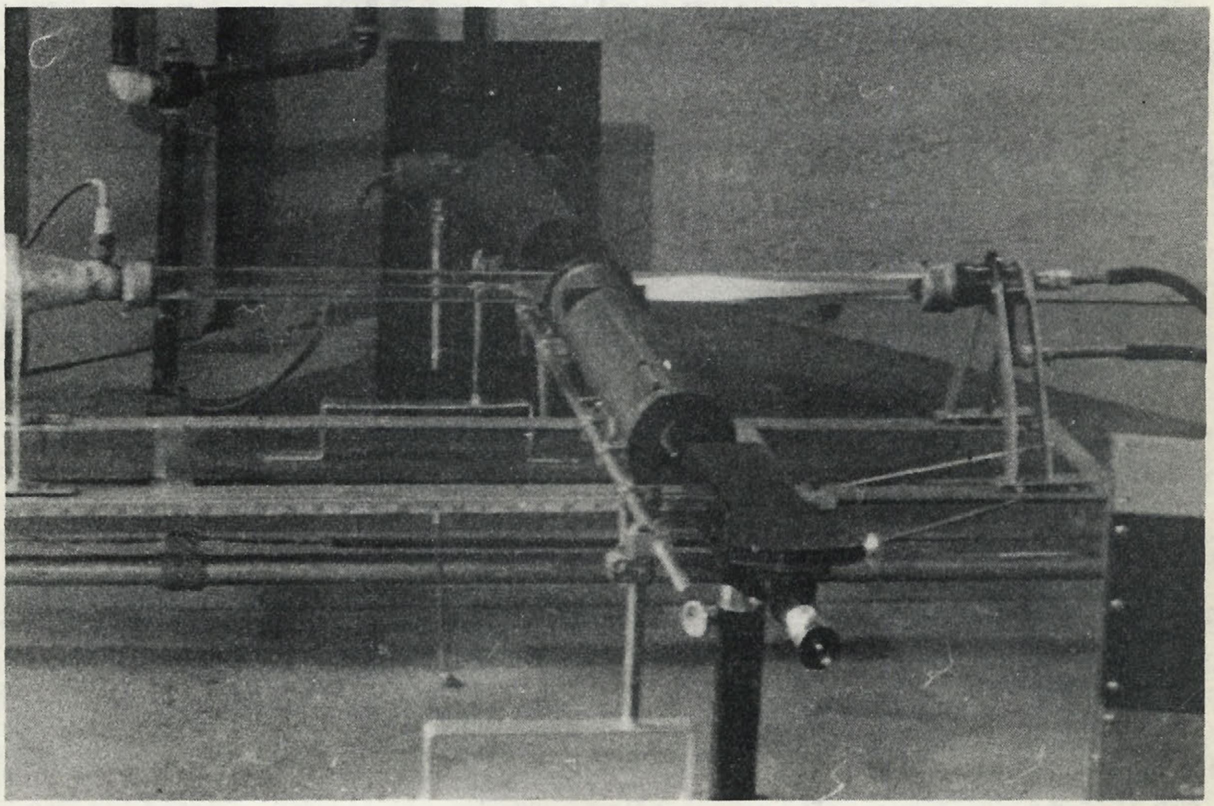


FIG 19 APPEARANCE OF FLAME NEAR WEAK EXTINCTION LIMIT

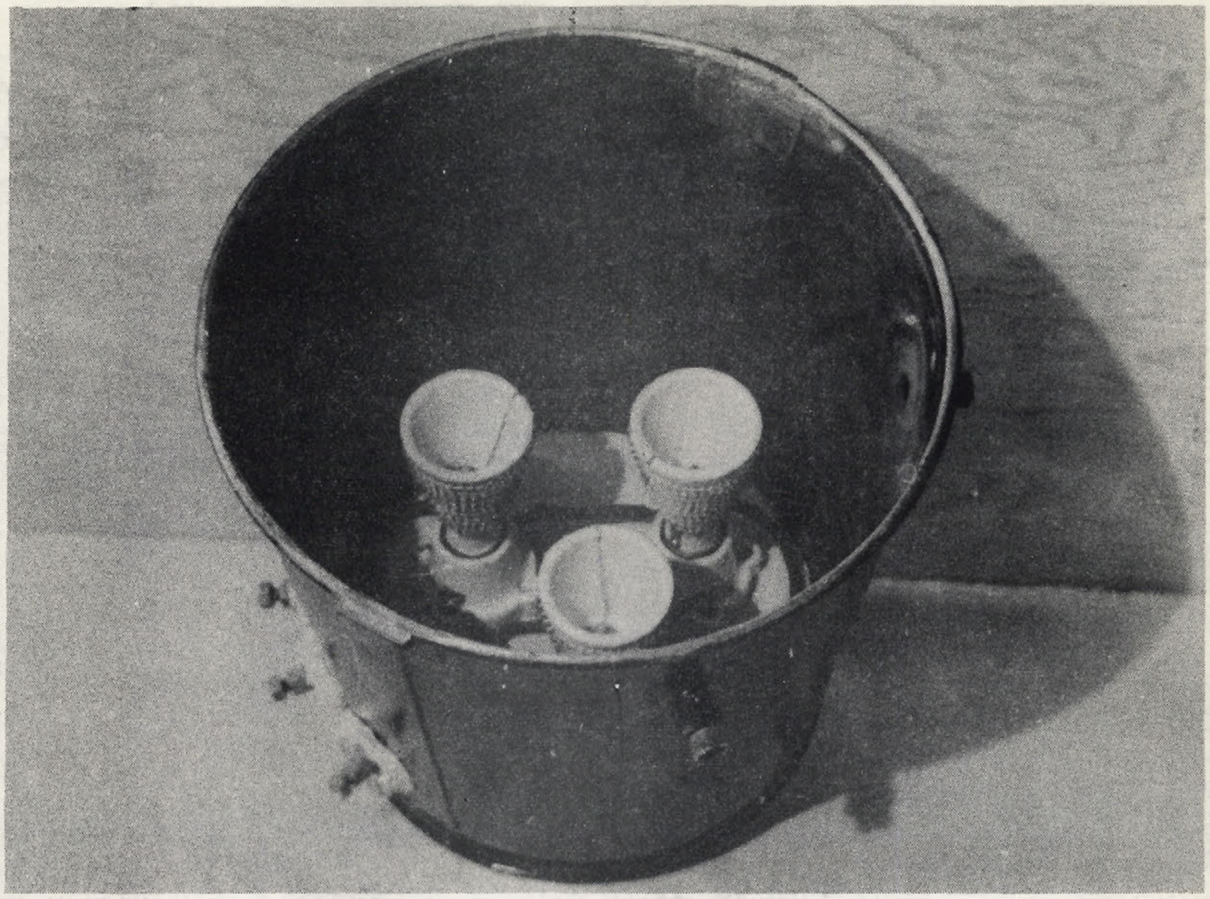


FIG. 20 ASPIRATOR

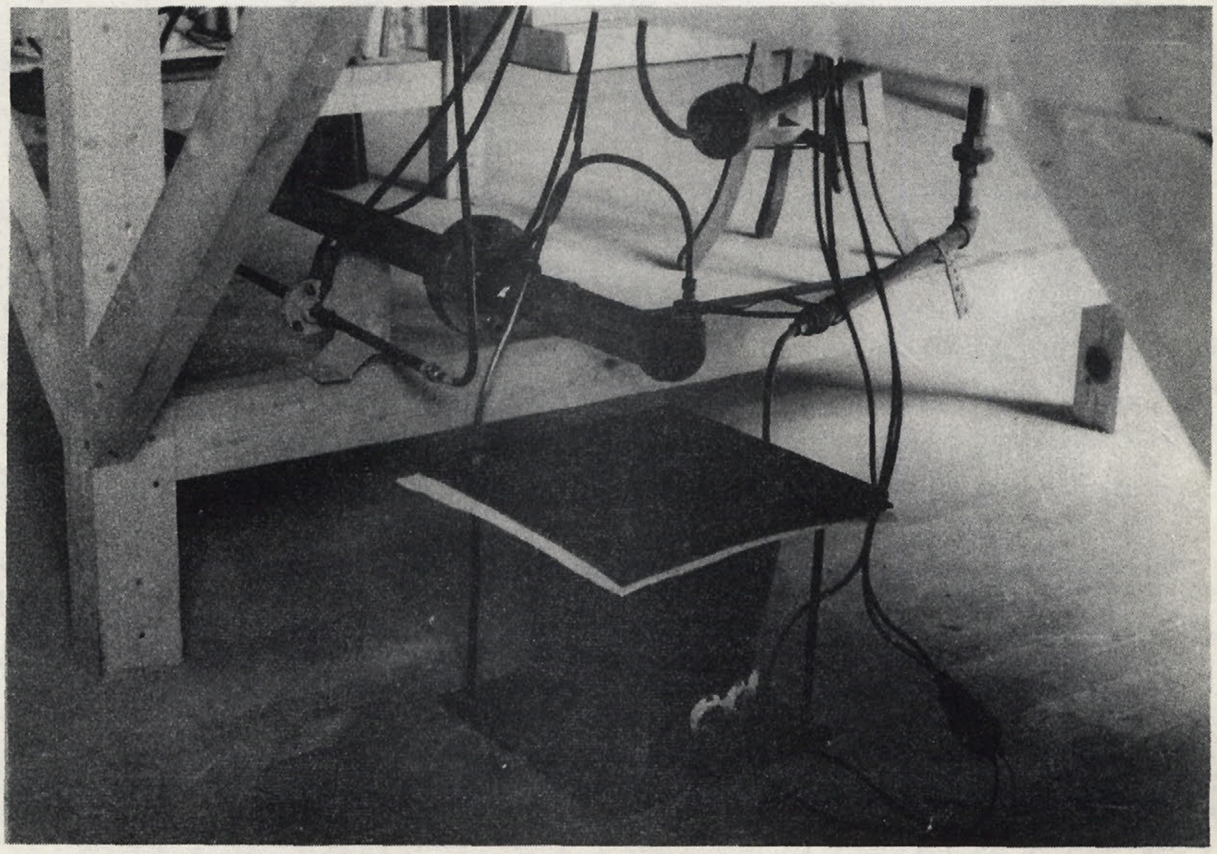


FIG. 21 ASPIRATOR INSTALLED IN AIR LINE

associated with brine aspiration. Water injected into a flame may absorb heat and, in the form of steam, take part in chemical reactions.

Several trials with powdered-salt aspiration proved unsatisfactory, and the aspirator finally developed is shown in Fig. 21.

Sinclair and La Mer(29) produced sodium chloride nuclei by vaporizing salt on a heated wire. The aspirator developed for the rig was based on this principle, and three standard radiant heater elements were used in order to provide an adequate heating surface. The elements were placed in cooling hot brine and withdrawn before heavy crystallization occurred. When dry, they were placed in the aspirator, and sufficient vaporization occurred when the coils were at a mild red heat, corresponding to a supply potential of about 90 volts, to produce an evenly coloured yellow flame. Variation in the concentration of sodium vapour in the flame was effected by varying the number of elements heated, and by varying the supply voltage in the range 90-110 volts.

Some salt was deposited on the heater coils themselves during the coating process, but most appeared to be absorbed in the ceramic body. The latter sweated salt when heated, and was probably the main source of supply of the vapour.

The aspirator could be used for about three running hours between coatings. The principal limitation was the rise in temperature of the aspirator and the gas stream during operation. A practical limit of about fifteen to thirty minutes operation for each set of trials was the consequence, during which time the rise in temperature of the air supply at the inlet to the combustion tube was about 15C°. Since a traverse could be made in about three minutes, however, the limitation was considered acceptable.

The temperature of the air supply at the inlet to the combustion tube was measured with a mercury-in-glass thermometer.

The tungsten ribbon filament lamp used as a comparison source was the one that had been used on the open flame rig. Check calibrations were made periodically, but no variation from the curve of Fig. 14 was detected. This indicated that there had been no deterioration of the filament.

The spectroscope, also, was transferred from the open flame rig.

The lenses were "Hardex" heat-treated lenses for use under high-temperature conditions. Each lens had a diameter of about 1 3/8" and a power of 8 dioptres, corresponding to a focal length of a little less than five inches.

The lenses were located so as to produce images equal in size to the comparison source.

The correction for the transmittance of the lens between the lamp and the combustion tube was found to be equal in magnitude, within a few degrees, to the correction to be applied to the brightness temperature of the lamp determined with the optical pyrometer, and was opposite in sign. As in the open flame work therefore, the curve of Fig. 14 was taken to give the brightness temperature of the lamp in the region of the D lines.

Combustion tube clouding

For the early experiments on the rig, combustion tubes of high initial transparency, available commercially under the names "Pyrex Vycor" and "Vitreosil" were used. The former has a composition of about 96% fused quartz, the remainder being largely boric oxide. The latter is practically pure quartz. The combustion tube shown in the photographs ~~is~~ a Pyrex Vycor tube, but the traverses were made on Vitreosil tubes. The windows used in later experiments were of practically pure quartz.

The most serious difficulty encountered in the early experiments was the progressive loss of transparency of the combustion tubes with use.

Two more or less distinct effects appeared to be responsible for this trouble.

When quartz is subjected to a high temperature, recrystallization may take place. This process is known as devitrification. Unfortunately, it is accelerated by the presence of alkali metal vapours.

The second process is that of "frosting", due to a reaction at high temperatures between sodium vapour and the silicon in the tube, producing sodium silicate.

Devitrification may thus affect the whole thickness of the tube, but devitrification in the presence of sodium vapour, and the frosting process, are most evident in an attack on the inside surface.

Some time was spent attempting to separate the factors influencing the progressive clouding-up of the tubes. The Pyrex Vycor tubes cost about ten dollars apiece, and the Vitreosil tubes cost about twenty dollars apiece. The useful life of each was found to be of the order of thirty minutes with sodium aspiration, after which the clouding-up appeared serious. Economic factors prohibited extensive research.

The earlier use of powdered-salt aspiration delivered salt particles to the flame. These particles settled on the tube wall and seriously attacked it, leaving foggy patches, and in some cases building-up as a crust-like deposit. The aspirator shown in Fig. 21 was developed as a direct result of this trouble. The corresponding attack on the tube consisted of an even, milky cloud on the inner surface. This clouding could be removed with a cloth in the cooler operating regions of the tube, but in the higher temperature zones the attack was permanent.

Devitrification was troublesome only in the case of the Pyrex Vycor tubes. At the flame temperatures used on the rig, subsequently found to be of the order of 2000°K, the devitrification of the Vitreosil tubes was negligible, except in so far as it may have occurred at the inner surface, where permanent clouding occurred in the presence of sodium vapour.

Temperature traverses using quartz tube

The results of five traverses on a Vitreosil combustion tube at approximately constant throughput and inlet temperature and at various mixture strengths, are given in Fig. 22.

The curves follow similar trends, the temperature rising to a maximum at from one to three inches downstream of the burner and then steadily falling towards the exhaust. The point of maximum temperature moves downstream as the richness increases, and the peaks of the rich curves appear flatter.

The maximum temperatures obtained at each mixture strength are plotted on Fig. 16 for comparison with results on open flames.

The five tests on the Vitreosil tube involved a total of approximately thirty minutes sodium aspiration. In an attempt to assess the effect on the suitability of the method of the loss of transparency experienced, the maximum temperature correction due to the reduction in transmittance was plotted on a sodium aspiration time basis. The resulting curve is shown in Fig. 23, and no sign of levelling off is evident. The useful life of the tube therefore appeared to be limited to about thirty minutes.

The method of determining the temperature correction was as follows: The tungsten lamp was observed through the combustion tube, before and after each test, with an optical pyrometer, and the apparent brightness temperatures so obtained compared with those for the same lamp

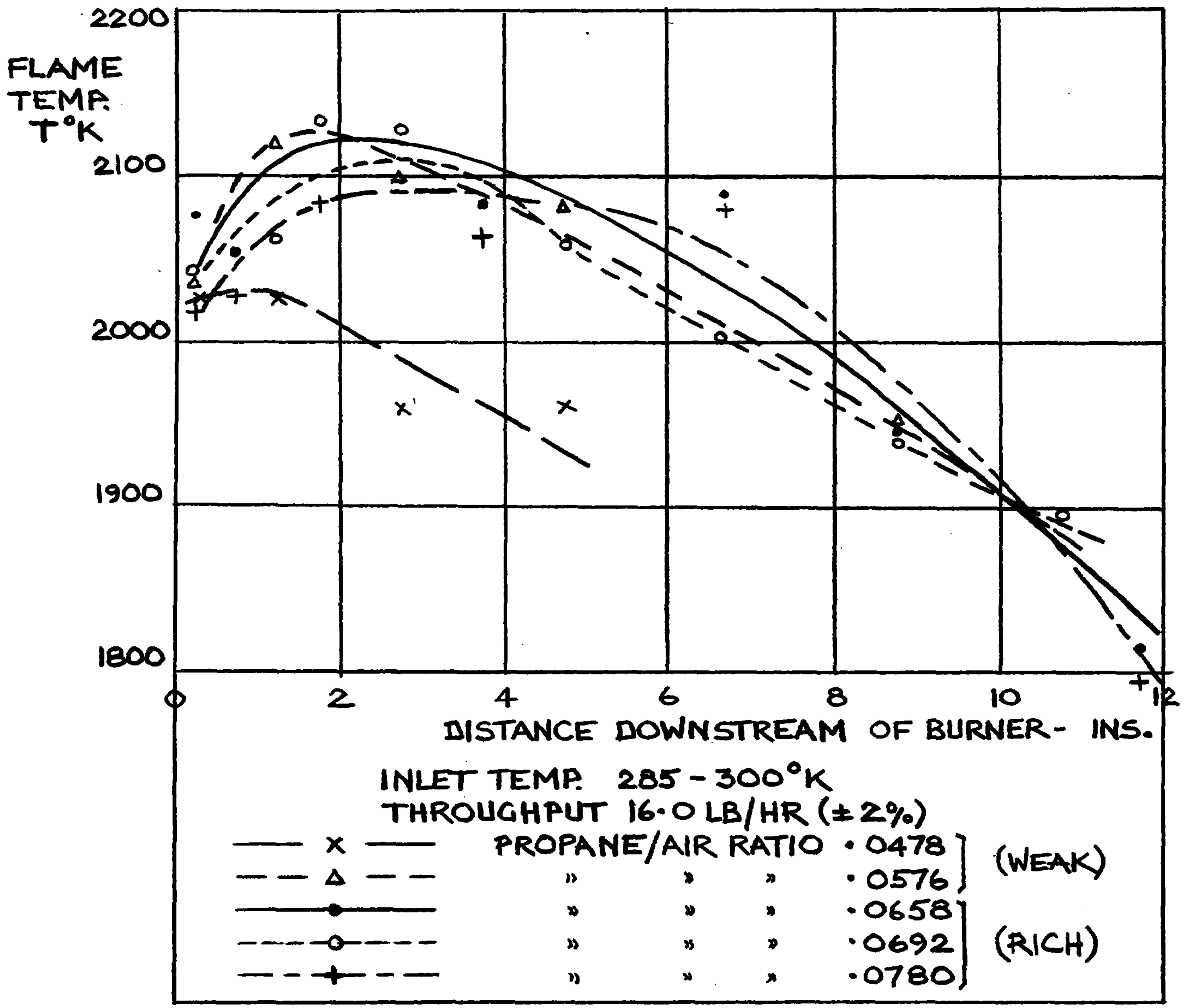


FIG 22: TEMPERATURE TRAVERSES USING QUARTZ TUBE

current when the lamp was observed directly. In making flame temperature determinations, a correction has to be applied for the transmittance of the wall of the tube nearer the lamp, and it was necessary to make the assumption that each wall had the same transmittance, for it was not feasible to split the tube and so observe through one wall alone. This assumption regarding transmittance seemed reasonable in that the clouding-up appeared fairly uniform to the eye. The further assumption was made that the transmittance in the D line region of the spectrum was equal to that in the region observed in the optical pyrometer. This seemed reasonable in that the clouding appeared white to the eye.

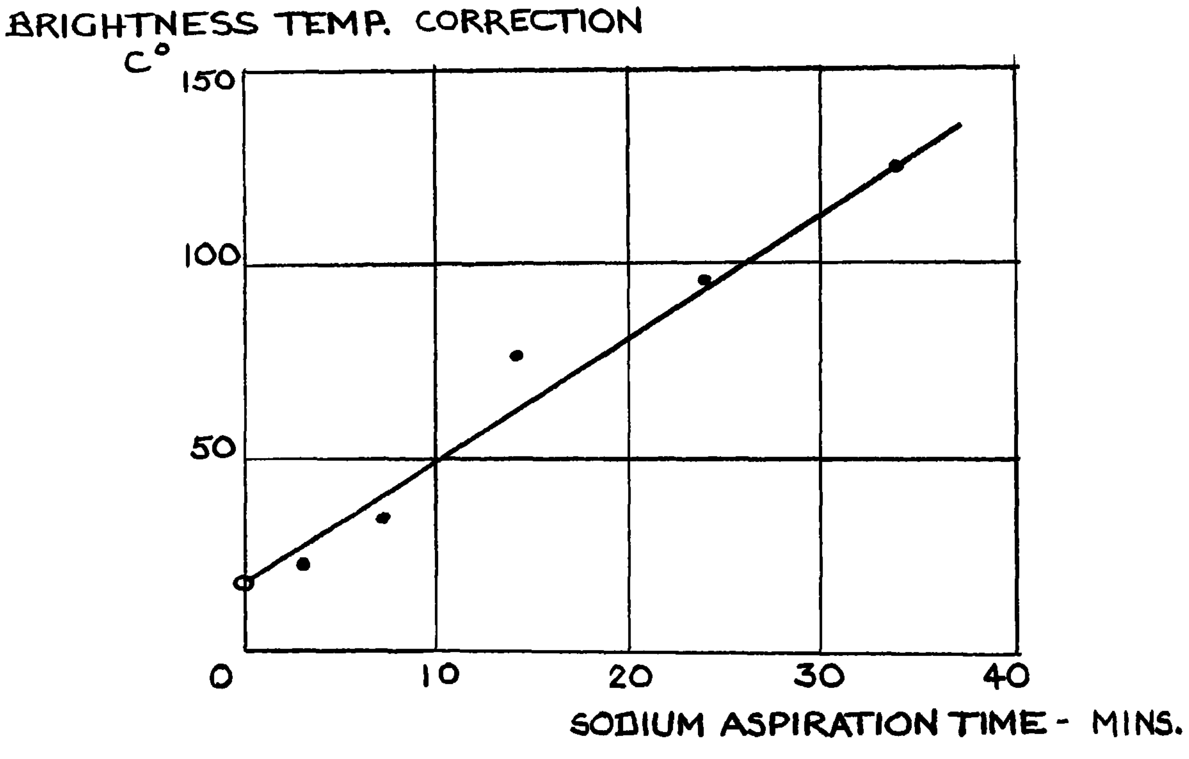


FIG 23: CORRECTION FOR SINGLE WALL CLOUDING

When the combined transmittance was high, the temperature correction due to the transmittance at one wall could be taken as one half that due to the two walls but, at lower values of the transmittance, the correction due to one wall was rather more than one half that due to the two walls, and calculations using Wien's formula (with $\lambda = 0.665\mu$) for the temperatures used led to the decision to use a figure of 0.55 times the temperature correction for two walls as the single wall correction.

A further factor was the possibility of the transmittance of the tube varying with temperature. To test this, the clouded tube used in the experiments described above was placed on the rig and run at approximately stoichiometric conditions without sodium vapour aspiration. The apparent brightness temperature of the lamp given by the optical pyrometer appeared to be higher when viewed through the hot tube than when viewed through the cold tube. The results are plotted in Fig. 24, and indicate that there was an increase in transmittance of the tube when hot. The tube was observed with the optical pyrometer during the run and a brightness temperature traverse taken. The results of this traverse are shown in Fig. 25.

By considering the radiation from the tube at a point 2 1/2 inches downstream from the burner, and the transmitted lamp radiation through the hot and cold tube respectively, at the same point, calculations based on Wien's formula (with $\lambda = 0.665\mu$) showed that the contribution of the radiation from the tube itself was negligible.

For practical purposes, then, the curves of Fig. 24 could be taken to indicate the effects of transmittance when the tube was respectively hot and cold. The brightness temperature differences shown corresponded to observation through two walls. The test indicated, then, that a correction of the order of +30 C° should be applied to those results of Fig. 22 which were taken when the clouding-up became serious, for the corrections that had been applied were based on the measurement of the effects of transmittance when the tube was cold. In view of the magnitude,

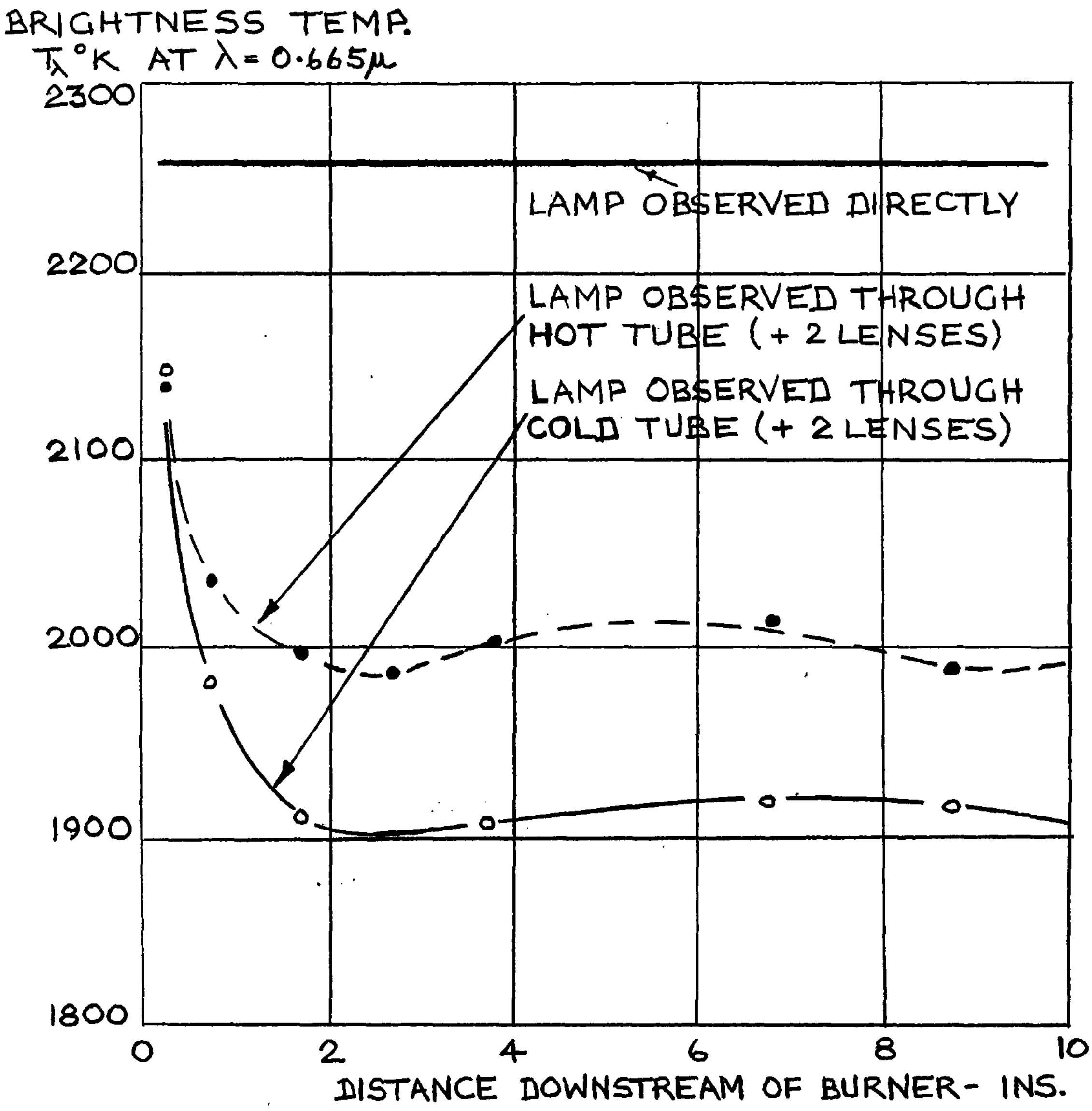

BRIGHTNESS TEMP.
T_λ °K AT $\lambda = 0{\cdot}665\mu$
2300
2200
2100
2000
1900
1800
0
2
4
6
8
10
DISTANCE DOWNSTREAM OF BURNER- INS.
LAMP OBSERVED DIRECTLY
LAMP OBSERVED THROUGH HOT TUBE (+ 2 LENSES)
LAMP OBSERVED THROUGH COLD TUBE (+ 2 LENSES)

FIG 24

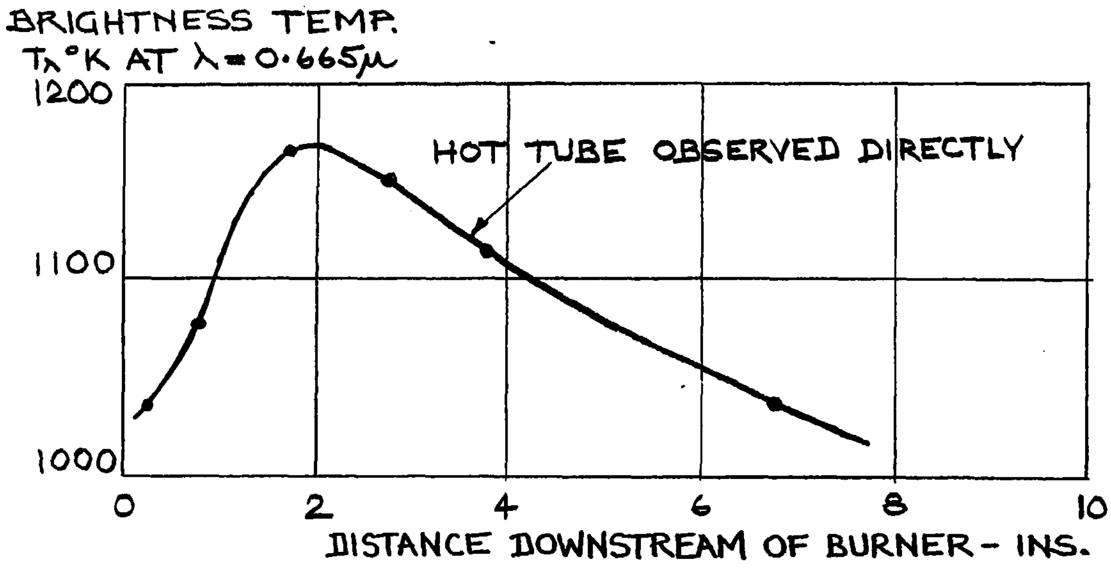

BRIGHTNESS TEMP.
T_λ °K AT $\lambda = 0{\cdot}665\mu$
1200
1100
1000
0
2
4
6
8
10
DISTANCE DOWNSTREAM OF BURNER - INS.
HOT TUBE OBSERVED DIRECTLY

FIG 25

and hence the uncertainty, of the temperature corrections applied in the later tests, however, no modification was made to the curves.

Attempts at checking the above results by aspirating lithium sulphate vapour and effecting a reversal on the red lithium line were not successful. The author was not able to obtain a dark absorption line at high lamp brightness temperatures.

Examination of the variation of transmittance with wavelength of clouded-up Pyrex Vycor and Vitreosil Tubes was made later with an electronic photometer. The results are presented in Fig. 26.

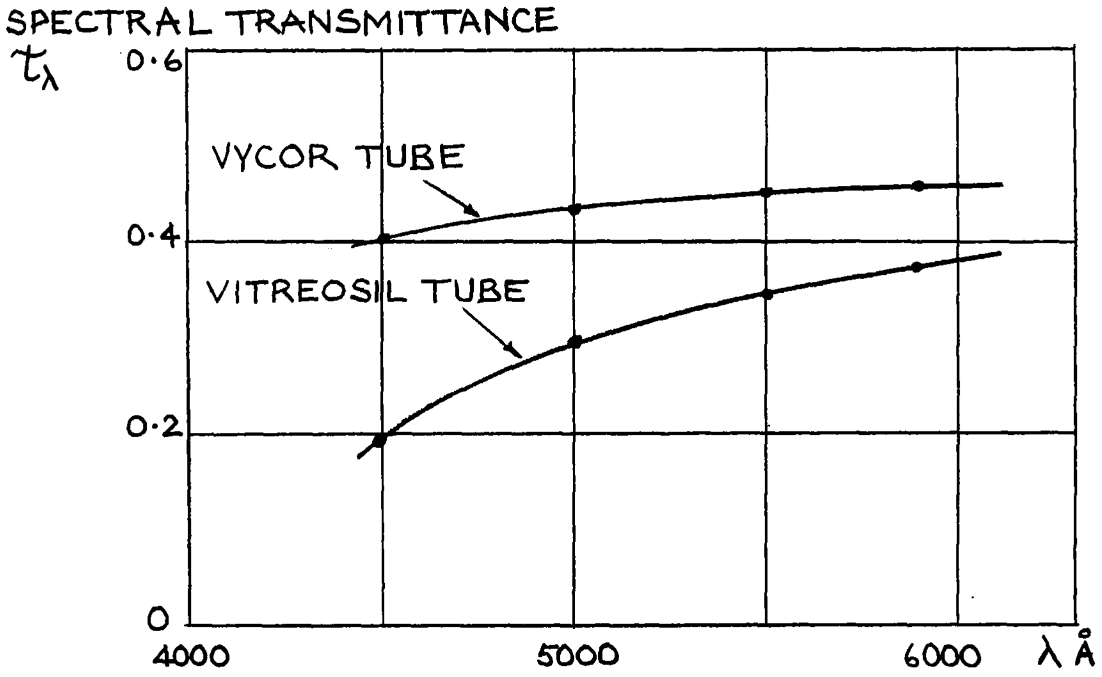


FIG 26 : VARIATION OF TUBE TRANSMITTANCE WITH WAVELENGTH

The transmittance appears to increase steadily with wavelength over the visible region of the spectrum, through the increase is not considered sufficient to necessitate modifying the results of Fig. 22.

Temperature traverses using steel tube

In an attempt to avoid the troubles associated with tube clouding, a steel tube with diametrically opposed observation holes was fitted to the rig. Light from the lamp could thus be observed at evenly spaced stations along the tube. No correction for transmittance was necessary, so the determinations were rapid. The rig was run at settings corresponding closely with those used in the tests with the quartz tube, and the curves obtained were in good agreement with the curves for the quartz tube. Owing to the fact that flames issued from most of the holes during the trials with the steel tube, little significance can be attached to these results. Nevertheless, traverses were readily made over a range of settings, and some results are given in an earlier paper by the author(11).

Clouding of recessed windows

The quartz windows on the spontaneous ignition rig are set back about 3/4" from the duct wall. It was considered that this might be expected to afford some protection by reducing the effects of direct flame impingement.

To test this effect, a 2" length of 1/4" pipe was welded around one of the holes in the steel tube used in the tests described above, and a small piece of clear quartz was secured to its open end to act as a window. After about thirty minutes running with sodium aspiration under approximately stoichiometric conditions no detectable clouding resulted. A reduction of the pipe length to 1/2", which was approximately the length of the visible flame emerging from the other holes near the burner, resulted in slight clouding after thirty minutes running, but the clouding was in the form of a light deposit, and was easily removed.

A steel combustion tube with windows recessed 3/4" at each observation station was tested on the rig, and the reduction in transmittance was determined after about forty five minutes sodium aspiration time in tests over a range of settings using weak and rich mixture strengths. The reduction in transmittance appeared to be about double that produced by a single wall in the experiments using a quartz combustion tube, but the deposit on the inner surface of each window was easily removed by rubbing with soft tissue, and the initial transmittance restored. In cases where some of the cement used in attaching the windows had deposited on the inner surface, a permanent attack resulted, and the transmittance was permanently reduced.

It was early recognised that, in work of this type, it is important to exercise care in handling quartz to avoid contaminating the surface to be presented to the flame.

Ignition of the mixture when using recessed windows was occasionally accompanied by windows blowing out. This may have been due to the general pressure rise in the tube as the flame travelled upstream to the burner, or possibly to mild explosions in the small chambers carrying the windows. The trouble was overcome by separating the burner head from the combustion tube, lighting the mixture at a low throughput, and then moving the burner head back into position in the tube.

TRIALS ON SPONTANEOUS IGNITION RIG

A spectroscope was constructed and mounted on a trolley which could be tracked parallel to the axis of the divergent duct on the spontaneous ignition rig. Apart from the spectroscope, the optical system was the same as that used on the temperature instrumentation rig. The optical bench carrying the lenses and the lamp was attached at one end to the trolley, and was supported at the other end by a second track parallel to the duct axis. The stop covering the lens nearer the spectroscope was reduced in size to allow for wider variations in alignment due to thermal distortion, for the duct radiated at a red-heat when in operation. The spectroscope and the optical bench were of heavy construction to permit reliable operation under the high-temperature conditions in the cell. A radiation shield was placed around the spectroscope to shield it from direct radiation from the duct. Prior to installation in the cell, the spectroscope was tested on the temperature instrumentation rig, and satisfactory sodium-line reversals were obtained and temperature determinations made.

Sodium aspiration

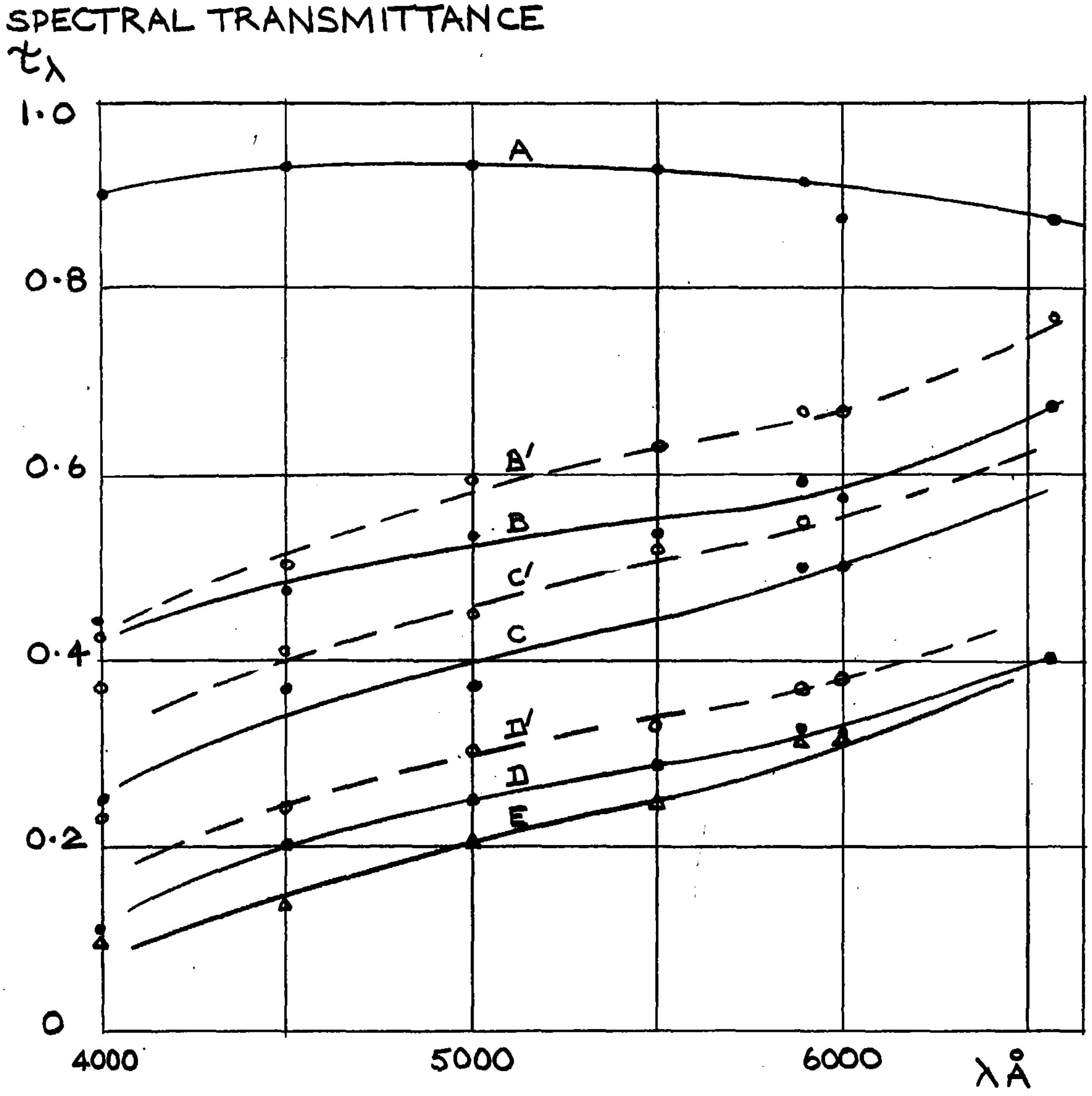
Attempts at injecting brine into the hot gas stream proved unsuccessful, as the injectors rapidly became clogged with salt.

The method finally adopted was one employed by Watts and Lloyd-Evans(31). A solution of sodium ethoxide in ethyl alcohol was mixed with the kerosene injected into the stream in the divergent duct. The flame, stabilized in the duct, emitted sodium D line radiation, but no radiation of this type was apparent in the region ahead of the flame front. The quantities of sodium ethoxide required to produce the radiation were considerably in excess of those used by Watts and Lloyd-Evans, owing presumably to the lower temperature levels on the spontaneous ignition rig.

As far as the author could determine, the sodium ethoxide solution was the only one that could be intimately mixed with kerosene. Sodium ethoxide is available commercially at a relatively high cost, but can be prepared with care and patience at a moderate cost on a laboratory scale using vacuum distillation methods. The compound is strongly caustic, and requires care in handling.

Window clouding

A new quartz window was fitted to the spontaneous ignition rig in a position where it was in contact with the flame whenever combustion was taking place in the duct. The history of the window in terms of its reduction in transmittance with time is given in Fig. 27.



CURVE		A	B	C	D	E
RIG OPERATION TIME	(HOURS)	0	2½	3½	½	1½
COMBUSTION IN DUCT	(")	0	1¾	2½	½	1
SODIUM ASPIRATION TIME	(MINUTES)	0	5	10	20	30

(DASHED CURVES SHOW TRANSMITTANCE AFTER CLEANING)

FIG 27 : VARIATION OF TRANSMITTANCE WITH WAVELENGTH - QUARTZ WINDOW ON SPONTANEOUS IGNITION RIG

Values of transmittance were obtained by means of an electronic photometer. The width of the spectrum seen by the photo-multiplier tube used as a receiver was about 10 Å in the region of 4000 Å, and about 40 Å at 6000 Å.

The initial transmittance of the window was approximately constant over the visible region of the spectrum, but the reduction in transmittance with use was evidently greater in the blue region than in the red. This had also been the experience obtained from visual observation of the flame.

Cleaning the window after each run was effected by lightly scrubbing with a wet cloth and allowing to dry.

The reduction in transmittance after a few hours running was considerable, but owing to the fact that the windows could be separately examined, the effect was not considered serious from a radiation viewpoint. Moreover, owing to the steepness of the spectral radiation flux versus temperature curves in the visible region, an error in the estimation of the transmittance was not considered liable to introduce a very serious error in a given temperature determination.

Attempts at temperature determination

Attempts at determining flame temperatures on the spontaneous ignition rig by the sodium line reversal method were unsuccessful.

In one trial, the rig was operated with an estimated temperature upstream of the flame front of 1220°K. This temperature value was obtained from a mean temperature determination in the gas stream ahead of the fuel injector, using chromel alumel thermocouples, a correction being applied for the drop in temperature of the stream caused by evaporation of the fuel droplets.

The fuel/air mass flow ratio was .0107, for which the theoretical temperature rise for complete combustion at an initial temperature of 1220°K would be approximately 330 C°. The maximum flame temperature would therefore not exceed about 1550°K.

A station considered to be in the region of the maximum flame temperature was selected for observation. The mean rear window transmittance at this station was 0.35 over the period of the trial, which would require a lamp brightness temperature about 100 C° higher than the flame temperature at reversal. The lamp was operated at brightness temperatures up to about 3000 °K, and yet it was not possible to detect dark absorption lines under these conditions. As the lamp brightness temperature was increased from a low value, the bright D lines gradually merged into the continuous spectrum, and no reversal was obtained. This effect was independent of variations in the width of the spectroscope slit.

Variations were made in the amount of sodium aspirated, up to a maximum of about 1/10 gram sodium ethoxide in 5 ml ethyl alcohol mixed with about 200 ml kerosene, but residual sodium in the fuel lines masked the effect of such variations.

Lower "limit" of sodium-line reversal method

Failure to determine flame temperatures of the order of 1500°K led to consideration of the possibility of assigning a lower practical temperature "limit" to the sodium-line reversal method.

Earlier experience on the temperature instrumentation rig showed that, with insufficient sodium aspiration, or at temperature levels below about 1600°K, reversals could only be effected with difficulty.

Under these conditions, dark absorption lines became difficult or impossible to detect visually. The effect was thought to be associated with the properties of the human eye, which is roughly insensitive to differences in radiation intensity less than a certain critical fraction of the mean radiation intensity. At low intensity levels, this fraction increases as the mean intensity level decreases, and it is possible that, at a low flame temperature, the intensity level at which a reversal should theoretically have occurred was too low for the necessary intensity difference to be obtained. A continued increase in the intensity of the continuum produced by the lamp would increase the general intensity level, and the necessary intensity difference might still not be obtained.

Only a few references to the possibility of a lower temperature "limit" were noted in the author's literature survey. Several writers make the statement that the sodium-line reversal method may be used at temperatures "above 900°C", but this is probably based on Kohn's checks on the properties of sodium vapour above that temperature. Marskell(21) observes that, in his experiments, the sodium line did not appear to be strong enough for accurate observations below 1100°C.

Fuller(9) made a deliberate attack on the problem, using aspirated vapour from heated sodium. The lowest temperature recorded was 1337°K (1064°C), and its general validity was confirmed with a double-shielded chromel-alumel thermocouple.

There appears to be sufficient experimental evidence to justify assigning a general lower practical temperature "limit" of about 1400°K to the sodium-line reversal method when visual observation is employed.

CONCLUSIONS AND RECOMMENDATIONS

An understanding of the fundamental aspects of the temperature concept is necessary in order to interpret adequately the significance of a flame temperature determination. Results need to be critically analyzed with reference to the particular conditions in which they were obtained.

It is desirable that methods not involving the insertion of a solid body into the flame should continue to be developed. Methods based on the laws of thermal radiation have received extensive examination for more than a half-century, and are currently in wide use. Such methods appear to be of most general application.

The visual sodium-line reversal method appears to be inapplicable at temperatures below about 1400°K. Quartz windows in contact with the flame may suffer a permanent reduction in transmittance owing to attack by hot sodium vapour. The reduction in transmittance may be rendered temporary in small-scale work by recessing the windows sufficiently from the flame. The aspiration of sodium compounds into the flame presents a further problem, but the sodium-line reversal method is basically simple and permits rapid temperature determinations to be made.

In future work it is recommended that the visual sodium-line reversal method be considered for use only at temperatures above 1500°K, and in the absence of significant temperature fluctuations. The method developed by Quinn using blackbody radiation at the peak of the sodium D lines might prove applicable to the determination of fluctuating temperatures above 1250°K, and attempts at determining flame temperatures on the spontaneous ignition rig by this method are currently under way. It is recommended that methods not involving solid body insertion should be continuously investigated in an attempt to apply at least one of them to this particular project.

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APPENDIX

THE EFFECTS OF COMPARISON SOURCE REFLECTANCE

In temperature determination work, the effects of comparison source emittance have been studied in detail, but the effects of reflectance appear to the author to have received little attention, apart from the obvious requirement of screening the comparison source from strong sunlight.

Where a comparison source is observed through a flame, it may, under certain conditions, reflect flame radiation back to the flame along the axis of the radiation system, and thus augment the observed radiation in the manner employed in the mirror method. In the case of a tungsten ribbon filament lamp, the spectral reflectance of the filament in the visible region is greater than 0.5, and this was considered to be a sufficiently high value to justify an investigation into its possible effects. For a radiation system of the type shown in Fig. 6, and using a comparison source with a plane emitting and reflecting surface, three conditions need to be satisfied for reflectance effects to influence temperature determinations:

1) $\rho_{S\lambda} > 0$
2) $\epsilon_{F\lambda} < 1$
3) The emitting surface of the comparison source is set approximately normal to the axis of the radiation system.

Under such conditions, and with reference to the methods of Kurlbaum and of Féry, a straightforward theoretical analysis showed that the temperature determined by these methods would be too high. The error increases with

1) Increasing $\rho_{S\lambda}$.
2) Decreasing $\epsilon_{F\lambda}$.

3) Increasing flame temperature.

Reflection of flame radiation by the tungsten lamp used as a comparison source on the temperature instrumentation rig was obtained by setting the lamp with the filament perpendicular to the axis of the radiation system. The lamp was viewed from the position normally occupied by the spectroscope, and was rendered visible by reflected light from the flame. At inclinations of the filament in excess of three degrees on either side of the perpendicular, the filament could not be seen through the flame owing to the fact that reflected flame radiation was not being received by the eye. Attempts at determining the extent of the errors produced by reflectance were made experimentally, but the control of important variables was not sufficiently good to produce a statistically significant result in the case of the sodium-line reversal method, while the number of determinations made using Kurlbaum's method was not sufficient to establish a conclusive result.

For the sodium-line reversal method, there is a tendency to work with high values of $\epsilon_{F\lambda}$ to obtain a sensitive reversal, so that comparison source reflectance effects, where they exist, are probably very small, and therefore escape detection.

For Kurlbaum's method, the concentration of emitters can not be separately controlled, but at low values of $\epsilon_{F\lambda}$, where comparison source reflectance effects are considered to be greatest, there is also a higher degree of uncertainty in determining the point of intensity balance. In consequence, comparison source reflectance effects, where they exist, may escape detection.