University of Aston in Birmingham

"The Influence of Additivies on the Emissivity and Temperature of Methane Flames"

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by

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Abstract

A small, premixed methane-air flame on a cylindrical burner has been studied with special reference to the influence of additives on the radiating properties of the system. Data on changes, due to the additives, in emissivity, temperature, radiance and smoke point have been obtained. The relative effects of the additives have been assessed and some correlation between emissivity and smoke point has been demonstrated. The industrial use of the additives as a means of achieving a highly radiating flame has been shown unlikely.

Nomenclature

A	area of image of field stop	in preliminary experiment to show radiation received by pyrometer is independent of distance from source
A'	area of near source	
A''	area of distant source	
A_p	absorptivity of a single particle	
C_p	specific heat at constant pressure	
c	mass concentration of soot particles	
c_1	constant of Planck's Law	
c_2	constant of Planck's Law	
D	diameter of flame	
d	diameter of burner	
d_p	diameter of particle	
E_p	emissivity of a single particle	
f	focal length of lens	
h	height of inner cone of flame	
h'	convection heat transfer coefficient	
I	radiation incident on a typical element of a cloud of particles	
I_o	radiation incident on a cloud of particles	
I_L	radiation transmitted through a cloud of particles of thickness L.	
k	thermal conductivity	
k'	constant in relationship between absorption coefficient and wavelength postulated by Hottel and Broughton (29)	
LN	luminometer number as defined by Wurster et al (127)	
L	thickness of a cloud of particles	
m	constant correcting for the field of view, thermopile, etc., of the pyrometer	
N	number of observations in preliminary experiment to estimate accuracy of results.	
N'	number of observations in preliminary experiments to estimate significance of results.	

N_H	number of observations in preliminary experiments on heating of additives supply and mixing chamber
N_1 N_2	number of observations in preliminary experiments on efficiency of mixing chamber.
Nu	Nusselt number
N_p	number of particles
n	constant correcting for the field of view, thermopile, etc. of the pyrometer
p	constant correcting for calibration distance of pyrometer
Q_f	volume rate of air and methane to idealised flame
q	constant correcting for near flame distance to pyrometer
R_{pyro}	internal resistance of pyrometer
R	radiation received by pyrometer in Schmidt method
Re	Reynolds number
r	constant correcting for distant flame distance to pyrometer
s	standard deviation of results in preliminary experiments to estimate accuracy of results
s_H	standard deviation of results in preliminary experiments on heating of additive supply and mixing chamber
s_M	standard deviation of results in preliminary experiments on efficiency of mixing chamber
T	true temperature of flame
T_B	temperature of a black body
T_P	brightness temperature measured at calibration distance, for estimating p, q and r.
T_Q	brightness temperature for near flame for estimating p, q, and r
T_R	brightness temperature for distant flame for estimating p, q and r.
T_b	brightness temperature of a source

T_w	temperature of furnace walls
T_1	brightness temperature of single flame
T_2	brightness temperature of two flames in line with axis of pyrometer
U_{rad}	overall radiation heat transfer coefficient
V_P	pyrometer output for flame at calibration distance
V_Q	pyrometer output for near flame
V_R	pyrometer output for distant flame
V_f	flame velocity
V_1	pyrometer output for single flame
V_2	pyrometer output for two flames in line with axis of pyrometer
W	radiance
$W_{B,\lambda}$	monochromatic radiance of a blackbody
x	values of emissivity, temperature or radiance in preliminary experiments to estimate accuracy of results.
x_H	values of emissivity, temperature or radiance in preliminary experiments on heating of additive supply and mixing chamber.
x_1	values of single flame readings in preliminary experiments on efficiency of mixing chamber.
x_2	
α	absorptivity
$\alpha_{F,F}$	absorptivity of radiation by a flame at temperature F from a source at temperature F.
$\alpha_{F,S}$	absorptivity of radiation by a flame at temperature F from a source at temperature S.
$\Delta\epsilon$	correction to combined emissivities of carbon dioxide and water vapour
ϵ	emissivity of flame
ϵ_F	emissivity of a flame at temperature F.
ϵ_g	emissivity of gaseous components of flame
ϵ_s	emissivity of cloud of soot particles

$\epsilon_{s,}$	monochromatic emissivity of cloud of soot particles
ϵ_{CO_2}	emissivity of carbon dioxide
ϵ_{H_2O}	emissivity of water vapour
λ	wavelength
ν	kinematic viscosity
σ	Stefan-Boltzmann constant
ρ	density of soot
τ	transmissivity
$\tau_{F,S}$	transmissivity of radiation by a flame at temperature F from a source at temperature S.

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1. Introduction

The discovery of natural gas, containing a high proportion of methane, in the North Sea, has led to much interest in possible uses for this fuel in Britain. The costs of locating and landing the gas are such that it is a serious competitor to oil imported from the Middle East and elsewhere.

For many furnace heating applications, oil has an inherent advantage over natural gas in that it burns with a strongly luminous flame with high emissivities. This means that high heat transfer rates by radiation from the flame can be achieved. Natural gas, when burned under conditions suitable for complete combustion, has a non-luminous flame of low emissivity and consequently there are difficulties in realising the full heating potential of such a flame.

A method of increasing the emissivity is by causing the formation of soot within the flame. Sooting may be induced by the use of additives in relatively small quantities to influence the chemical equilibria within the flame.

There has been a great deal of work on the effects of additives on various properties of flames but little on their influence on those properties relating to radiation from the flames.

The concern of this work is with the effects of additives on the radiating properties of methane flames.

The work was carried out on a small scale and consisted of a vertical premixed methane-air flame, with provision for the addition of other compounds, burning on a circular nozzle. The flame was enclosed by a water cooled calorimeter and there was provision for measuring some of the properties of the flame.

2. Industrial applications of natural gas

2.1 The advantages of natural gas

There have been several reviews of the possible applications of natural gas as an industrial fuel (1, 2, 3, 4). It has the following advantages compared to oil or solid fuels.

a) The gas does not require storage facilities, pumps, preheaters, steam or special auxiliary equipment to maintain supply.

b) Since the auxiliary equipment is eliminated the flow is even and easily controlled.

c) The quality of the fuel is virtually constant.

d) Natural gas is the cleanest fuel available with little carry over to choke checkers and flues. Experience has shown that on the rebuild of a typical industrial furnace up to half of the original checker bricks may be used again.

e) Sulphur content is very low, approximately 0.2 ppm, advantageous in applications such as steel making, and presents no pollution problems. The latter point is of increasing significance.

f) The flame is less oxidising than an oil flame. This is of particular importance in the steel industry, a reduction in the oxidation of exposed scrap during the melt period would mean a saving in the amount of pig-iron necessary (5).

g) In some cases a lower cost per therm.

Table 1.

The Performance of different types of Flames as calculated by Thring

	Fuel Input Rate lb/h	Total Melt Time (hr)	Fuel req'd. ton/100 ton charge
Flame 1	4000	5.02	9.0
	2000	8.00	7.15
	1000	17.7	7.9
Flame 2	4000	3.15	5.6
	2000	6.73	6.0
	1000	17.3	7.7
Flame 3	4000	7.88	14.1
	2000	11.8	10.5
	1000	24.4	10.9
Flame 4	4000	3.76	6.7
	2000	7.54	6.75
	1000	18.5	8.25

2.2 The iron and steel industry

The iron and steel industry can be expected to make extensive use of natural gas. In Russia the alternative fuels are usually coke-oven gas or blast furnace gas, natural gas has compared well with the help of incomplete combustion in the ports or in some cases with oxygen enrichment (6, 7, 8). America has tended to favour enrichment with oil for use in open-hearths, this is more efficient than oil alone but the additional expense of two fuel systems and difficulties with control are disadvantages.

Finlayson and Durrant (2) foresaw considerable scope for utilising natural gas in the metal-finishing processes and in the production of inert atmospheres. The most desirable application however would be in the open-hearth furnaces which spotlight the main disadvantage of natural gas flames. They have very low emissivities and consequently are able to radiate only a small proportion of their calorific value. The experiments of Lhospied and Reveillard (9) and Jaegle and Malmezat (10) have shown maximum emissivities of about 0.25 for thick industrial-sized flames on conventional burners.

It appears that the first documented attempt to utilise the radiation from a luminous flame was made in a glass furnace by Siemens in 1884 (11). Work on the theoretical aspects of radiation heat transfer soon followed, the major interest being in pulverised coal flames (12, 13, 14).

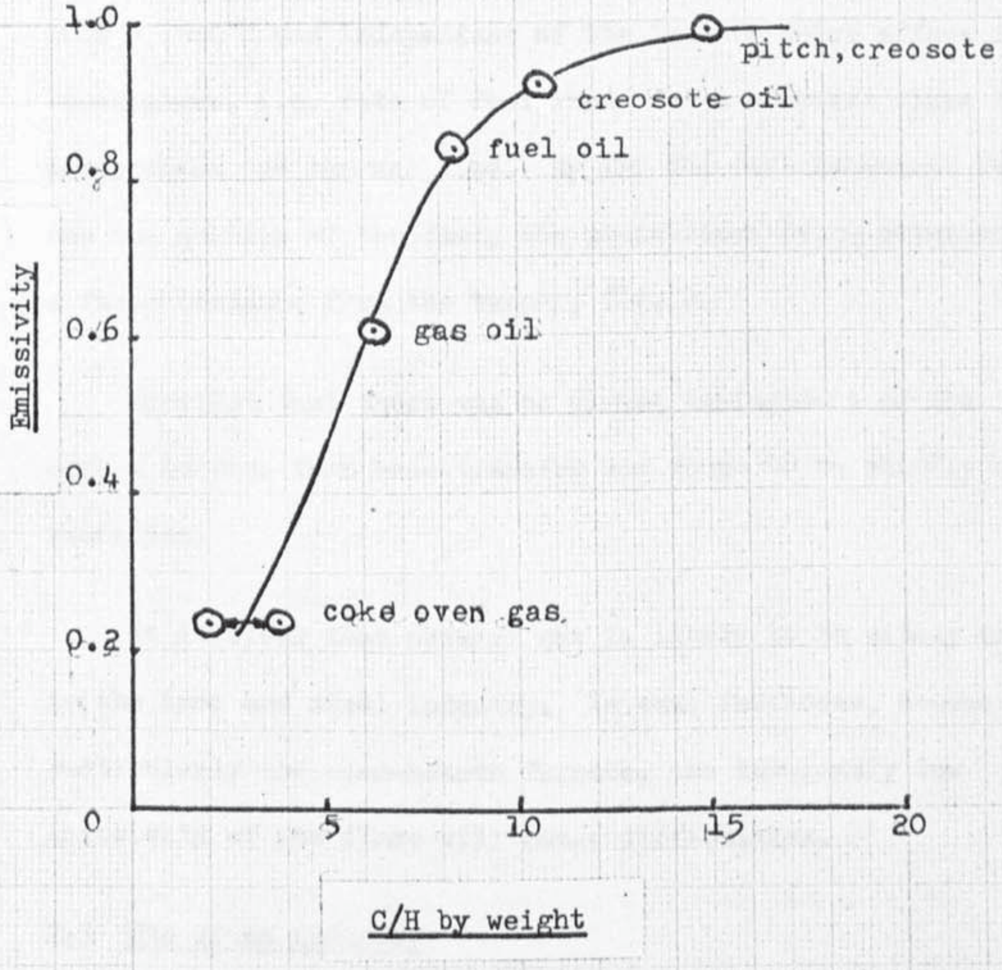
The type of flame which would be most efficient in an open-hearth has been considered in some detail by Thring (15) and the results of his calculations are shown in Table 1. In flame 1 the emissivity was unity over the first sixth of the furnace, fell to 0.1 over the next sixth and was sustained at 0.1 for the remainder. This corresponds to an oil flame with rapid combustion and short flame length. The second flame was similar in that combustion was assumed to be completed in the first third but the emissivity remained at unity throughout. As yet it has not been possible to achieve a flame of this type. In flame 3 combustion occurs uniformly along the entire length of the furnace but the emissivity is as for flame 1. A coke-oven gas flame or natural gas flame with low jet momentum would burn in this manner. Finally, the fourth flame, similar to an oil or pitch-creosote flame with low jet momentum, has combustion uniform along the length and a constant emissivity of unity. A furnace charge of 100 ton was considered and a thorough examination of the heat transfer made.

It can be seen that the flames with an overall emissivity of unity give much quicker heating and are more efficient than those with lower emissivities. Furthermore, it is preferable to have a fuel which is completely burned over the first third of the furnace rather than have uniform combustion along the length.

Pearson et al (16) tested similar theories in an industrial installation and showed that radiation accounts for virtually the whole of the heat transfer within the furnace.

The heat transfer from oil and coke-oven gas flames has been studied experimentally at Ijmuiden in Holland (21). Thring and Hubbard found that for fuels with a high carbon/hydrogen

Figure 1.



The dependence of the emissivity of industrial flames on the C/H ratio of the fuel, (Thring and Hubbard ratio a peak emissivity of approximately 0.8 was achieved at about half the flame length, after which it fell linearly to the non-luminous value of about 0.3. For coke-oven gas, however, the emissivity was more or less constant at 0.3 throughout the flame length.

The concluded that the emissivity of normal flames at 1000 - 1800°C was independant of the factors which affect flame temperature, i.e. rate of fuel input for a constant flame length, air preheat and thermal load. By far the most important factor was the quality of the fuel, the graph shown being obtained for a fixed distance from the burner, fig. 1.

Provided that there was no direct impingement of the flame onto a surface then heat transfer was found to be chiefly by radiation.

It is clear that natural gas is likely to be widely used in the iron and steel industry. In some instances, however, particularly the open-hearth furnace, the inherently low emissivity of its flame will cause difficulties.

2.3 The glass industry

The glass industry will also provide a large demand for natural gas, its cleanliness and ease of control making it especially attractive (4). There is considerable controversy over the importance of a radiant flame in glass tanks. Most evidence (17, 18) suggests a luminous flame is required but Datschefski has achieved success with a largely non-luminous flame (19). Datschefski claimed that with a luminous flame most of the heat reradiated and reflected from the furnace roof is absorbed by the flame and not transmitted to the bath. It should be remembered that this heat energy is not lost from the furnace and can be reradiated again to roof and bath.

In the case of a non-luminous flame, some of the radiation reaching the roof in the bands of the spectrum corresponding to carbon dioxide and water vapour is

a) reflected at the same wavelengths to be abosrbed by the flame; and some is

b) reradiated at all wavelengths to pass through the flame and reach the bath.

It will be realised, however, that the sum of these cannot exceed the heat originally radiated by the flame to the roof and that this has been severely limited by the non-luminous characteristics.

To achieve greater radiation from the roof it would be necessary to heat it by convection. This may have occurred in the tests of Datschefski which lasted only two months so that any damage to the refractories may not have been apparent.

Alternatively, the flame may have been close to the glass surface with convection directly to it, so that radiation from the flame and roof were less significant. The end result might well have been the overall decrease in thermal efficiency of 4% by the use of luminous flames; but due to the characteristics of the heat transfer within the glass the throughput of the furnace would have been reduced. Such data was not published.

In a later paper (48), Datschefski showed a numerical example of a mathematical model of a cross-fired regenerative glass furnace. The results showed little difference in radiation into the bath when considering flames of different emissivities. Since the roof, flame, glass surface and exit gas temperatures were all chosen arbitrarily a more rigorous examination would be essential before drawing any definite conclusions.

For some types of glass tank at least, it seems that a luminous flame is necessary.

2.4 Other industries

There are many other fields in which natural gas will find applications. Probably the largest of these is steam raising plant. In many cases the gas will be quite suitable in its natural form; many types of boilers rely on heat transfer by convection but particularly in water-tube boilers there may again be a need for a radiant flame.

Finally it will be desirable to have the facilities to use natural gas for rotary cement kilns, lime kilns, chemical processing furnaces, rotary brass melting furnaces and billet heating. Luminous flames would certainly be necessary in some of those cases.

The low emissivity of natural gas flames causes another problem in addition to that of efficiently transferring heat. The transparent nature of the flame makes it difficult to direct with accuracy, the roof of the first furnace converted to natural gas at La Consolidada steel works was burned down after only nine heats (20). Gas had tended to float upward or be deflected off scrap and onto the roof. Increasing the emissivity of the flame would render it more easily visible and therefore simpler to direct accurately.

The industrial demand for natural gas will be considerable, therefore. In order to achieve its full potential as possibly the most important new industrial fuel available, it will be necessary to compensate for the inherently low emissivity of its flame.

2.5 Heat transfer in furnaces

The main aims of furnace design are to use as small a combustion chamber volume and as small a heating surface area as possible, combined with the most efficient heat transfer which can be achieved. The thermal efficiency of the system may be rather simply defined by

$$\text{efficiency} = \frac{\text{useful heat supplied to the charge}}{\text{calorific value of fuel consumed}}$$

High efficiencies will be favoured by good insulation of the structure, thereby reducing heat lost through the walls, and by ensuring that as little heat as possible is removed with the products of combustion. The latter requirement means that the temperature of the products of combustion must be as close as possible to the temperature of the charge; this demands high heat transfer coefficients between flame and absorbing surface to compensate for the low driving force.

In many installations, particularly those at high temperatures, significant wall losses are inevitable since extensive insulation and the consequent high refractory temperatures would lead to rapid deterioration of the structure. In such cases the losses may be maintained as a small proportion of the calorific input by the use of high throughputs. High heat transfer coefficients are necessary to achieve this aim.

2.5.1 Convection heat transfer coefficients

Considering a flame as a fluid flowing as if in a tube,

$$Nu = 0.02 . Re^{0.8}$$

$$\text{i.e.} \quad h = 0.02 . D^{0.2} . \frac{k}{\nu^{0.8}} . V_f^{0.8}$$

If flame has a diameter of 2m and the thermal conductivity and viscosity are similar to those of air, then at 1000°C

$$h = 0.0023 . V_f^{0.8} \quad \frac{\text{kcal}}{m^2.h.\text{deg K}}$$

The highest flame velocities which have been achieved are of the order of 32 $m.s^{-1}$ at the heating surfaces of boilers or furnaces (22). Using this value

$$\underline{h = 25 \text{ kcal}.m^{-2}.h^{-1}. (\text{degK})^{-1}}$$

This is approximately the highest value obtainable in normal combustion chambers by forced convection.

2.5.2. Radiation heat transfer coefficients

The overall radiative heat transfer coefficient is given by

$$U_{rad} = \frac{\sigma . \epsilon . (T^4 - T_w^4)}{T - T_w}$$

With a flame temperature of 1000°C,

if $T_w = 100°C$, $U_{rad} = 3550.$ kcal.m.$^{-2}$ h.$^{-1}$ (deg K)$^{-1}$

if $T_w = 900°C$, $U_{rad} = 1420.$ kcal.m.$^{-2}$ h.$^{-1}$ (deg K)$^{-1}$

Hence it can be seen that radiation is markedly more significant than convection provided that the emissivity is greater than about 0.1. Therefore the most important method of improving the heat transfer is by increasing the emissivity of the flame.

3. The radiation from a flame

3.1 Factors influencing the radiation from a flame

The radiation from a flame is a function of its temperature, the types of molecule present, the shape and thickness of the flame and the concentration, size and nature of any solid particles which may be present.

The temperature influences the amounts of radiation from the several different sources in the flame. The most significant sources of non-luminous radiation are carbon dioxide and water vapour present in the flames, these molecules and to a lesser extent carbon monoxide molecules radiate in small discrete bands of wavelength outside the visible spectrum. Their contribution can be determined from graphs published by Hottel (23) and others (24, 25).

The recombination of free atoms and radicals may cause a small amount of radiation as experienced by Saleh (26). More significant may be chemiluminescence which has been measured at up to 5% of the radiation of a premixed flame (27, 28).

Solid particles most frequently found in flames are soot, Hottel and Broughton (29) have shown that the monochromatic emissivity of a cloud of soot particles was given by

$$\epsilon_{s,\lambda} = 1 - \exp(-c.L.f(\lambda))$$

$f(\lambda)$ represents the absorption coefficient which may be a function of particle size. For soot, after reviewing previous experimental results of others, Hottel and Broughton suggested that in the infrared above 0.8

$$f(\lambda) = \frac{k'}{\lambda^{0.95}}$$

and in the visible spectrum

$$f(\lambda) = \frac{k'}{\lambda^{1.39}}$$

Experimental evidence, at Ijmuiden in particular, has confirmed a relationship of this sort (21, 30).

Thring and Hubbard (21) and Sato et al (37) have obtained the following relationship between flame emissivity and the separate soot and gas emissivities of the flame

$$\epsilon = \epsilon_s + \epsilon_g - \epsilon_s . \epsilon_g$$

It is clear that the emissivities of the soot and the gases are equally weighted in determining the resultant emissivity of the flame. However, because the gases radiate over such a restricted portion of the infrared there is little scope for increasing their contribution. A better way of increasing the flame emissivity is by loading the gas with small uniformly dispersed solid particles at gas temperature, radiating at wavelengths covering a wide section of the infrared spectrum. It is very important that the flame temperature is not greatly reduced by the introduction or formation of the particles since the radiation is proportional to the fourth power of the absolute temperature.

3.2 Radiation from clouds of particles in a flame

As has previously been stated for radiation, the emissivity of a flame is a function of its temperature, the types of molecule present, the shape and thickness of the flame and the size, concentration and nature of any solid particles which may be present.

The absorptivity and transmissivity are functions of the same properties as the emissivity and also of the quality of the incident radiation as defined by its spectral distribution. Since the wavelengths of any radiation are dependent on the temperature of its source it follows that the absorptivity of particles in a flame will be a function of the temperature of the source of the radiation being absorbed. The absorptivity and transmissivity may, therefore, be given subscripts to indicate first the temperature of the flame and secondly the temperature of the source.

i.e. $\alpha_{F,S}$ and $\tau_{F,S}$

Shack has estimated that for soot particles in a flame the temperature difference between the particles and the gases is of the order of 1°C (31). The particles gain heat from the gases by convection to replace that lost to the surroundings by radiation. For most purposes, then, the particles can be considered to be in thermal equilibrium and Kirchoff's law will apply. For bodies in thermal equilibrium the emissivity at a particular temperature is equal to the absorptivity which the body exhibits for radiation from a black body at the same temperature.

i.e. $\epsilon_F = \alpha_{F,F}$

For certain bodies the absorptivity is independant of the quality of the incident radiation and is, therefore, also independant of the source of radiation. These are referred to as grey bodies and

$$\alpha_{F,S} = \alpha_{F,F} = \epsilon_F$$

for all flame and source temperatures. Bodies whose absorptivity is a function of the wavelength of the incident radiation are described as non-grey.

Thus there are two situations in which it can be assumed for a flame that

$$\epsilon = \alpha$$

a) If the background source of the radiation is at the same temperature as the flame.

b) If the flame can be considered as a grey body.

The Schmidt method as used by the I.F.R.F. at IJmuiden for emissivity and temperature determination assumes that emissivity and absorptivity are equal although the flame and background temperatures are different (32,33). Luminous flames were found to give satisfactory results, acting as grey bodies; Hottel suggests that this is not always the case (34) and non-luminous flames are decidely non-grey. This probably accounts for the errors encountered with non-luminous flames of coke-oven gas. Emissivities of 0.345 have been measured when in theory they should be about 0.21 (35). It is possible to avoid this difficulty by the use of a black body background of variable temperature. Series of readings for backgrounds above and below the flame temperature are taken and the desired values obtained by interpolation. Such a system has been used but the experimental procedure and treatment of results was extremely tedious and time consuming (36).

By assuming Kirchoff's law it can be shown that for a cloud of black particles

$$\underline{\epsilon_s = 1 - \exp(-\tfrac{3}{2}.\tfrac{c}{\rho}.\tfrac{L}{d_p})} \qquad 3.1$$

see Appendix 1

Using the data of Thring (38) for fly ash

$$\rho = 2.10^3 \text{ kcal.m}^{-3}$$

$$C_p = 0.25 \text{ kcal.kg}^{-1}.\ (\text{deg C})^{-1}$$

A flame of thickness 1 m at 1500°C has

$$C_p \simeq 0.3 \text{ kcal.kg}^{-1}.\ (\text{deg C})^{-1}$$

If the particles have no more than 10% of the heat capacity of the gases to avoid excessive cooling then

$$\frac{\text{maximum mass of particles}}{\text{mass of gases}} \simeq 8.3$$

whence maximum concentration of particles $\simeq$ 0.023 kg.m^{-1}

i.e. $\frac{c}{\rho} \simeq 10^{-5}$

From equation 3.1 can be obtained Table 2, showing particle cloud emissivity for different particle sizes.

Table 2

$d_p(\mu)$	$\frac{L}{d_p}$	$\frac{3}{2}\cdot\frac{c}{\rho}\cdot\frac{L}{d_p}$	ϵ
10^3	10^3	0.015	0.015
10^2	10^2	0.15	0.14
10	10	1.5	0.78
1	1	15	1.0

The non-luminous emissivity of such a flame can be calculated from Hottel's curves (23). At 1 atmosphere with 14% carbon dioxide and 11.5% water

$$\epsilon_{CO_2} = 0.12 \qquad \epsilon_{H_2O} = 0.12 \qquad \Delta\epsilon = 0.04$$

$$\epsilon_g = \epsilon_{CO_2} + \epsilon_{H_2O} - \Delta\epsilon$$

$$= \underline{0.20}$$

A 10% reduction in the flame temperature due to the presence of the particles means a reduction of 40% in T_f^4. For this to be compensated and for a gain in overall radiant heat transfer it is clear that the particles must be rather less than 10μ.

The addition of such particles to a flame would necessitate extremely fine and therefore expensive grinding operations. They are, however, to be found as the fly ash remaining after the combustion of a pulverised coal flame. Such particles also occur in cement kilns when the dust from the limestone-clay feedstock falls through the flame.

It has been found that soot particles formed in flames fulfil the above requirements with regard to size. This possibility has the advantage that as much of the soot is ultimately burned there is likely to be less loss in overall heat transfer due to cooling of the flame.

At Ijmuiden electron microscopic studies of soot formed in the experimental furnaces have shown the particles to be individual particles in a size range 0.01 - 0.08 μ, a mean of approximately 0.04 μ (38).

3.3 Previous attempts to produce luminous flames

As early as 1927, Haslam and Boyer (50) found that radiation accounted for a minimum of 25 - 30% of the heat transfer within a furnace. The transition from a non-luminous to a luminous flame, in their case by the use of different fuels, caused an increase in rate of heat transfer of up to four times. They suggested that some means of innoculating non-luminous flames with an illuminating agent would find many industrial applications.

3.3.1 Preheating

While experimenting with glass tank burners Trinks and Keller (14) found that preheating the air gave useful increases in the luminosity of the flame. Preheating the natural gas, however, caused a reduction. The reasons for this are not clear but the aerodynamics of the flow around the burner may well have altered with preheat temperatures up to 1100°C causing expansion of the reactants.

In 1965 Guenbant and Gaydon (53, 54) observed an increase in thermal radiation from a methane-air flame which had been preheated to 750°C. They claimed this was due to a change in the shape of the flame and not simply a function of the rate of reaction in the flame front.

Lhospied and Reveillard (9, 51) experimented with preheating of the air supply to an experimental furnace, although there was some cracking of the methane early in the flame the maximum emissivity was scarcely affected, in contrast to the results of Trinks and Keller. Jaegle and Malmezat (10) confirmed the findings of Lhospied and Reveillard.

3.3.2 Precracking

Recent research in Europe has been concentrated on the production of carbon particles by thermal cracking of the methane before it enters the combustion chamber. This precracking may be achieved by heat transfer via checkers and flues with hot products of combustion leaving the furnace. By applying this heating to about one fifth of the natural gas supplied to an open hearth furnace Andoniev et al (6) produced a luminous flame containing 15-20 g soot/ft^3 natural gas. The performance of the hearth was similar to that using coke oven or blast furnace gas.

Using a similar technique Levitasov et al (7) increased the soot concentration of a natural gas flame from 6.9 to 14.8 $g.m^{-3}$. The throughput of the furnace was increased by 10%, the flame temperature by 20-60°C and the utilisation of heat in the refining period by 15.10^3 $kcal.m^{-2}.h^{-1}$. Foaming in the hearth at the end of the melting and the beginning of the refining period was markedly reduced.

Considerable work is being done in France, Holland and Britain on the design of new types of burner to produce a luminous flame (9, 10, 51, 52). Most of these burners have two stages, in the first a portion of the methane is burned with a less than stoichiometric supply of air. The excess methane is cracked by the heat of combustion and the resulting carbon particles are carried forward by the primary combustion products to the second stage where they are mixed with the main methane supply. Stable flames and emissivities of about 0.8 can be achieved by these burners.

3.3.3 Mixed fuels

The suggestion of Haslam and Boyer of innoculating non-luminous flames with an illuminating agent has been considerably exploited in both America and Russia (55, 56, 57). In America it has been common practice to run open hearth furnaces with up to 50% of the thermal demand coming from oil injected with the natural gas.

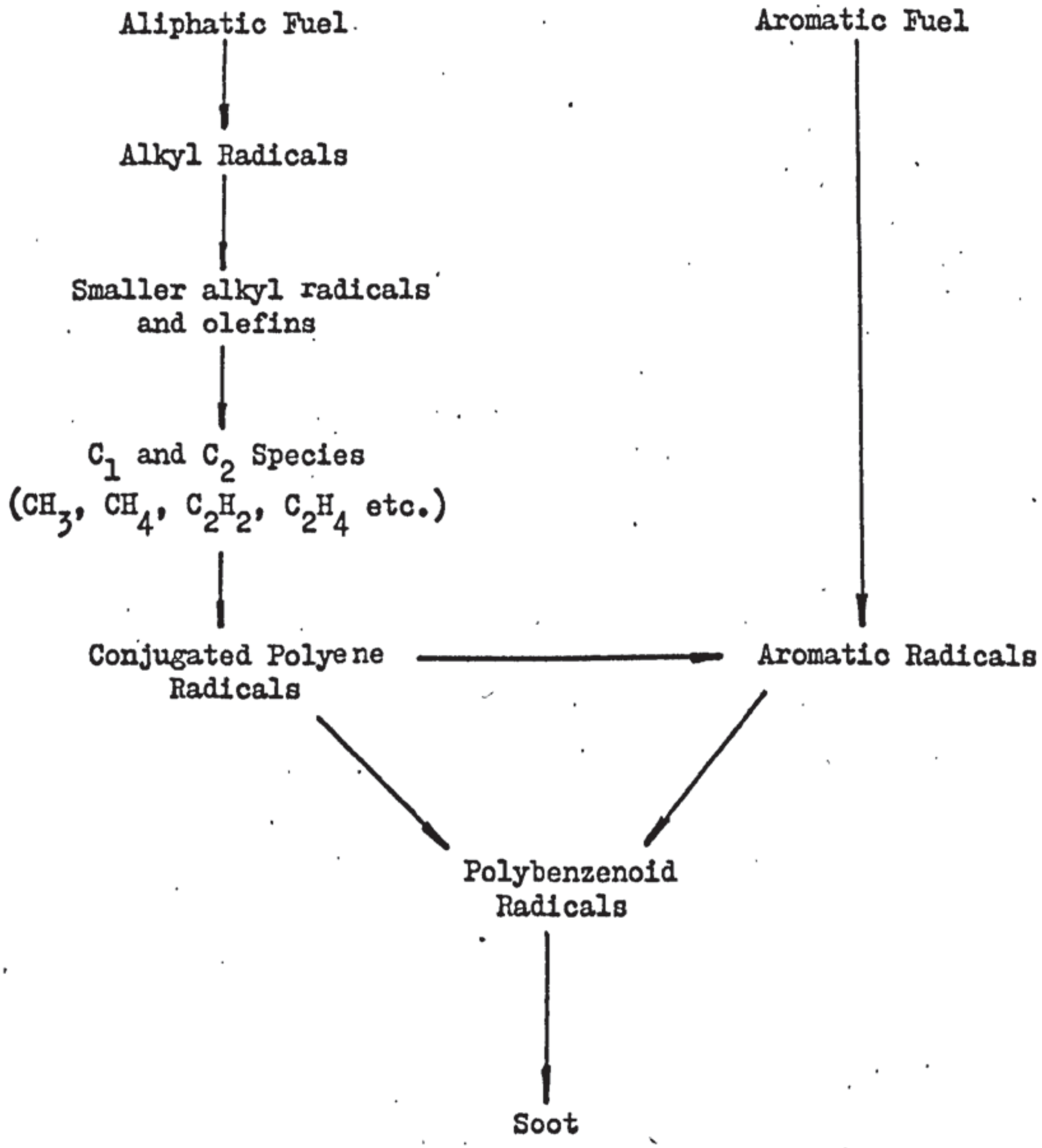
There has been more use of mixed gas and solid fuels such as pulverised coal in Russia. By the use of 6 - 12 g crude oil/m^3 peat gas Zakharikov and Rozhanskii (58) were able to shorten the melt time in a glass tank by 14 - 28% and effect fuel economics of 11 - 34%.

Kapustin et al (8) found that the injection of a little oxygen into the air supply of an open hearth furnace greatly increased the luminosity of the flame. There was a reduction in melt times and saving in fuel costs. A possible explanation is that the additional oxygen at the burner port caused extremely rapid combustion. The poorly mixed condition of fuel and oxidant at this point would cause very high local temperatures, resulting in thermal cracking of some of the methane providing carbon particles and a luminous flame.

Solid fuels in particulate form were added to a natural gas flame by Dewerth and Zalavadia (59) as 4 - 15 w/w % of the gas. Increases in radiation of up to 270% were recorded with charcoal less effective than coke but more so than pulverised coal. In addition, Dewerth and Zalavadia thought it might be possible and useful to inject some of the raw materials of certain furnaces into the flame. Lime, silica and cement were tested and the maximum increase in radiation was found to be 55%. These authors concluded that the fuels were superior due to their additional heat input into the furnace and the increase in the partial pressure of carbon dioxide. Before this conclusion could be accepted information on particle size, size distribution and surface emissivity would need to be obtained.

Figure 2

The Mechanism of Soot Formation according to Thomas



Dewerth and Zalavadia also showed that the addition of pulverised coal caused a greater increase in radiation than did a similar quantity of methane.

3.4 The formation of soot in flames

Though it has long been realised that the luminosity of hydrocarbon flames is caused largely by the presence of particles consisting mainly of carbon, the mechanism of their formation is by no means clear (60). Furthermore the composition of these particles has been found to vary considerably (61, 62), the main constituents being carbon and hydrogen. These particles will be referred to as soot rather than carbon.

There have been many theories put forward to explain soot formation in a flame as opposed to simple thermal cracking of the fuel. These have been summarised by Gaydon and Wolfhard (60). In general all those theories agree that polymerisation occurs at some point, the difficulty being to establish at what stage in the process. Porter (63) and Booth (64) have suggested that there may be two mechanisms occurring simultaneously producing two different types of soot. Particles which have polymerised sufficiently in the preheating zone are able to survive pyrolysis while smaller particles may be broken down in the reaction zone to acetylene and hydrogen before forming soot.

In 1961 Thomas (65) suggested the mechanism shown in fig. 2. Aliphatic fuels first form radicals by hydrogen abstraction. The resulting weak carbon skeleton then breaks easily giving simple radicals and olefins, the latter may be dehydrogenated to polyolefins or broken down further. Once conjugated species have formed they are less likely to be broken down and are more likely to undergo addition. The conjugatedpolyene radicals cyclize to polybenzenoid radicals which amalgamate to form soot. Aromatic fuels also form radicals as a first step but these already have a stable conjugated structure and can build up immediately.

This theory accounts for the dark space between the reaction zone and luminous zone in an aliphatic premixed flame. The aromatic route being quicker, there is no such dark space in flames of this type.

Halogenated compounds which encourage soot formation as additives probably increase the rate of dehydrogenation, thereby assisting in olefin and polyene formation and ring closure. Sulphur trioxide might yield similar results by way of dehydrogenation.

The non-equilibrium formation of soot as detected by Street and Thomas prompted Millikan (66) to analyse large, flat, premixed ethylene-air flames. He found that about 1% acetylene and a smaller amount of methane are present in the reaction zone and postulated that pyrolysis of the acetylene is the source of soot. Millikan thought the dark space is due to oxidation of some of the acetylene by an above equilibrium concentration of OH radicals. As the OH concentration decreases so pyrolosis predominates and soot formation is observed in the luminous zone.

Ray and Long (61) also established that acetylene is an important step in the process but distinguished between "carbonaceous residue" and pentane-soluble material present in the soot. While studying propane-air diffusion flames they found that 90% of the pentane-soluble material was polycyclic aromatics and concluded that these were not intermediates in the formation of the carbonaceous residue but byproducts.

Foster (67) has calculated that above 1140°K 95% of the carbon should be deposited during the pyrolysis of pure methane. Experimental results show a maximum yield of approximately 50% (63). The work of Tesner (68) suggests that hydrogen formed during the pyrolysis retards the production of soot. Tesner found that an increase in hydrogen concentration from 0 to 10% caused a 75% decrease in the soot surface growth rate. The pressure of oxygen means a reduction in the yield due to an increase in the formation of the oxides of carbon. From purely chemical equilibrium considerations carbon can only exist when the oxygen/carbon atom ratio is less than 1.0, i.e. less than one third of the stoichiometric air for hydrocarbons. In practice carbon has been observed at much higher ratios, deviation from equilibrium being accentuated at increased pressures up to 15 or 20 atomospheres. Francies (69) and Narasimham and Foster (70) have shown that the decomposition of hydrocarbons can occur much more rapidly than the oxidation reactions of hydrocarbons or soot by carbon dioxide or water vapour which would be necessary to prevent the formation of soot.

Considerable work has been done on soot formation by Homann and Wagner (71, 72, 73). They classified premixed flames into two types:

1. The acetylene type in which soot appears above the whole flame cone.
2. Other types showing soot formation at the tip of the cone,

either close to the flame front or a short distance above it.

Methane falls into the first category along with other light hydrocarbons.

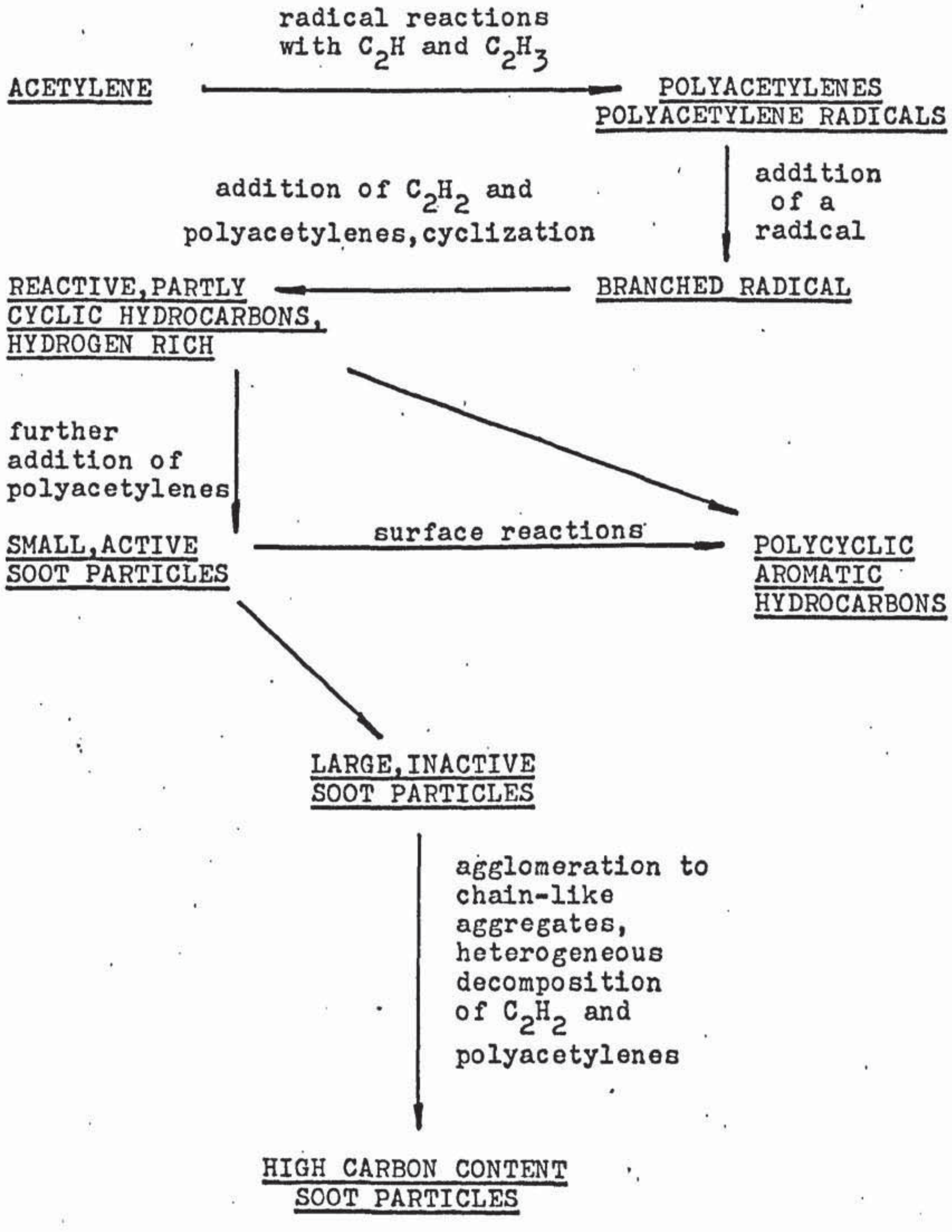
Soot formation is not exclusively controlled by the flame chemistry. In addition to the effects of temperature and pressure the aerodynamics of the flame play an important role. Identical fuel-oxident mixtures which, by the use of different burners, exhibit a variety of shapes of flame fronts can have markedly differing tendencies to soot. It seems that the greater the curvature of the flame front so more soot formation will occur. In part this may be due to hydrogen atoms and light radicals diffusing back into the unburnt gas just upstream of the reaction zone, heating the fuel molecules and causing pyrolysis and thence yielding a flame of the second type. When this diffusion does not occur a flame of the first type is obtained.

The effects of temperature and pressure differ depending upon the physical structure of the flame, e.g. in a flat benzene-air flame of the first type, soot formation is reduced by raising the temperature. If an identical mixture is burned as a cellular flame, by using a cylindrical premixing burner, however, the opposite effect is observed.

Homann and Wagner determined concentrations of CO, H_2, H_2O, CO_2, C_2H_2 and polyacetylenes throughout an acetylene-oxygen flame. In addition, to these molecules they found the following radicals, C_2H_3, C_2H, C_2, CH, H, O and OH together with polycyclic aromatics such as naphthalene, pyrene, phenanthracene, 3, 4-benz-pyrene and

Figure 3

Mechanism of soot formation according to Homann and Wagner



coronene. They concluded that in the acetylene flame most of the soot formation takes place in the burning zone since radicals occur there in high concentrations following oxidation processes. The burnt gases from this zone contain soot particles, acetylene, polyacetylenes, polycyclic aromatics, water vapour and carbon dioxide. Further soot deposition is very slow.

The polyacetylenes are thought to be formed by way of

$$\begin{aligned} C_2H_2 \quad + \quad O \quad &\rightarrow CH_2 + CO \\ CH_2 \quad + \quad C_2H_2 \quad &\rightarrow H.C_2.CH_3 \\ &\rightarrow CH_3.C_2.CH_3 \\ &\rightarrow C_4H_4 \\ &\rightarrow C_4H_2 \end{aligned}$$

if there is an excess of acetylene. At the point in the flame where the concentration of polyacetylenes is at a maximum, polycyclic molecules begin to appear. It is suggested that the addition of hydrocarbon radicals to large linear hydrocarbon molecules, the polyacetylenes, leads to the formation of branched radicals. These either form closed rings with side chains, polynuclear aromatic molecules, or add further unsaturated molecules to become the precursors of soot particles having a variety of configurations. Homann and Wagner agree with Ray and Long that pure polycyclic aromatics are byproducts and not intermediates in the process of most formation. Their mechanism is summarised in fig. 3.

4. Additives and flames

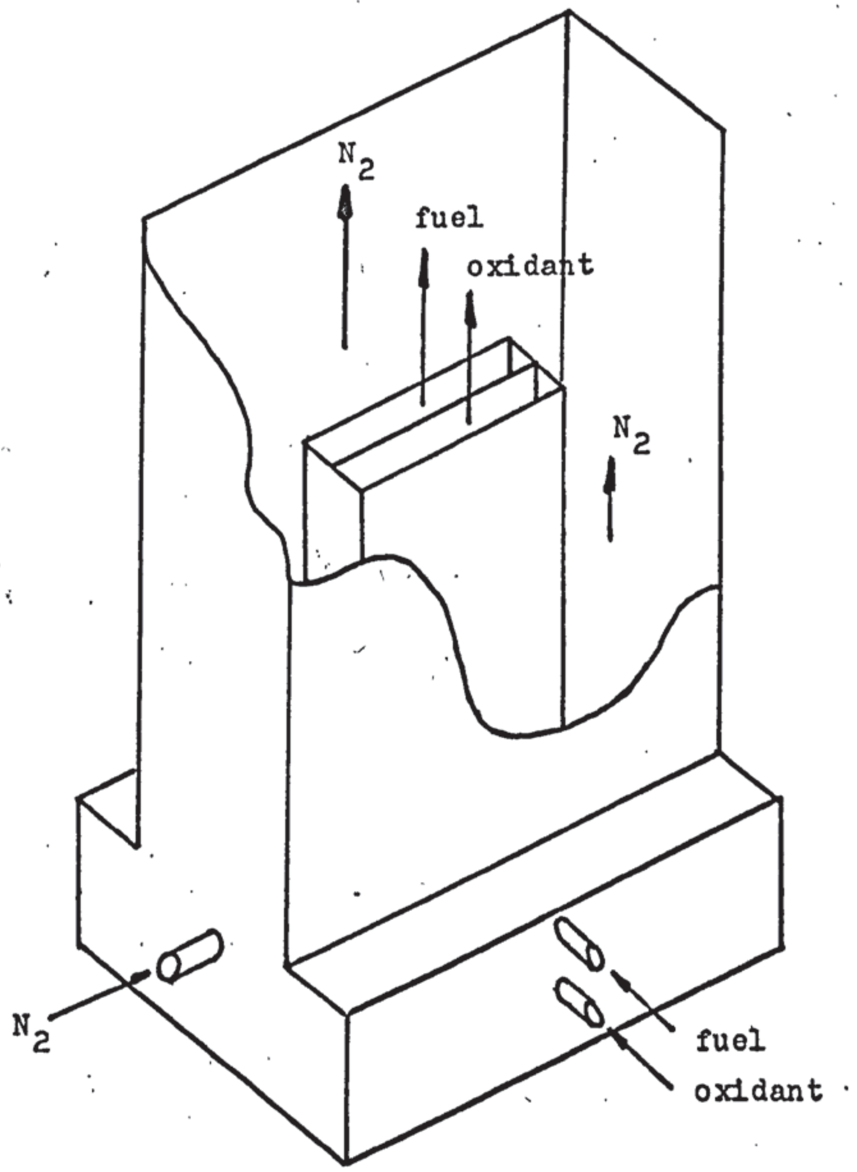
There has been a considerable amount of research into additives and their effects on flames. The reasons for using additives are diverse, possibly to achieve a particularly desired characteristic such as high or low flame speed or measuring effects of the addition as a means of establishing reaction mechanisms. An attempt has been made here to pick out the most significant and interesting points from the literature.

In 1945 Whittingham et al (74, 75, 76) obtained the spectra of a variety of premixed flames to which sulphur dioxide and trioxide were added. With coal gas burning on a bunsen burner they found that sulphur dioxide caused a reduction in the intensity of the carbon continium. Sulphur trioxide when introduced into the air stream in proportions as low as 0.1% v/v greatly increased the soot formation. They felt that the sulphur trioxide probably initiated polymerisation of hydrocarbons which were then thermally decomposed to solid carbon. The town gas used was specified as

CO_2	3.5 % v/v
CO	11.2
CH_4	23.3
H_2	46.1
O_2	0.7
h/c	2.9
N_2	12.3

Sulphur dioxide had the same effect on methane as on coal gas but sulphur trioxide was not tried with this gas though it

Figure 4.



Wolfhard-Parker flat flame burner

had little effect on hydrogen or carbon monoxide.

Wolfhard and Parker (77) published further work on these additives using their flat-flame burner shown in fig. 4. Methane-oxygen and ethane-oxygen flames were used. Sulphur dioxide addition resulted in a decrease in luminosity whether present in the fuel or oxidant stream of both flames. Sulphur trioxide in quantities of the order of those used by Whittingham et al had no significant effect on the soot formation but if present in larger quantities than sulphur dioxide then a similar reduction in luminosity occurred. Wolfhard and Parker therefore suggested that in cold regions sulphur trioxide had no promoting influence on soot formation and dissociates according to

$$SO_3 \rightleftharpoons SO_2 + \tfrac{1}{2} O_2$$

Furthermore, above 800°C on the fuel side where there is no oxygen and above 1500°C on the oxygen side, such dissociation is complete and no sulphur trioxide reaches the reaction zone.

The addition of nitric oxide to a methane-oxygen flame has been found to cause a slight decrease in soot formation (78). Nitric oxide is known to be a chain-breaking molecule and so this result suggests that soot formation is not a chain reaction as has been suggested.

Extending their work to ethylene-nitric oxide flat diffusion flames, Wolfhard and Parker (79) observed marked similarities to ethylene-oxygen flames. With nitrogen dioxide-ethylene flames, however, two reaction zones were detected, separated by up to 2 mm. In the first zone the nitrogen dioxide was thought to undergo decomposition to nitric oxide, the reverse reaction to which causes a yellow continuum to be radiated. The second zone was very similar to that in a nitric oxide-ethylene flame. In fuel rich mixtures a soot zone sometimes formed between the reaction zones and was thought to be due to thermal cracking of the fuel in the hot first zone. The two zones were observed in methane flames also.

Arthur (80) found that the addition of large quantities, up to 45% of the total volume, of carbon dioxide or nitrogen would suppress soot formation in a methane-air diffusion flame. This was claimed to be not solely due to cooling of the flame since preheating the gases did not change the critical additive concentration necessary to cause complete suppression of soot formation. Others, however, have found preheat to enhance soot formation to varying degrees (9, 10, 81).

Mellish and Linnett (82) and Clingman et al (83) studied the addition to or substitution of the nitrogen in hydrocarbon-air flames with regard to flame velocity and inflammability limits. No changes in the luminosity of the flames were noted.

Methane-air diffusion flames on both a normal cylindrical burner and a reversed type with air passing through a tube into an atmosphere of methane were examined by Arthur and Napier (84).

Table 3

Street and Thomas

Additive	Effect
Carbon dioxide	No change
Carbon monoxide	Yellow streak increased in size and intensity, cone remained unchanged.
Hydrogen	Slight increase in yellow luminosity and a considerable increase in the intensity of the green colour in the cone.
Chlorine	The cone, normally blue-green in colour, became intensely green, the flame elongated and the yellow tip increased in size and intensity.
Methyl bromide	Flame cones became much greener and more intense, the yellow tip increased in size, at large additive rates an orange glow appeared above the flame.
Carbon tetrachloride	Marked increase in yellow luminosity and change of blue-green cone to intense green, elongation of the flames.
Nitrogen peroxide	Yellow tip disappeared and a greenish white shroud surrounded the flame.
Amyl nitrate	Small increase in yellow luminous tip, an increase in air supply was necessary to eliminate the yellow.
Tetraethyl-lead	Mauve glow surrounding the cone, a greysih black deposit quickly formed on the glass sleeve and proved to be mainly metallic lead with traces of lead monoxide and lead sulphide.
Sulphur dioxide	Violet glow above the cone.
Sulphur trioxide and sulphuric axid	Benzene flame was extinguished and copious carbonaceous deposits formed in the burner tube; large amounts of carbon started to form in the kerosene flame which took on the appearance of a very rich flame.
Carbon disulphide	Yellow streak increased in size but remained weak in intensity, a violet glow appeared above the cone and sulphur was deposited on the burner rim and the glass sleeve.

Table 3 (cont.)

Additive	Effect
Methyl ethyl ketone	Increase in size of yellow streak for both fuels and a decrease in green component of the benzene flame.
Methyl alcohol	Yellow streak increased in size but not in intensity, an orange glow appeared over the cone and proved to be due to sodium.

Figure 5

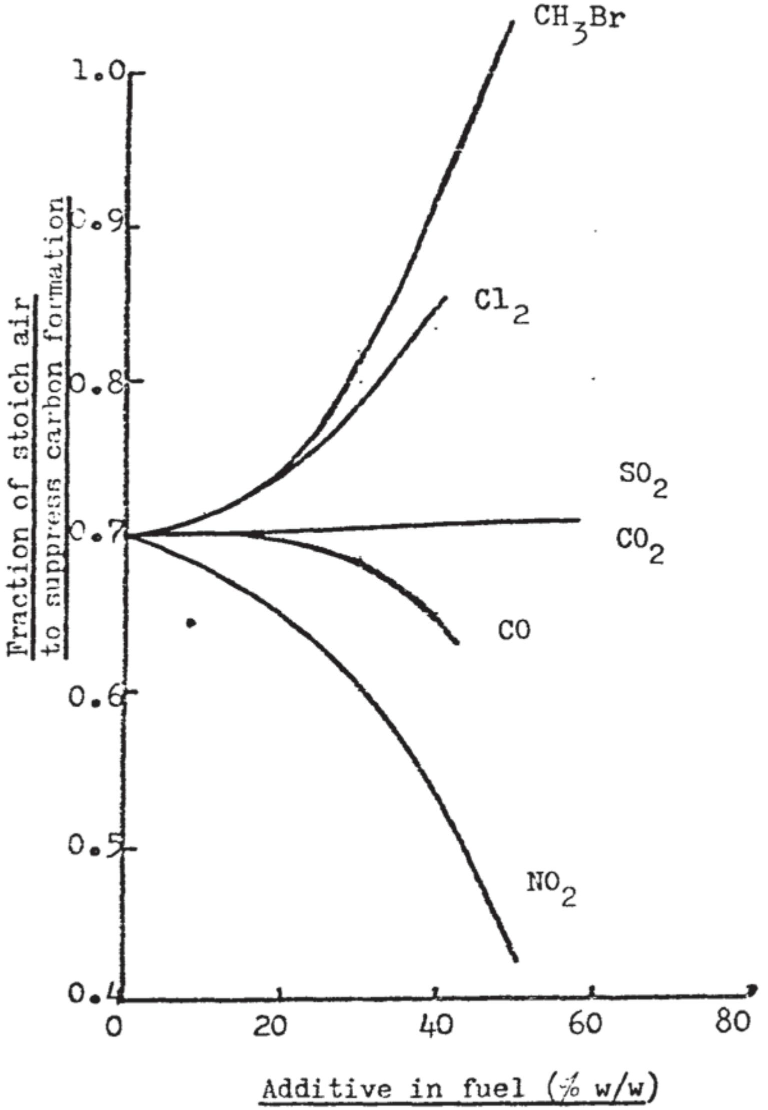
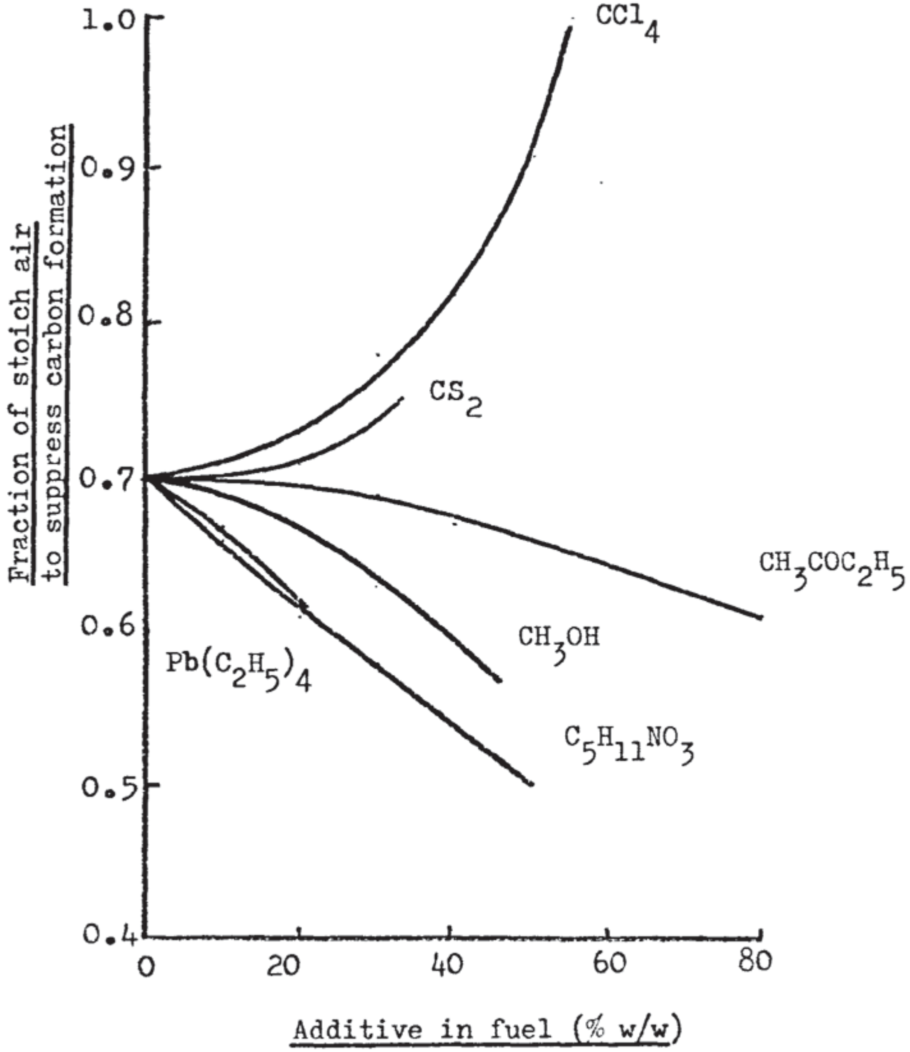


Figure 6



Effect of additives on the smoke point of benzene-air flames, Street and Thomas

Figure 7

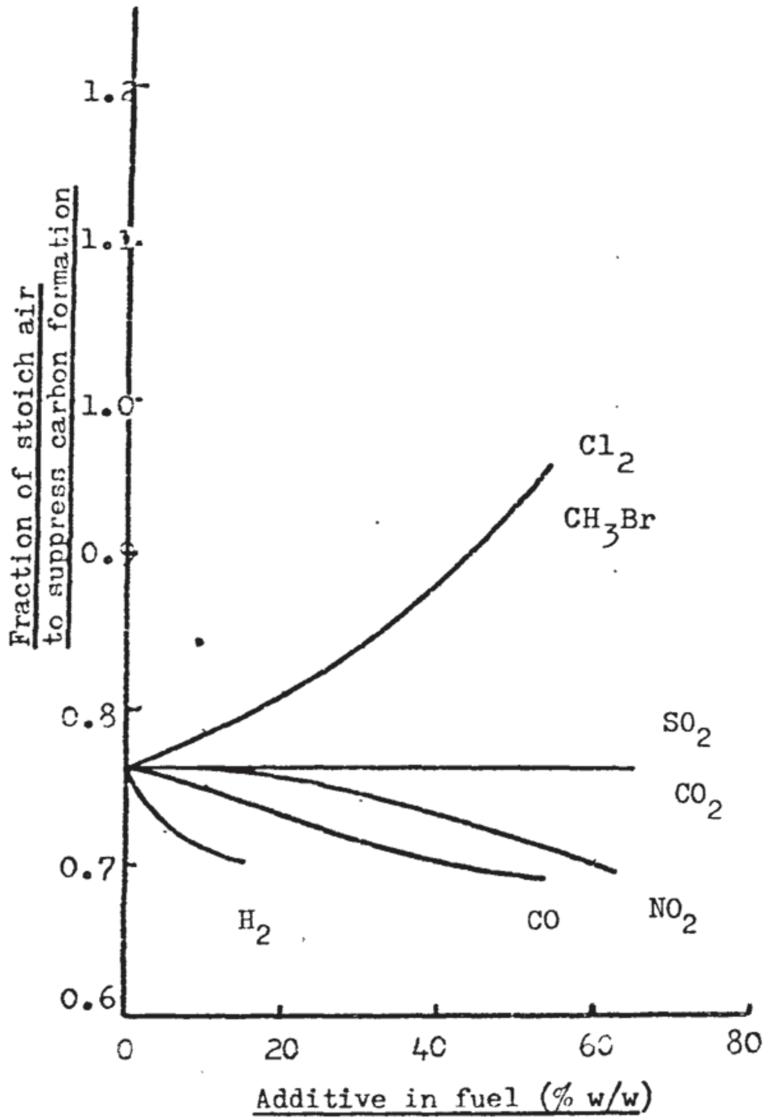
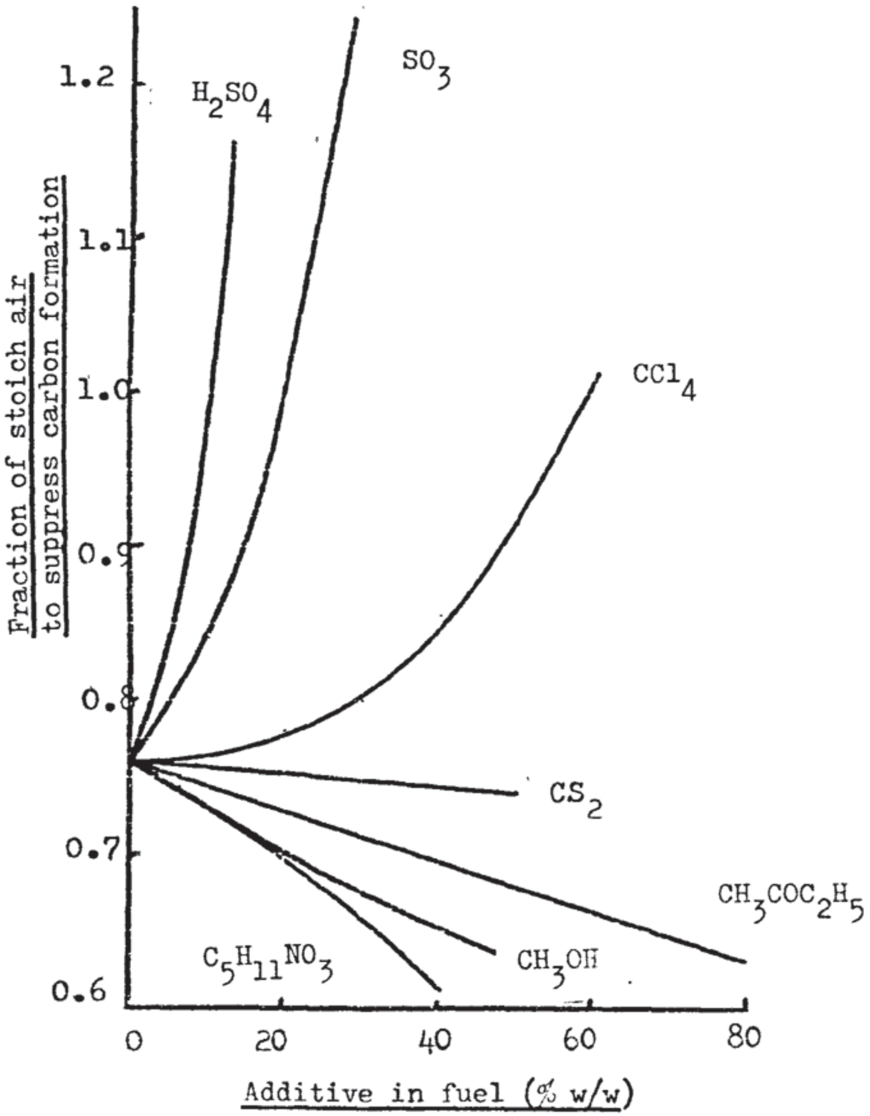


Figure 8



Effect of additives on the smoke point of kerosene-air flames, Street and Thomas

The smoke points, defined by the air-fuel ratio when soot formation is just visible to the naked eye, were determined with several additives which all decreased soot formation. In order of effectiveness they were sulphur dioxide, carbon dioxide, nitrogen and carbon monoxide; up to 300% v/v of the methane were necessary for complete suppression. Light output from the flames was measured by a photocell. Much smaller additions were required to cause reductions of intensity of the order of ten times. The wavelengths of radiation to which the photocell was responsive are not known and so the results can hardly be considered as a measure of soot formation. The addition of about 0.5% sulphur trioxide had no obvious visual effects.

The major work on the influence of additives upon soot formation in flames was performed by Street and Thomas in 1955 (85). The effect of a variety of additives on the 'critical concentration of air required to suppress carbon formation in kerosene and benzene flames' was measured. A premixed flame with no secondary air was employed, the critical air flow being a mean of the air flows when yellow luminosity could just be observed continuously and when the yellow luminosity had just disappeared. Additives used and their effects were as shown in Table 3 and figs. 5 - 8.

Street and Thomas explain the increase in soot formation in the presence of halogenated compounds by their known properties as catalysts for the polymerisation of hydrocarbons. In addition Rust and Vaughan (86) have shown that alkyl halides reduce the chain splitting which occurs during low temperature oxidation of hydrocarbons. It is possible, therefore, that large molecules necessary for soot formation are preserved by the halides. It seems likely that the use of halogenated compounds to increase soot yields would be less successful with lower hydrocarbons, especially methane, in which large molecules are not present intially.

Both sulphur trioxide and sulphuric acid caused large quantities of soot to be formed in both flames, the former being very difficult to control. The additives reacted with the benzene depositing 'carbon' in the burner tube, even before the flame, this did not occur with kerosene. The reaction rates may be slower with kerosene than with benzene or the fact that the benzene was a homogeneous vapour whereas the kerosene was a mist of droplets may be the explanation.

Methyl alcohol, methyl ethyl ketone, carbon monoxide and amyl nitrate all suppressed soot formation, probably due to a simple blending process rather than affecting the normal reactions in the benzene and kerosene flames.

Nitrogen dioxide had a greater effect on the benzene flame than on the kerosene flame. It is thought that in the former case the dioxide dissociates according to

$$2NO_2 \longrightarrow 2NO + O_2$$

whereas in the latter by

$$4NO_2 \longrightarrow N_2 + 2NO$$

followed by partial dissociation of the nitric oxide. There is thus more oxygen available in the benzene flame. The benzene flame is thought to be hotter causing the more complete dissociation.

Tetra-ethyl lead suppressed soot, probably because of its known chain-breaking properties.

Water, very difficult to vaporise due to wetting of the heating surface of the vaporiser, carbon disulphide and sulphur dioxide had no effect on the critical air ratio up to 50% w/w. The sulphur dioxide reduced the intensity of the yellow luminosity but not the limits, contrary to the evidence of others (74, 75, 76, 77).

Nitrogen was found to provide soot formation and oxygen to suppress it more than in proportion to their concentrations.

Methane-chlorine trifluoride flat diffusion flames were studied by Skirrow and Wolfhard (87). The carbon continium was very strong and C_2 and C emitters were also detected, the chlorine trifluoride being contaminated by traces of nitrogen. The addition of oxygen or nitrogen caused marked reductions in the intensity of the continuum. Thehigh cost of chlorine trifluoride, approximately £80/200 $ft.^3$, would probably eliminate it as a potential additive for industrial use.

While measuring temperature profiles of hydrogen-air diffusion flames Stephens et al (88) used a sample of calcium oxide as a luminescor to locate the position of the inner cone. Addition of small quantities of oxygen led to temperatures above the calculated adiabatic flame temperature. This was thought to be due to the catalytic action of the surface of the thermocouples, bare metal couples producing higher temperatures than ceramic ones but a complete explanation cannot be provided.

Fenimore et al (89) determined the smoke point of several premixed hydrocarbon-air flames with gaseous additives. Nitrogen, argon, helium, carbon monoxide, carbon dioxide and especially water were all found to suppress soot formation. Adding 20% W/W hydrogen to propane caused an increase in the critical propane/air ratio of 13%, i.e. soot formation was encouraged, as opposed to the results of Street and Thomas for kerosene and benzene fuels.

The compositions of diffusion flames of simple alcohols burning in air were measured by Smith and Gordon (90). They found that methanol flames produced no carbon while ethanol flames exhibited a small amount of yellow tipping, n-propanol and i-propanol flames produced relatively large quantities of soot. The same burner with a wool wick and natural circulation of air was used in all cases. It is interesting to note that the methanol flame had less than 0.004% w/w acetylene whereas the other three flames all had about 0.1% w/w benzene and 1-2% w/w acetylene. The quantity of soot formed did not, therefore, appear to depend on the concentrations of acetylene or benzene though more work would be necessary to be sure.

During the course of their work on the flame front structures of lean diborane-air flames Breisacher et al (91) added small quantities, less than 6% v/v of methane and propane. A large proportion of the hydrocarbon was cracked in the first reaction zone giving rise to a luminous region and the formation of ethylene as well as soot. At sufficiently high temperatures a second reaction zone was established downstream where the oxidation of the hydrocarbons was completed. It is unlikely that reversing the situation and adding small quantities of diborane to methane flames would produce a similar luminous zone.

As part of a study on the mechanism of soot formation Cole and Minkoff (92) made a spectroscopic analysis of methane-oxygen flames supported on a Wolfhard-Parker burner (77). Hydrogen, water, ethanol, tetralin, carbon dioxide and ethylene were added as 3% w/w of the fuel and no change in the intensity of the carbon zone was observed. It was necessary to add 15% w/w of methyl bromide to significantly increase the soot formation though it was impossible to deduce whether the carbon came from the methyl bromide or the methane. 3 - 4 % w/w of sulphur dioxide rendered the luminous zone almost invisible and 1% w/w acetylene had no measureable effect.

Tesner et al (93) differentiated between the mass of carbon and the number of particles of soot at different points in methane-air diffusion flames. The addition of nitrogen or hydrogen caused a reduction in the mass of soot formed although the number of particles increased for additive concentrations up to 20% v/v of nitrogen and 34% v/v of hydrogen after which it decreased again.

Several hydrocarbons were also added (ethane, ethylene, acetylene, propane, hexane, benzene and naphthalene). The number of particles was greatly increased by benzene and naphthalene but hardly affected by acetylene or ethylene. The mass of soot was increased by all the additives, the increase being greater for the higher molecular weights and the higher concentrations of additive. Details of the masses of soot formed might show whether the type of molecule or the molecular weight is more significant but these are not available.

Fuels containing mono- and polycyclic aromatic compounds were investigated by Schirmer et al (94) in gas turbine combustors. At pressures from 5 - 15 atmospheres high flame emissivities were noted with the formation of large carbon particles reradiating as black bodies. At these elevated pressures the polycyclic compounds produced greater increases in radiation from the flame than did the monocyclic compounds. At atmospheric pressure the aromatics had no measureable effect on the radiation though this may have been due to recirculating products of combustion screening the radiation measurement apparatus.

When a stream of nitrogen is passed through an electrical discharge at low pressures the effluent gas stream emits a yellow glow and is known as 'active' nitrogen. It is generally agreed that the reactive species present is atomic nitrogen. Jennings and Linnett examined (95) the spectra produced by introducing a variety of compounds into a stream of active nitrogen. When studying hydrocarbons they tested flames of acetylene, ethylene and methane and found that the brightness decreased as the carbon to hydrogen ratio decreased. Methane produced one of the weakest flames of all, being lilac in colour due to the emission, in the red and violet regions of the spectrum, of CN.

Schmidt and Schulze (96) encountered difficulties caused by soot formation in burners using natural gas. The trouble was traced to small quantities of iron pentacarbonyl which were formed during the underground storage of the gas despite its low carbon monoxide content. The concentration was reported as less than that which could be detected by ordinary analytical means. Bonne et al (97), however, found no pronounced carbon continuum when studying the spectra of methane-air flames containing small quantities of iron pentacarbonyl. As little as 0.01% w/w was sufficient to reduce the flame speed by 25%.

The reduction in propagation velocity of premixed methane-air flames by the addition of metal salts has been investigated by Rosser et al (98). 0.006 $mg.cm^{-3}$ of sodium carbonate was sufficient to reduce the velocity from 65 $cm.s^{-1}$ to 16 $cm.s^{-1}$. No observations on soot formation or luminosity of the flames were made. While at first sight soot formation might be expected to occur as inhibition takes place, the theory of Rosser et al that the metal salts deactivate such species as C_2, CH and OH suggests that there may be a consequent shortage of the radicals necessary for building larger molecules. The inherent reduction in flame speed renders unlikely the industrial use of any similar additive which might induce soot formation. The relatively low flame speed of methane alone is proving to be a source of difficulty in many installations.

Fenimore and Jones (99) studied the inhibition of hydrogen-oxygen flames by methyl bromide, probably on a premixed flame thought this is not clear. They concluded that methyl radicals were formed in the flame according to

$$H + CH_3Br \rightleftharpoons CH_3 + HBr$$

and these react with oxygen atoms causing inhibition of the flame

$$O + CH_3 \rightleftharpoons H + HCHO$$

In addition they suggested that methane would yield methyl radicals and hydrogen in a similar manner

$$CH_4 + H \rightleftharpoons CH_3 + H_2$$

the methyl radical again inhibiting the flame. Their study of the flammability limits of hydrogen-methane and hydrogen-methyl bromide mixtures support this view and so adding methyl bromide to a methane flame is likely to have a similar effect as using a fuel-rich mixture. The formation of formaldehyde as shown above suggests that the addition of formaldehyde to a methane flame might increase the rate of propagation of the flame and reduce the likelihood of soot formation.

The effects of several known inhibitors on methane-air and ethylene-air diffusion flames have been measured by Ibiricu and

Gaydon (100). All were found to encourage soot formation when present in quantities up to 5% v/v. In order of effectiveness they were carbon tetrachloride, phosphorus oxychloride, chlorine and methyl bromide; the intensity of the carbon continuum increasing by a factor of up to six times. In all cases the increased radiation was accompanied by quite considerable cooling of the flames from approximately 1150°K to 900°K. The absolute temperatures as measured by thermocouple must be open to doubt but the trend will be correct, of course.

Ray and Long (61) determined the effects of various additives and changes in air flow on a commercial 'propane'-air diffusion flame. In fact the 'propane' contained 63% propylene but the significance of this has not been investigated. The soot from the flame was washed with pentane and the remainder referred to as carbonaceous residue. The polycyclic aromatic content of the soluble material was also measured. Increasing the air flow rate caused a drop in both soot and carbonaceous residue formation. Dichloro-methane increased the soot and carbonaceous residue levels in the flame but large amounts were required to do so, 60% w/w of the propane flow to double the soot concentration. The pentane-soluble material was not affected. Nitroethane, 1-nitropropane, ethyl nitrate and t-butylhydroperoxide all caused a reduction in the soot formation though the carbonaceous residue contents were unchanged. These results would be expected from the oxidising nature of the additives.

The effects of changing the fuel : oxidant ratio in premixed methane-perchloric acid flames burning in an atmosphere of argon were examined by Pearson (101). Methane concentrations from 2 - 18 times stoichiometric were used. He found that in all cases only two molecules of methane per molecule of perchloric acid were reacted, the rest acting solely as a diluent. No carbon formation was observed in these flames, probably due to insufficiently high temperatures, details of which are not available. Oxygen was added to the flames and carbon formation was then detected. The oxygen may well have raised the temperature sufficiently to cause cracking of the methane.

Scully (102) injected an additive plus nitrogen axially into the products of combustion of a 10% rich town gas-air flame on a Meker burner. The soot produced was collected and measured. 33⅓% v/v benzene gave five times more soot than 33⅓% v/v acetylene butusing the same masses of benzene and acetylene, i.e. 100% v/v of the latter, resulted in equal quantities of soot formed, the aromatic ring apparently making no difference. Chlorobenzene however produced over twice as much soot as benzene, possibly due to the formation of hydrogen chloride and consequent polymerisation of phenyl radicals. Methyl groups attached to the benzene ring helped in a similar way but hydrogen gas inhibited carbon formation. The production of soot by the use of these aromatics depends on the additives themselves being converted to soot rather than causing part of the fuel supply to be degraded.

The luminescence of some common phospors and oxides of calcium in hydrogen and methane flames have been studied by

Mason (103). He observed that in a hydrogen flame luminescence occurred both when the flame impinged on a phospor spread on a support and also when the gases flowed through a porous body and burned on the coated surface. When methane was used luminescence was found only with the first arrangement. Phosphors were not added to the flame as part of the feed but it seems unlikely that the luminescence would occur over a wide enough band of the spectrum to usefully increase the radiation from the flame.

It is interesting to note the work of Blake et al (104) who measured carbon deposition from irradiated methane. The work was conducted at pressures 0.164 - 2.58 cm Hg, up to 10% of the methane being reduced to carbon depending on the dose of radiation. It was thought that the carbon was formed by way of ethane, propane, iso-butane and n-butane. Addition of carbon dioxide in large quantities considerably increased the deposition, up to 36%, there was no oxidation of the methane with production of carbon monoxide as had been expected. The addition of oxygen to the methane reduced the carbon formation at low dosages of radiation but had little effect at the higher rates. The pure methane and methane-carbon dioxide mixture experiments were repeated in the presence of graphite, higher yields were obtained in all cases. The carbon was preferentially deposited on the graphite rather than on the glass walls of the vessel being used. In the presence of graphite the levels of the saturated hydrocarbons were reduced and ethylene and acetylene were present in quantity. Similar results for atmospheric pressure would be useful.

During his work on the inhibition of methane and acetylene diffusion flames, Miller (105) studied the effects of the addition of carbon tetrachloride, iron pentacarbonyl and chromous hypochlorite. Additive concentrations of less than 0.5% v/v were used, all three were observed to promote soot formation, carbon tetrachloride rather less so than the other two. Miller used additive concentrations much higher than those of Bonne et al (97) who did not find carbon formation when using iron pentacarbonyl. It is also significant that Miller used a diffusion flame whereas Bonne used a premixed flame.

Extensive work on the formation of soot and polycyclic aromatic hydrocarbons in ethane-air and ethylene-air diffusion flames has been carried out by Chakraborty and Long (62). In both cases the addition of oxygen to the fuel supply caused an initial increase in the amount of soot formed, a maximum was detected at the oxygen: ethane molar ratio of 0.62, corresponding to 18% of the stoichiometric oxygen. The soot formation at ratio 0.95 was almost the same as with no additional oxygen. The addition of hydrogen to ethylene flames caused a reduction in the soot formation but the effect on ethane flames was not measured. Adding methanol to the ethylene flame resulted in a steady decrease in the soot formed, a methanol:ethylene ratio of 1.0 reduced the soot by a third, the decrease being approximately linear with the methanol rate. Chakraborty and Long suggest that the methanol provided, through its own oxidation, species which either remove or prevent the formation of an intermediate in the production of soot.

Following the work of Homann et al (71, 73) Fenimore and Jones (106) compared premixed ethylene-oxygen and ethylene-nitrous oxide flames. They found that the latter produced eight times more soot than the former. Flame temperatures and concentrations of acetylene, diacetylene, triacetylene and hydrogen radical were similar in both types of flame. It was found that the concentration of oxygen and hydroxyl and oxygen radicals rapidly became the same although clearly the oxygen flame must be rich in oxygen radicals since it is known (107) that oxygen in hydrocarbon flames reacts according to

$$H + O_2 \rightleftharpoons OH + O$$

No reaction for the formation of oxygen atoms is known in nitrous oxide-hydrocarbon flames. It seems likely, therefore, that acetylene,polyacetylenes and their radicals which form early in the oxygen flame are being oxidised immediately by oxygen atoms. The soot formation is in fact promoted by the shortage of oxygen rather than the presence of nitrous oxide. Fenimore and Jones further found that adding hydrogen chloride to acetylene oxygen flames increased the green emission of C_2 and also the yellow luminosity. 60% w/w hydrogen chloride added to the acetylene trebled the yield of soot.

The effects of several inert additives on the smoke point of an ethylene-oxygen diffusion flame were measured by McLintock (108). All the smoke points were increased, i.e. the luminosities were decreased, and in order of effectiveness the additives were carbon dioxide, water vapour, nitrogen, helium and argon. It was found that the helium could be made to have a greater effect than the nitrogen by decreasing the size of the fuel nozzle relative to the oxygen port. This phenomenon has not been explained but is probably due to the different gas flow rates and therefore gas velocities and the different rates of propagation of the flames producing dissimilar flame fronts and temperature profiles.

Dearden and Long (109) worked on flat diffusion flames of ethylene-air and propane-air. They found that raising the oxygen content of the air caused an increase in the sooting rate, ethylene producing more soot than propane. With ethylene a maximum sooting rate was not reached at an oxygen : ethylene molar ratio of 0.26 as Chakraborty and Long (62) had encountered. The discrepancy was probably due to the difference in burners, Chakraborty and Long used a cylindrical type. The addition of nitrogen to the fuel stream of the ethylene flame caused a decrease in soot formation, as did hydrogen in both flames studied. Acetylene caused a large increase in the soot formed in both. Oxygen in the fuel increased the sooting of the ethylene flame but slightly decreased that of the propane flame. Methane and acetylene concentrations were measured in both flames. In the ethylene flames with oxygen and acetylene as fuel additives it was shown that the sooting rate increased linearly with the quantity of acetylene present in the luminous zone, suggesting that acetylene is a stable intermediate during soot formation. The acetylene concentration fell sharply between the luminous region and the main reaction zone and so must be the main hydrocarbon oxidised in the latter. When oxygen was added to the propane the acetylene concentration was increased in the luminous region as it was in the ethylene flame. On this occasion, however, the sooting rate fell contrary to the above theory.

Tischer and Scheller (110) carried out an investigation of the effect of adding boron trichloride to small cyanogen-oxygen diffusion flames. They found that the spectral intensity could be increased up to eight times in the range 0.44 - 0.67 and by consideration of their own results and those of Kaskan et al (111, 112, 113) concluded that the emission was due to boron dioxide. Since the increase in luminous intensity is restricted to such a narrow portion of the electromagnetic spectrum it is unlikely that the addition of boron trichloride to a methane flame would significantly increase its radiation.

The influence of a variety of organic solvents on the emission of acetylene-air flames seeded with sodium, potassium, calcium or magnesium salts was studied by Tesarik (114). The effect of the different solvents varied with the metallic radical present in the flame but in general the largest increase in emission was caused by n-propanol followed by acetone, iso-propanol, ether, methanol, ethanol, pyridene, water, ethylene glycol and tri-ethylamine. Only the emissions of the radicals, in narrow bands of the spectrum were measured and these cannot be related to the overall emissivities of the flames.

It is apparent that there has been a considerable amount of work done on additives in flames. Many types of flames have been studied and a wide variety of parameters have been measured but little has been published about the emissivity, radiance or even the temperature of flames with additives.

As part of his work in this field Comerford (125) used the method of Kurlbaum (126) to determine the spectral emissivity at 0.65 of propane diffusion flames. Propane and nitrogen were preheated in a furnace and partial pyrolysis took place before the fuel was burned in a stream of air. Comerford used the spectral emissivity as a measure of the soot concentration, however the theoretical treatment in Appendix 1 and considerable experimental evidence (21, 37) have shown that the emissivity of a cloud of particles is a function of the size of the particles, the path length and the particle density in addition to the mass concentration of the particles. No account of these factors was taken by Comerford, who found that the majority of the soot formation occurred in the flame rather than the pyrolysis tube. The length of the luminous zone was dependent on the air/fuel ratio rather than the velocity of the fuel. Since with high air/fuel ratios a definite point was reached along the flame where carbon combustion was completed and the soot zone had a sharp boundary, Comerford concluded that the burning of the soot was controlled by diffusion of air rather than the rate of reaction. With a limited air supply Comerford stated that the carbon concentration remained approximately constant after all the air was consumed despite having observed a gradual decline in the emissivity.

In 1961 Wurster et al (127) compared the luminosities of flames of several liquid and gaseous organic compounds using a 'luminometer'. The fuel was burned as a diffusion flame and the fuel rate adjusted so that the radiation was fixed at some arbitrary, constant level determined by a photocell. A highly luminous flame, therefore, burned at a slower rate than a less luminous one. A thermocouple was positioned above the flame, the indicated temperature rising as the flame height increased. The difference between this temperature and ambient was assumed to be in some way inversely proportional to the luminosity. Any differences between the flame speeds and adiabetic flame temperatures of the different field were not taken into account. The 'luminometer number' was defined

$$\text{LN liquid} = \frac{T_{\text{test fuel}} - T_{\text{tetralin}}}{T_{\text{iso-octane}} - T_{\text{tetralin}}} .100$$

$$\text{LN gas} = \frac{T_{\text{test fuel}} - T_{\text{acetylene}}}{T_{\text{ethylene}} - T_{\text{acetylene}}} .100$$

Since the characteristics of the photo-cell used are unknown and because of the simplifications made the 'luminometer number' is unlikely to be of significance.

The aim of this work is to provide information on the effects of a variety of additives on the radiating properties of flames. The information obtained is intended to be of use in predicting the performance of larger industrial-sized flames using similar additives. To this end it is intended to report on the effects of the additives on the important properties of the flames, rather than make a more fundamental investigation of the changes in reaction mechanism, within the flame, caused by the use of each additive.

5. Theoretical treatment of the proposed investigation

With the hope of finding an additive which would tend to increase the emissivity of a natural gas flame it was proposed to carry out an investigation into the influence of a range of additives on the radiation and associated properties of a premixed methane-air flame. Methane was chosen as the fuel since it comprises over 90% of the natural gas found in the North Sea and was preferred to the latter because it was available with constant composition.

Dependant variables to be measured were emissivity, flame temperature and radiance at different distances from the burner. Measurement of radiance alone was not considered to be of great value, the prediction of the radiance of similar flames of different size from this data being extremely difficult if not impossible. The radiance at any point in a flame may be considered as a function of the emissivity and temperature at that point. Considerable information is available about the scaling of emissivity of flames and temperatures can be predicted with reasonable accuracy by heat balances. It was felt, therefore, that measuring the emissivity and temperature would be of value.

In addition a measure was to be made of the heat transferred from the flame to its immediate surroundings, in this case a water-cooled calorimeter. It was hoped that the calorimeter would to some extent simulate the load in a furnace and some correlation between the temperatures and emissivities and the heat transferred might be obtained. Thesmoke points of the different flames, as defined by Street and Thomas (85), were also to be determined to permit comparison with earlier work.

In order to reduce the effects of the experimental error involved in the tests and to improve the accuracy it was decided to carry out each run three times.

5.1 The measurement of emissivity, temperature and radiance

To reduce the amount of work it was decided to try to find one experimental method which would allow the determination of these three variables. The choice had to be made from the Schmidt method (115), the two path method and the two colour method, both described by Hottel and Broughton (29). The Schmidt method was rejected because of the difficulties outlined in section 3.2. Some of these problems were circumvented by Pengelly (116) who used a modified total radiation pyrometer. The method requires three values for radiation received by the pyrometer to be obtained. These are for the pyrometer sighted though the flame onto a cold, black backgroud, R_F, through the flame onto a hot, black background, R_{F+B}, and directly onto the hot, black background, R_B.

Then, $R_{F+B} = R_F + R_B . \tau_F$

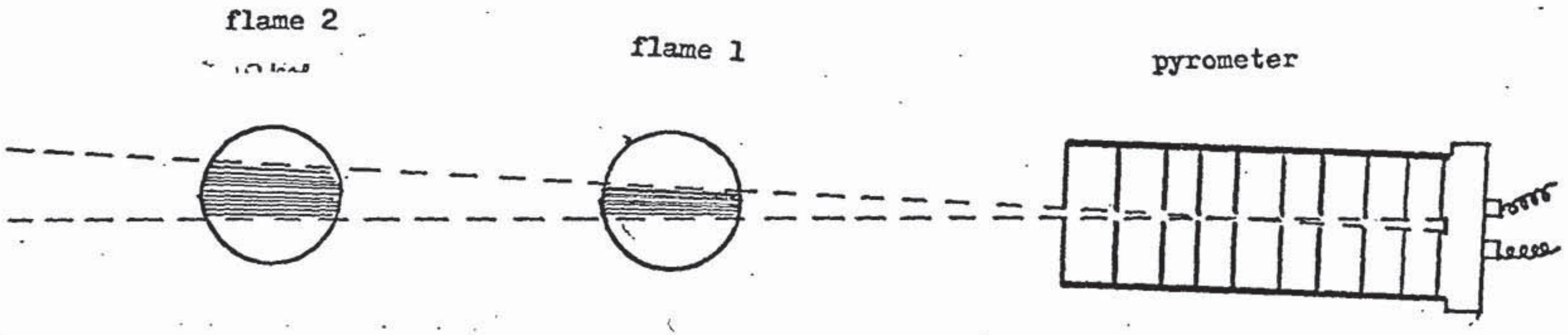
whence ϵ_F provided that Kirchoff's Law may be assumed to hold, as discussed previously. Pengelly's instrument was fitted with two thermopiles which could simultaneously be sighted through the flame onto hot and cold, black backgrounds.

The two colour method as conceived by Hottel and Broughton required the use of two pyrometers operating in different, extremely narrow bands of the spectrum. The pyrometers were calibrated against a black body and the readings obtained when sighting them at flames were referred to as 'colour temperatures'. From the two temperatures at the same position in the flame Hottel and Broughton were able to evaluate the true flame temperature and the emissivity. To perform this calculation, however, it was necessary to assume a value for the absorption coefficient of the soot. An average value was used but the evidence against the validity of the assumption, on the grounds that the coefficient is a function of the particle size, is considerable (117). Variations of the method have included the use of an optical pyrometer for measuring the red brightness temperature together with a total radiation type (118, 119) and the three colour method (120). In both cases it is still necessary that the absorption coefficient is known. The only alternative to assuming a value is to obtain the particle size and size distribution for the soot and evaluate it.

The two path method could be considered as a modification of the Schmidt method. The main disadvantage of the latter, that to avoid assuming the flame is a non-grey body then the hot background must be at the flame temperature, is circumvented by using an identical flame as the hot background. The background is then automatically at the correct temperature.

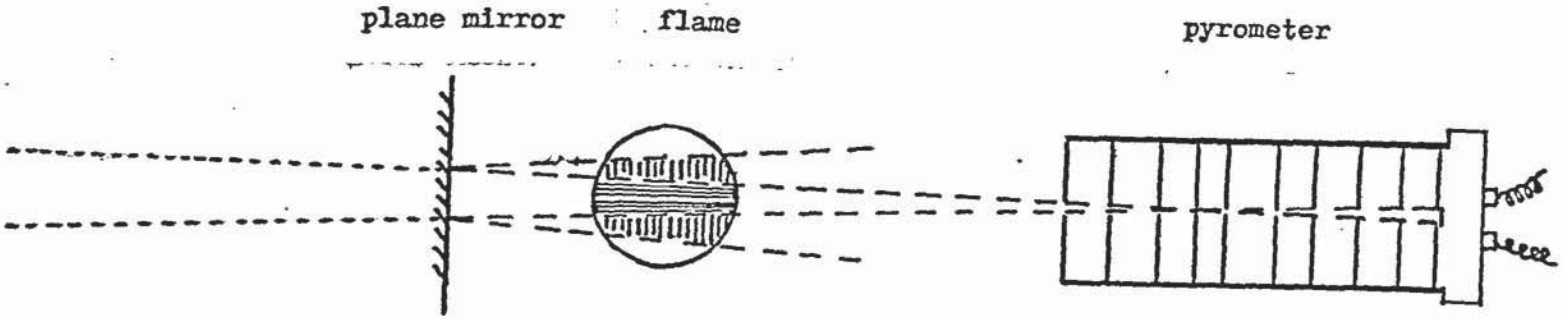
The two path method was recommended by Dyne and Penner (121) for use in situations in which spectral emissivity data are not available. It has to be accepted, however, that the emissivity

Figure 9



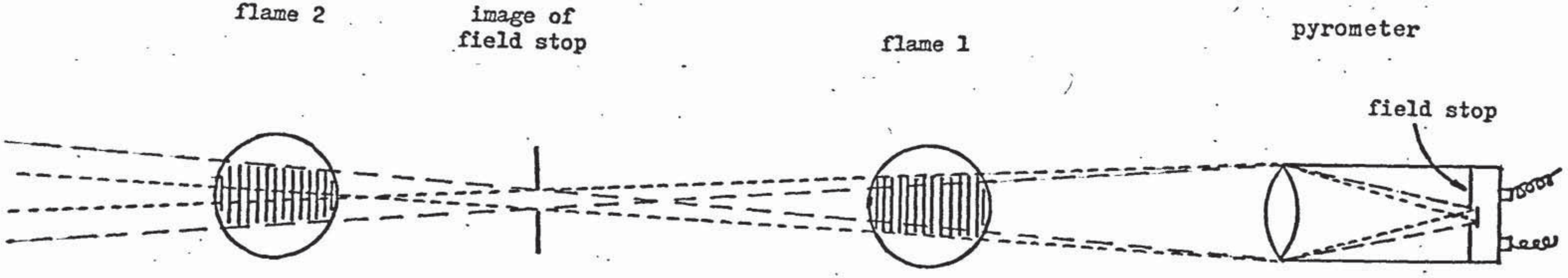
The two path method as used by Hottel and Broughton

Figure 10



The two path method using a mirror

Figure 11



(Not to scale)

The two path method using a lens-type pyrometer over the range of wavelengths to be covered will be represented by a single average value. This restriction does not prove a disadvantage in an engineering investigation such as this, when it is wished to compare the emissivities of flames averaged over all wavelengths. It should be noted, however, that the measuring of average emissivities for the flames does not imply that they behave as grey bodies.

Hottel and Broughton used a diaphragm-type total radiation pyrometer viewing first one flame and then the same flame with an identical one beyond it, as shown in fig. 9. More recent applications (122, 123, 124) have used a mirror of known reflectance in place of the second flame as shown in fig. 10. It is clear that a much larger area of the 'second flame' than of the first flame falls within the fieldof view of the pyrometer. If the flame is relatively large and areas within the field of view can be considered isothermal then errors resulting from viewing different areas of the two flames will be small. This is undoubtedly the case when the technique has been used for measuring temperatures in pulse jets and rocket chambers (122, 123). For use with small flames the errors may be much more serious and the values for emissivity and temperature would become meaningless.

To overcome this problem it was decided to utilise a property of the field of view of the lens-type total radiation pyrometer which was available, fig. 11. It can be seen that the field of view converges up to the image of the field stop and beyond this point it diverges.

By positioning one flame in each part of the field of view almost exactly similar portions of the two flames were detected and errors due to assumptions of isothermal regions were minimised.

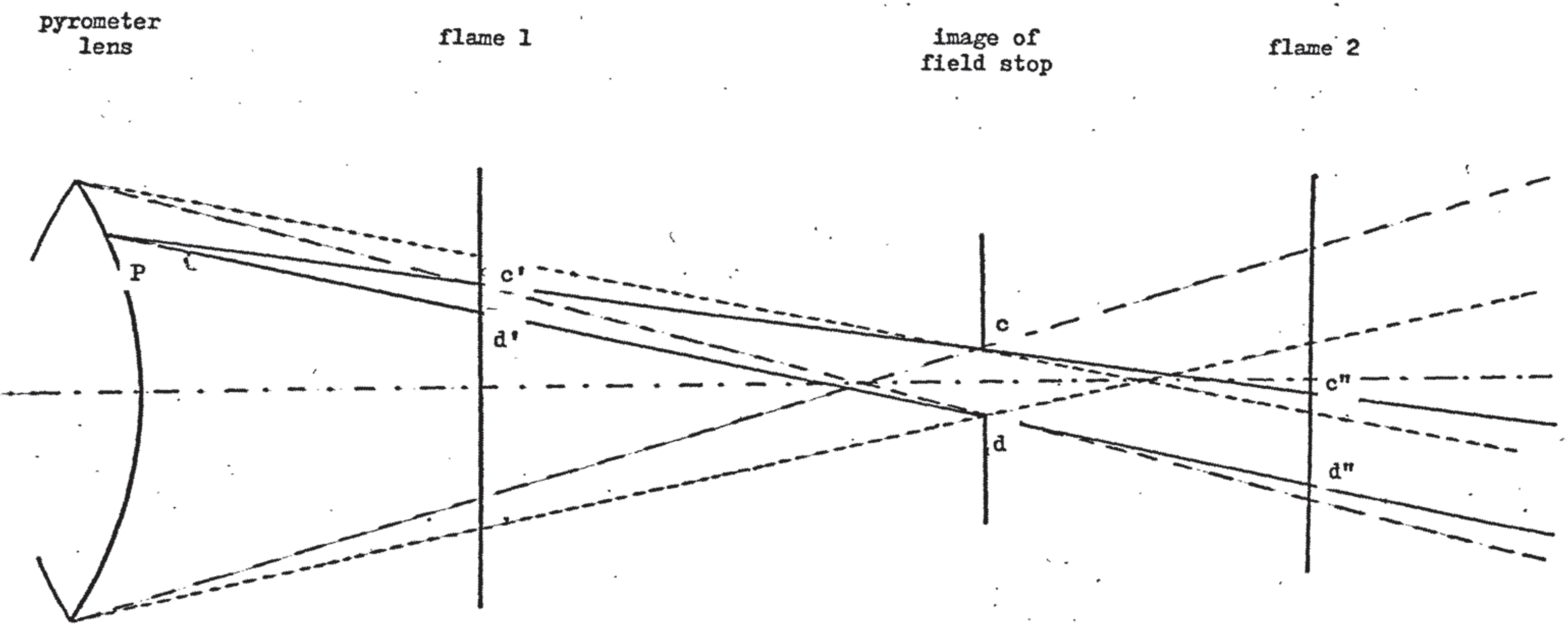
5.2 The Pyrometer

5.2.1 The field of view of the pyrometer

The total radiation pyrometer used, which is described in more detail in section 7.3, had a lens of diameter 3.5 cm, focal length 5.5 cm and the field stop was of 0.4 cm diameter, positioned 8 cm from the lens. The lens was of the convex-convex type and was 4.67 mm thick at the axis so the position and size of the image of the field stop could be found by use of the thin lens formulae. The image was 17.606 cm from the lens and was of 0.88 cm diameter.

The field of view of the pyrometer was drawn out as shown in fig. 11. It should be noted that due to the finite size of the field stop the two sections of the field of view converge and diverge at slightly different angles. This was assumed to be insignificant when the positions of the two flames were selected, equal diameters in the field of view at the centre line of each flame being the criterion used. The differences in volume and shape of the portions of flame viewed were very small and considered to be of little consequence; but rather than calculate the resultant error, which would have been extremely difficult, a preliminary experiment was carried out to obtain suitable correction factors. This is described in sections 5.2.4 and 8.1.

Figure 12



To show that theoretically the radiation received by the pyrometer is the same from both flames

It was decided to position the flames at 14.1 cm and 19.6 cm from the lens of the pyrometer. The field of view at both these points was of 1.4 cm diameter.

5.2.2 The radiation received by the pyrometer

Considering the situation shown schematically in fig. 12 with a pyrometer viewing a large flame, the radiation reaching the thermopile must pass through the lens aperture, and depending on the relative positions of pyrometer and flame, must either pass through or appear to pass through the image of the field stop that would be formed by the lens. The only part of the flame radiating to the thermopile via point P on the surface of the lens is that represented in flame 1 by c' d' or in flame 2 by c" d". If A is the area of the image of the field stop and A' and A" the areas of c' d' and c" d" respectively then by similar triangles

$$\frac{A}{(Pc)^2} = \frac{A'}{(Pc')^2} = \frac{A''}{(Pc'')^2}$$

by the Inverse Square Law

$$\text{Irradiance} \propto \frac{\text{Area of source within view}}{(\text{distance})^2}$$

$$\text{irradiance of P by flame 1} \propto \frac{A'}{(P'c')^2}$$

$$\text{and irradiance of P by flame 2} \propto \frac{A''}{(P''c'')^2}$$

If flames 1 and 2 are similar, therefore, then the irradiance of P, by radiation which will pass to the thermopile, will be the same in both cases and, indeed, for similar flames at any distance provided they fill the field of view. This argument may be extended to all points on the surface of the lens and so in theory the radiation reaching the thermopile is independant of the distance of the pyrometer from the flame.

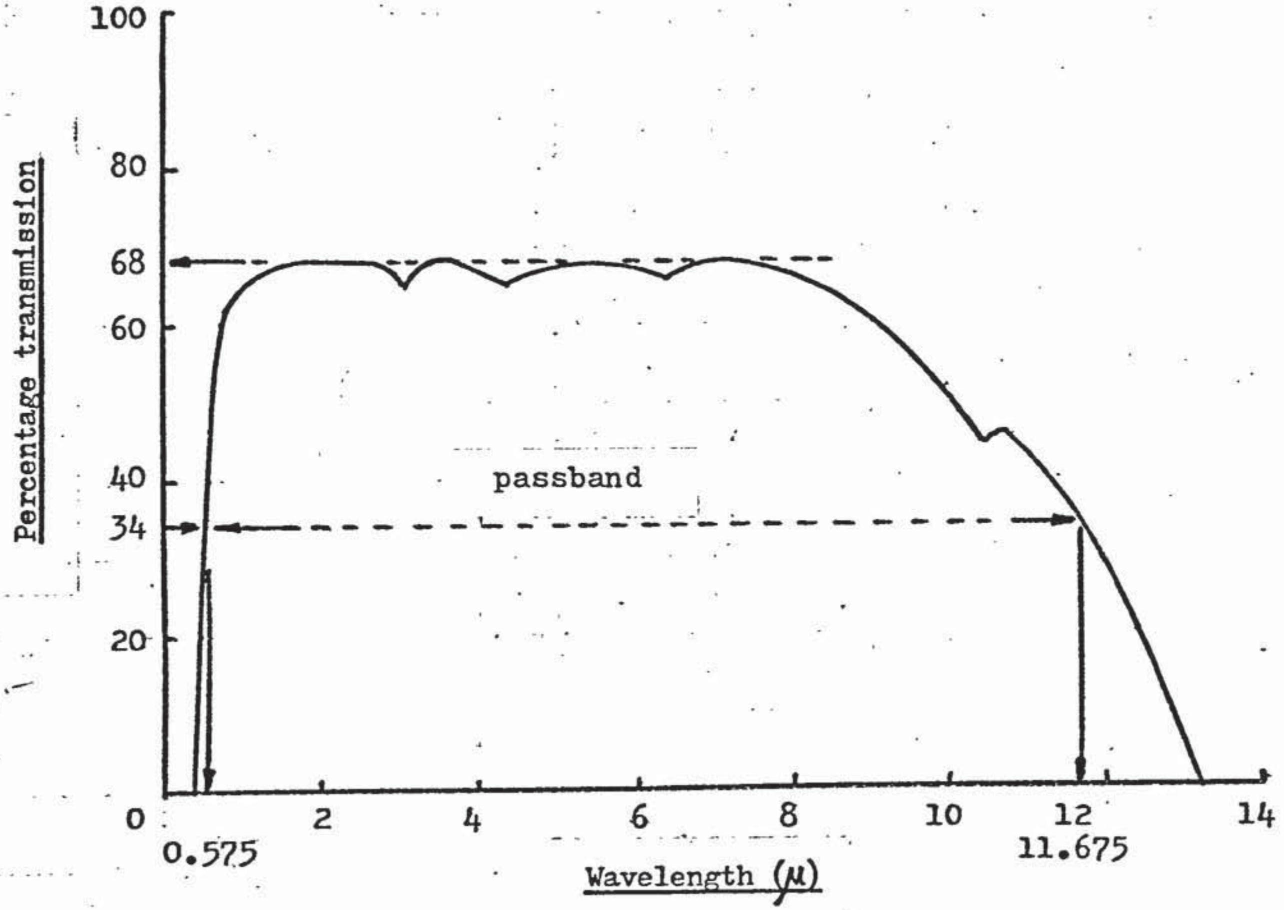
From this it may be concluded that identical readings should be obtainedfor the two identical flames located at 14.1 cm and 19.6 cm from the pyrometer lens. In practice atmospheric absorption of radiation by water vapour might occur though the loss would be relatively small. It is possible to calculate corrections for this phenomenon from a knowledge of the humidity and temperature (128). For the purpose of this work it was considered satisfactory to use a constant correction factor, determined experimentally and incorporated into the correction for field of view mentioned previously and detailed in Section 5.2.4.

5.2.3. The passband of the pyrometer lens

The main disadvantage of lens-type radiation pyrometers, such as that used for the present work, is that radiation of all wavelengths is not transmitted equally through the lens material. It is not strictly accurate, therefore, to state that such an instrument measures total radiation, some absorption and reflection of radiation is unavoidable to an extent which varies with wavelength.

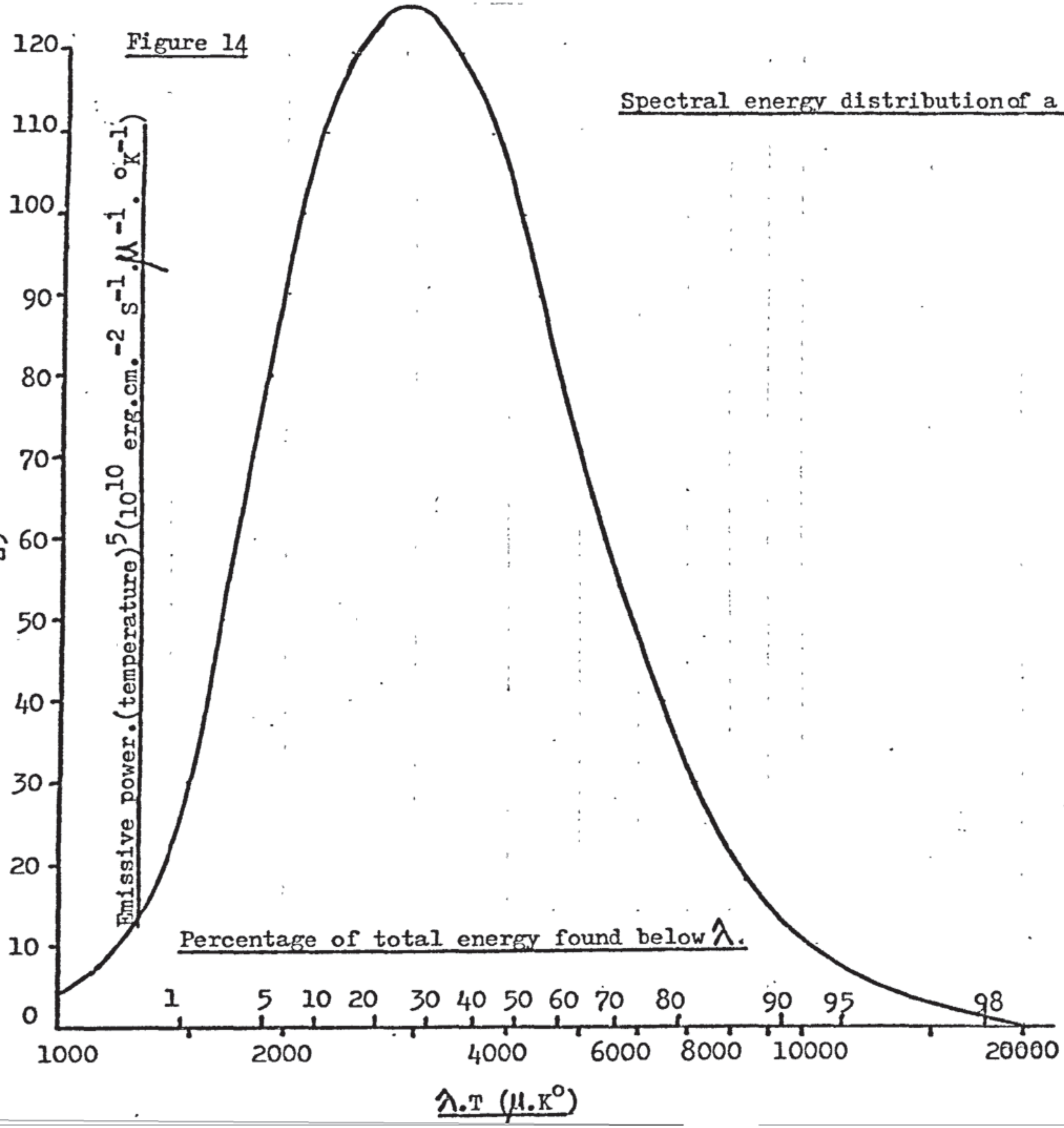
Daws and Thring (33) pointed out that the radiation of significance in most heat treatment furnaces had wavelengths within the limits 1 - 7μ. To fulfil the aims of the present work

Figure 13



The passband of arsenic trisulphide 3mm thick

Figure 14



Spectral energy distribution of a blackbody and provide meaningful values for the emissivities of the various flames examined it was, therefore, necessary to detect the radiation from the flames within those limits of wavelength. Several different lens materials have been used for investigations in this region of the spectrum, among them are fluroite and arsenic trisulphide. The latter was considered to be most suitable since calcium fluoride lenses are subject to extremely bad chromatic aberration leading to difficulty in defining the field of view. A plot of percentage transmission against wavelength for arsenic trisulphide is shown in fig. 13. The refractive index in the range shown is approximately 2.4, giving a reflection loss for two surfaces of about 30%. The reflection loss could have been reduced to about 5% by the use of anti-reflection coatings; this would have increased the output voltage of the pyrometer at any particular target temperature but would not have significantly extended the range of radiation detected. As the output of the pyrometer was considered sufficient the anti-reflection coatings were not used.

The limits of the pass band of a lens are defined as those wavelengths at which the transmission is 50% of the maximum. From fig. 13 it can be seen that the passband of an arsenic trisulphide lens is 0.575 - 11.675μ, which more than fulfils the requirements of Daws and Thring. The distribution of energy in the spectrum of a black body is shown in fig. 14 (129), only 3% of the total energy radiated is of wavelengths outside the passband of the arsenic trisulphide lens. The soot particles in the flames may be considered approximately as black bodies, see Appendix 1, and so the distribution of spectral energy will be similar to that in fig. 14. While the approximately 3% unmeasured energy has to be taken into account, any inaccuracy due to measuring radiation in a restricted portion of the spectrum will be very slight.

5.2.4. The calibration of the pyrometer

The basic equation for the output of the pyrometer may be written as

output $\propto$ (radiance of the source).(transmission factor)

The radiance of the source is given by the Stefan-Boltzmann law

$$W = \epsilon . \sigma . T^4$$

The transmission factor is made up of two parts, one being a function of the pass band of the lens and compensating for the radiation not detected. The other part is a function of the temperature of the source and accounts for the variation of the spectral energy distribution with the temperature of the source. The monochromatic radiance can be seen to be a function of temperature by reference to Planck's law for a black body,

$$W_B = \frac{c_1 . \lambda^{-5}}{\exp\left(\frac{c_2}{\lambda T_B}\right) - 1}$$

This correction is, again, necessary because the pyrometer only detects radiation in a limited portion of the spectrum.

Table 4

The Pyrometer Calibration data

Temp.(°C)	Emf.(mV)	Temp.(°C)	Emf.(mV)	Temp.(°C)	Emf.(mV)
100	0.014	400	0.315	700	1.615
110	0.017	410	0.337	710	1.688
120	0.020	420	0.361	720	1.761
130	0.023	430	0.385	730	1.837
140	0.026	440	0.410	740	1.917
150	0.030	450	0.438	750	1.999
160	0.035	460	0.466	760	2.083
170	0.040	470	0.494	770	2.169
180	0.045	480	0.525	780	2.260
190	0.050	490	0.557	790	2.353
200	0.057	500	0.591	800	2.447
210	0.064	510	0.626	810	2.542
220	0.071	520	0.662	820	2.640
230	0.079	530	0.700	830	2.742
240	0.087	540	0.740	840	2.852
250	0.096	550	0.780	850	2.964
260	0.105	560	0.823	860	3.078
270	0.115	570	0.867	870	3.195
280	0.126	580	0.913	880	3.315
290	0.137	590	0.961	890	3.438
300	0.149	600	1.011	900	3.563
310	0.161	610	1.063	910	3.691
320	0.174	620	1.115	920	3.823
330	0.189	630	1.170	930	3.958
340	0.204	640	1.227	940	4.095
350	0.220	650	1.287	950	4.237
360	0.237	660	1.349	960	4.383
370	0.255	670	1.412	970	4.533
380	0.274	680	1.475	980	4.685
390	0.294	690	1.543	990	4.841
400	0.315	700	1.615	1000	5.000

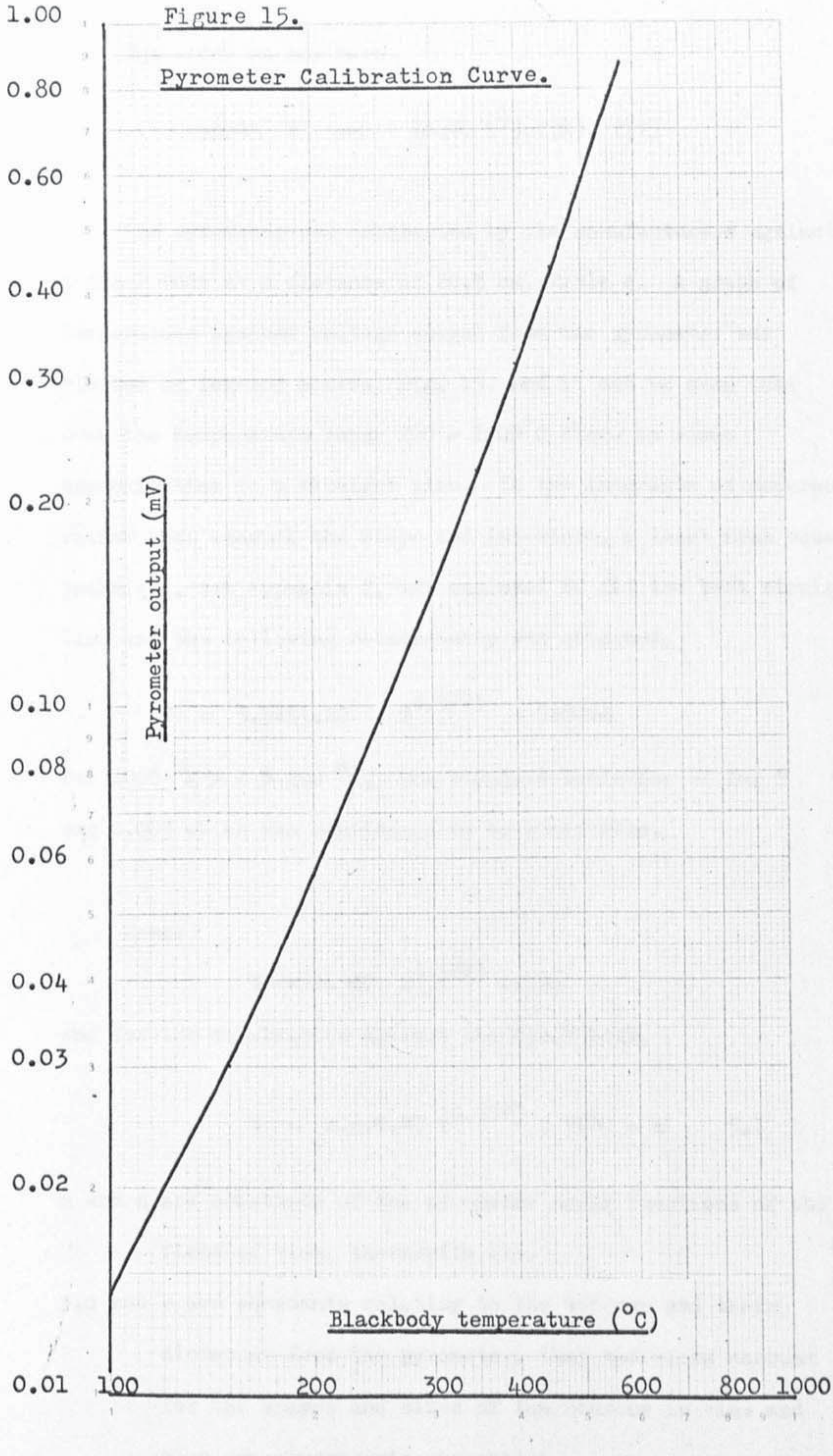


Figure 15.

Pyrometer Calibration Curve.

Therefore we now have

$$\text{output } V \propto (\epsilon.\sigma.\ T^4).f(\lambda).\ f(T)$$

The pyrometer was calibrated by the manufacturers against a black body at a distance of 20.3 cm, Table 4. A graph of temperature against voltage output from the pyrometer was plotted on log-log scales, fig. 15, and it can be seen that over the temperature range 200 - 1000°C there is close approximation to a straight line. In the interests of accuracy, rather than measure the slope and intercept, a least mean squares technique, see Appendix 2, was employed to fit the best straight line and the following relationship was obtained,

$$V = 3.5481.10^{-4}.\ T^{4.5773} + 0.0024$$

for $1000\ ^{\circ}K > T > 200\ ^{\circ}K$. The standard deviation of log T was 0.003 which was considered to be acceptable.

Hence

$$V \propto \epsilon.\ \sigma.\ T^{4.5773}\ .f(\lambda)$$

and for the calibration against the black body,

$$V = m.p.\epsilon.\sigma.\ T^{4.5773}\ .\ f(\lambda) + n \qquad 5.1$$

m and n are constants of the pyrometer being functions of the field of view, thermopile etc.

p,q and r are constants relating to the sources and their distances from the pyrometer, they therefore account for the shapes and sizes of the sources in view and also any atmospheric absorption.

p is for a source at the calibration distance
of 20.3 cm.
q and r are for sources at 14.1 cm and 19.6 cm
respectively.

It is important to realise that for a non-black source the temperature indicated by the pyrometer will not be its true temperature, but the temperature of a black body which would cause the pyrometer to give the same output, this is referred to as the brightness temperature of the source, T_b. Therefore in addition to equation 5.1

$$V = m.p.\sigma.\ T_b^{4.5773}\ .\ f(\lambda) + n \qquad 5.2$$

For a flame of true temperature T which has a brightness temperature T_P, measured at the calibration distance,

$$V_P + m.p.\epsilon.\sigma.\ T^{4.5773}.f(\lambda) + n = m.p.\sigma.T_P^{4.5773}.f(\lambda) + n$$

whence

$$\epsilon.T^{4.5773} = T_P^{4.5773} \qquad 5.3$$

Theoretically the brightness temperature should be independent of the distance from the pyrometer provided that the field of view is filled. However, because of the reasons detailed in sections 5.2.1 and 5.2.2 this may not be the case.

For the same source having a brightness temperature T_Q measured at 14.1 cm,

$$V_Q = m.q.\epsilon.\sigma T^{4.5773}.f(\lambda) + n = m.p.\sigma.\ T_Q^{4.5773}.f(\lambda) + n$$

Whence

$$q.\epsilon.\ T^{4.5773} = p.T_Q^{4.5773} \qquad 5.4$$

For the same source having a brightness temperature T_R measured at 19.6 cm,

$$V_R = m.r.\epsilon.\sigma.T^{4.5773}.f(\lambda) + n = m.p.\sigma.\ T_R^{4.5773}.f(\lambda) + n$$

whence

$$r.\epsilon.\ T^{4.5773} = p.T_R^{4.5773} \qquad 5.5$$

From equations 5.3 and 5.4

$$\frac{p}{q} = \left(\frac{T_p}{T_Q}\right)^{4.5773} \qquad 5.6$$

From equations 5.4 and 5.5

$$\frac{q}{r} = \left(\frac{T_Q}{T_R}\right)^{4.5773} \qquad 5.7$$

Since the pyrometer constants, m and n, could be eliminated in every case as above their values were not required. As will be shown in the next section the absolute values of p, q and r were also not necessary. The two ratios p/q and q/r were calculated from equations 5.6 and 5.7 after a simple preliminary experiment in which the brightness temperatures of identical flames were measured at the three distances, see section 8.1.

5.2.5 The calculation of emissivity, temperature and radiance

For a flame, true temperature T, emissivity ϵ and brightness temperature T_1 measured at 14.1 cm,

$$V_1 = m.q.\epsilon.\sigma.\ T^{4.5773}.f(\lambda) + n = m.p.\sigma.\ T_1^{4.5773}.f(\lambda) + n$$

Whence

$$\epsilon.q.T^{4.5773} = p.T_1^{4.5773} \qquad 5.8$$

For two identical flames, true temperature T, emissivity ϵ, combined brightness temperature T_2 measured with the pyrometer viewing one flame at 19.6 cm through the other at 14.1 cm,

$$V_2 = m.f(\lambda).T^{0.5773}.(q.\epsilon.\sigma.\ T^4 + \tau.r.\epsilon.\sigma\ T^4) + n$$
$$= m.p.f(\lambda).\sigma.\ T_2^{4.5773} + n$$

Whence

$$\epsilon.q.T^{4.5773} + \tau.\epsilon.\ r.T^{4.5773} = p.T_2^{4.5773} \qquad 5.9$$

From equations 5.8 and 5.9

$$1 + \tau.\frac{r}{q} = \left(\frac{T_2}{T_1}\right)^{4.5773} \qquad 5.10$$

By Kirchoff's law when the source of the transmitted radiation is at the same temperature as the transmitting body, as in this case

$$\tau = 1 - \epsilon \qquad 5.11$$

From equations 5.10 and 5.11

$$\epsilon = 1 + \frac{q}{r} - \frac{q}{r}\left(\frac{T_2}{T_1}\right)^{4.5773} \qquad 5.12$$

By rearranging equation 5.8

$$T = \left(\frac{p}{\epsilon . q}\right)^{1/4.5773} . T_1 \qquad 5.13$$

By the Stefan-Boltzmann law

$$W = \frac{\epsilon . \sigma . T^4}{\pi} \qquad 5.14$$

5.3 The smoke point

The definition of smoke point to be used was similar to that of Street and Thomas (85) being the critical quantity of air required to suppress carbon formation. The critical air flow was a mean of the air flows when yellow luminosity could just be observed all the time and when the yellow luminosity had just disappeared. The flow was to be expressed as a fraction of the stoichiometric air for the methane, no allowance being made for the additive.

6. Plan of the experimental work

6.1 The methane flow

As previously stated methane was selected as the fuel to be used since it was available with constant composition. Natural gas was not available from the local gasboard and so would have had to have been obtained in cylinders, as did the methane. The natural gas would not have had a fixed composition which was considered a serious disadvantage when comparing the effects of additives in small quantities.

The methane used had composition

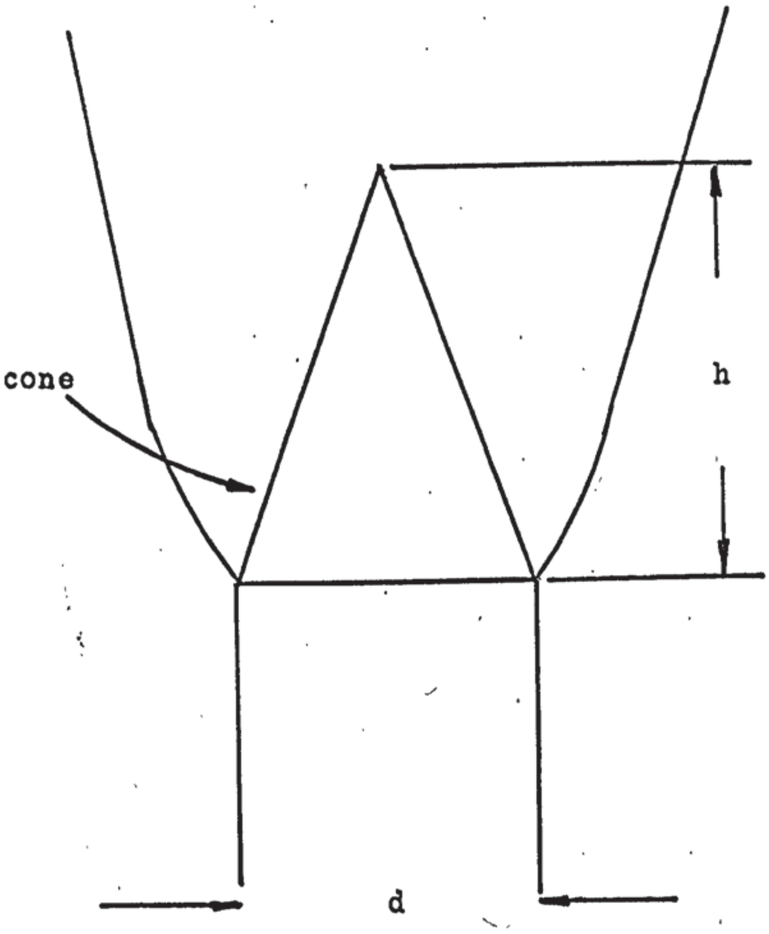
CH_4	99.9% +
O_2	less than 10 v.p.m.
CO_2	less than 5 v.p.m.
N_2	balance

The methane was supplied in cylinders of 62300l measured at S.T.P., capacity at a pressure of about 102 atm. For reasons of cost and also to reduce delays caused by changing cylinders it was necessary to use a small bench-scale flame rather than an industrial-sized flame. It was anticipated that a complete investigation of a single additive would take up to 5 hours. A methane flow of about 0.0264 $l.s^{-1}$ per burner was, therefore, equivalent to approximately 730 l per additive.

6.2 Burners

Preliminary calculations of theoretical flame dimensions from burner size and air and methane flow rates were performed using the following equation:

Figure 16.



Idealised flame used to calculate approximate dimensions at various flow rates

$$Q_f = 0.25.\ V_f.\pi.\ d^2.(1 + (\frac{2h}{d})^2)^{0.5}$$

which is based on the idealised flame shown in fig. 16.

The results of these calculations, the requirement that the flames should fill the field of view of the pyrometer; and factors concerning the air supply to the flame which will be discussed in section 7.2, were all considered before arriving at the final choice of burner size and methane and air rates. Burners of 1.9 cm diameter were used, positioned with their vertical axes 14.1 and 19.6 cm from the lens of the pyrometer. The methane flow rate per burner was fixed at 0.0264 $l.s^{-1}$, premixed with 50% stoichiometric air. This methane rate corresponded to eight additives per cylinder but in practice this was bettered as experimental technique improved.

A preliminary test showed that the burner chosen gave a flame of shape similar to that suggested by the calculations and that all the conditions were fulfilled. The flame had a visible height of about 10-12 cm and a cone height of about 6 cm.

6.3 Additive flows

The relatively low methane flow caused difficulty because of the very low additive flows necessary. Although it would have been preferable to have used another lower additive flowrate, around 1% w/w of the methane rate, it was felt that the additive rates 2.5, 5, 10, 15 and 20% w/w of the methane rate adequately covered the range of interest without creating too many problems.

Figure 17.

The burners.

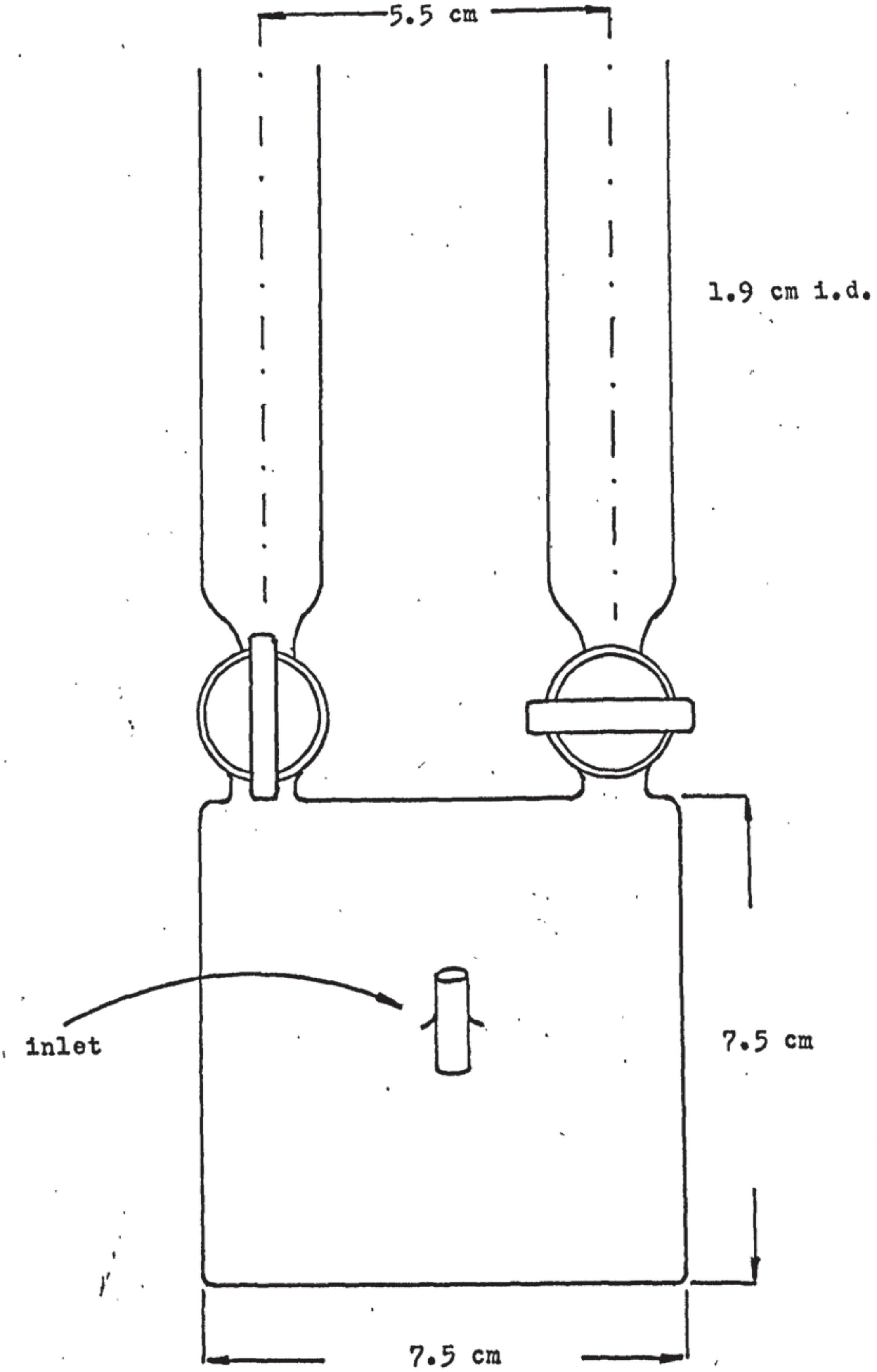
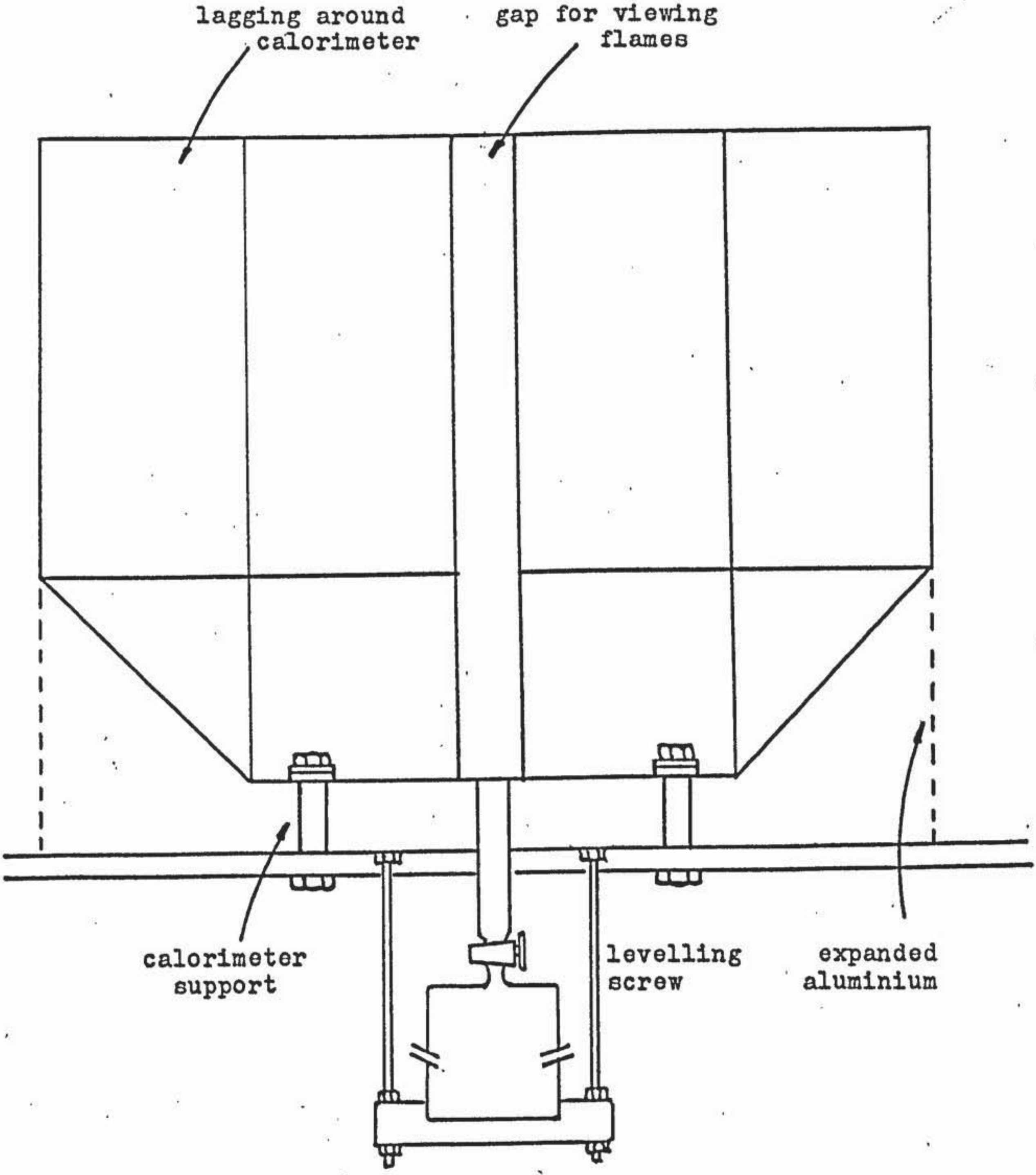


Figure 18.



Arrangement of the burners and calorimeter

7. The apparatus and equipment

7.1 The burners

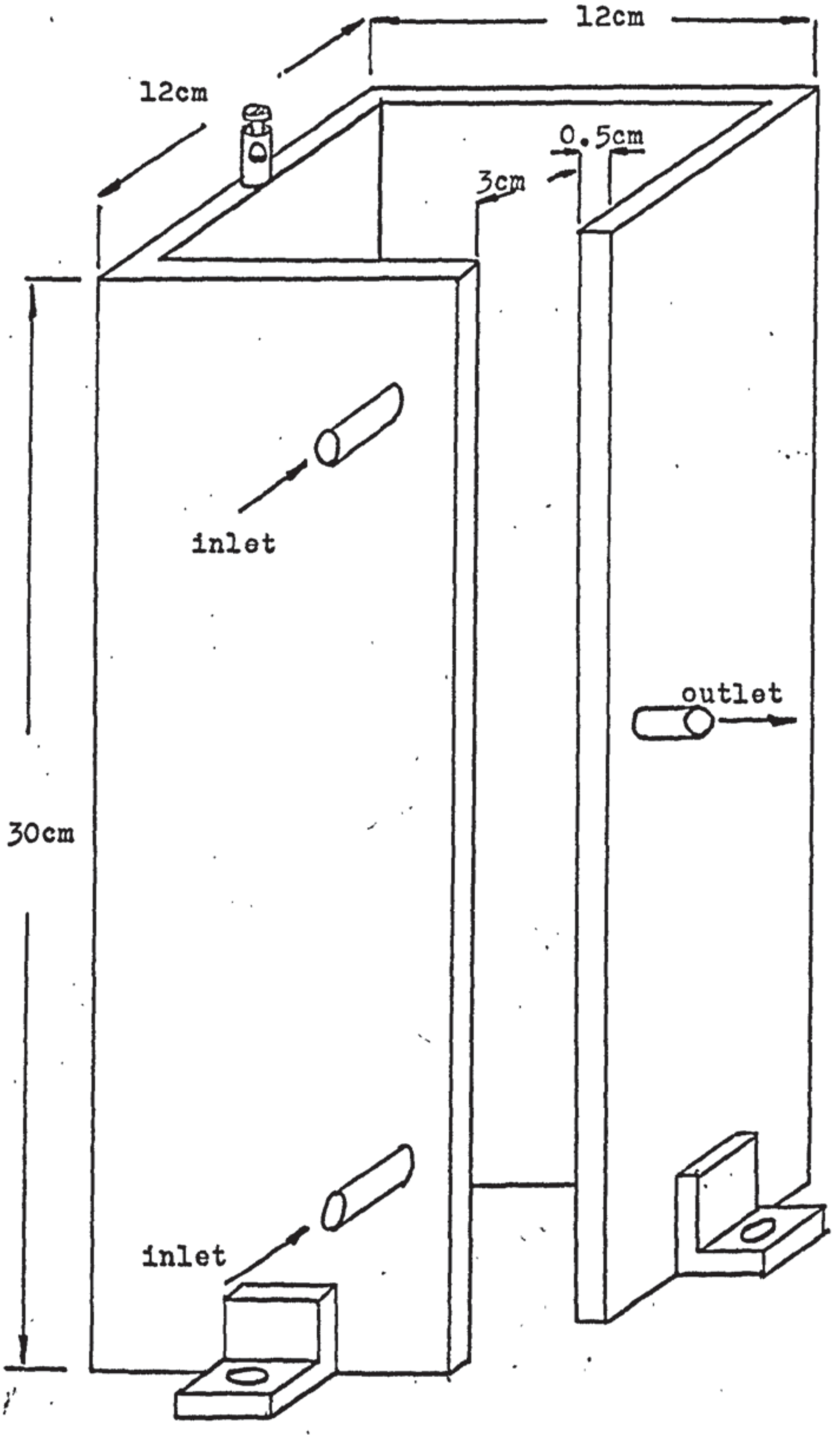
The burners, shown in fig. 17, were glass tubes 8 cm long and 1.9 cm internal diameter and were mounted on a glass mixing chamber. The methane was admitted via a tube in one side of the mixing chamber and the air plus additive, if any, entered through a similar tube opposite. The mixture was passed to one or both of the burners by way of stop-cocks at the bases of the burner tubes. It was expected that some positive means of mixing the methane with the air and additive, such as baffles, would have to be provided. Tests conducted on the burners showed, in fact, that they were not necessary and they were not used in the investigation of the additives, see section 8.4. A mesh of stainless steel wire was positioned just inside the top of each burner to act as a flame trap and prevent lighting back into the mixing chamber. The mesh was supported on a length of stiff wire standing on the stop-cock.

The mixing chamber was carried in a wooden frame hanging by three brass screws from the calorimeter base-board, fig. 18. By adjusting the screws it was possible to alter the height of the mixing chamber and set the burners vertically, the latter projecting through the calorimeter base-board.

The mixing chamber and the lower parts of the burner tubes were wrapped with heating tape which was used to prevent condensation of the higher boiling point additives. Preliminary tests showed that the small amount of heating, 0.24 Kw, did not

Figure 19.

The calorimeter.



affect the emissivity or temperature of the flames significantly see section 8.3.

7.2 The calorimeter

The calorimeter was constructed from 16 gauge copper sheet, fig. 19, all joints being soldered. The internal dimensions of the calorimeter were dictated by the size and position of the flames. To reduce the size as much as possible the flames were positioned on a diagonal. It was intended that the flames would not impinge on the walls of the calorimeter. A height of 30 cm was chosen to accommodate the longest possible flame which might have been obtained by the use of additives. The gap of 3 cm in one corner through which the pyrometer viewed the flame was selected so that none of the radiation from the flames was intercepted A small vent was fitted to enable all the air to be bled from the calorimeter.

So that the warm up time of the calorimeter was not too long and to achieve a fairly quick response in outlet temperature to any change in the flame conditions it was necessary to keep the thermal capacity of the calorimeter low. This was achieved by positioning the inner and outer surfaces relatively close together, at 0.5 cm, and having a small volume of water in the calorimeter at any time.

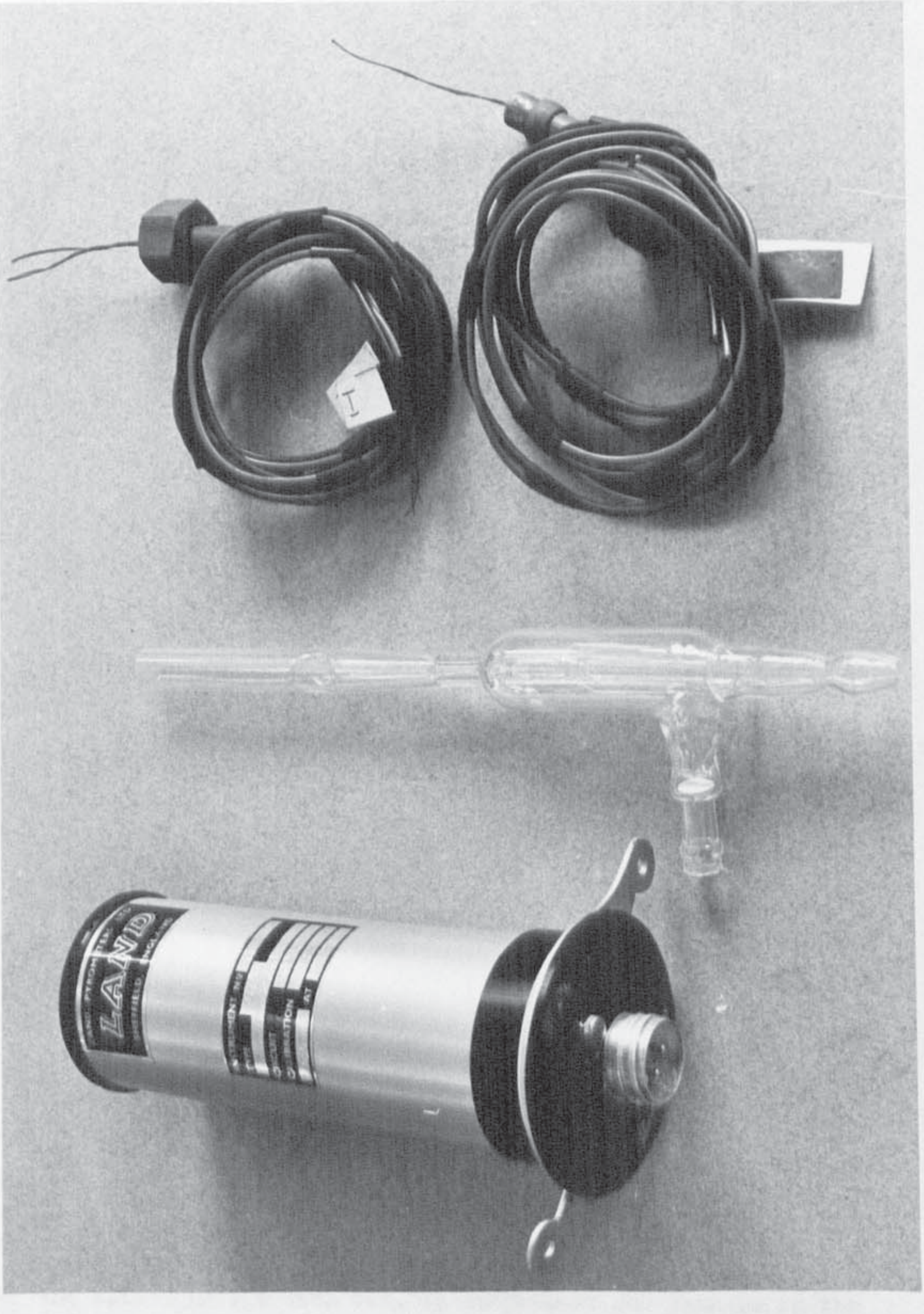
The inner surface of the calorimeter was painted with a mixture of lampblack and waterglass (sodium silicate solution) which has an emissivity of 0.95 - 0.96 (130, 131). The effective emissivity of the walls to the pyrometer was also brought closer to the unity because they were not normal to the axis of the field of view but at 45°. Approximately 1 g of lampblack was used per 4 ml water glass. It was necessary to apply the solution in a very thin coat, otherwise the glass would flow resulting in a shiny surface.

The outside walls of the calorimeter were lagged with a 15 cm thick layer of expanded polystyrene. Assuming a mean outside wall temperature of 45°C the rate of heat loss through the lagging was calculated to be approximately 0.2 $cal.s^{-1}$. The heat supplied by the methane was approximately 236 $cal.s^{-1}$, although only a fraction of this heat was transmitted to the calorimeter, the wall losses could be considered negligible. Losses due to radiation through the gap in the calorimeter could not be calculated without prior knowledge of the flame temperature and emissivity.

In order to promote good circulation of the water in the calorimeter and to avoid local hot spots, two water inlets were provided as shown in fig. 19. It was not possible to use two outlets also since this would have caused difficulty in obtaining the mean outlet temperature. A Fischer-Porter flowrator, FP - 1/8 - 20 - G, with a stainless steel float was used to measure the water flow which was maintained constant at 115 $ml.m^{-1}$. The flowrator calibration was checked before and after the additive investigations, Appendix 3.

The temperature of the water was measured by chromel-alumel

Figure 20 Pyrometer, vacuum pump and thermocouples.



thermocouples. The relatively low temperatures to be measured necessitated the use of two thermocouples in series at the outlet and the inlet. The thermocouples were made by scraping the insulating lacquer from the wires and welding the ends together. They were calibrated against an accurate mercury-in-glass thermometer at approximately 0°C and 100°C, their outputs being measured with a potentiometer, due accountwas made of the cold junction temperature. Those couples which did not satisfy the requirements of B.S.1827 were rejected and replacements made up. The thermocouples, singly or in pairs as required, were fixed into short lengths of 3/8 in. outside diameter copper tube using Araldite. The couples were so positioned that when the tubes were connected to the brass compression fittings at the inlets and outlet of the calorimeter their junctions were just inside the outer wall. Thermocouples in their tubes are shown in fig. 20.

Temperature teadings were taken from a moving coil galvanometer, Electroflo Meters Co. Ltd. Model 1511, which had been specially calibrated for two chromel-alumel thermocouples in series and had a full scale deflection of approximately 8 mV. Changing from inlet to outlet temperature reading was by a Model 151/23 two-way switch with platinum contacts. All the wiring from the couples to the galvanometer was chromel or alumel, compensating leads were not used. The recalibration of the meter for use with two thermocouples meant that the automatic cold junction compensation would notbe employed. It was necessary, therefore, to adjust the zero of the meter, before each run, to compensate for changes in the ambient temperature.

The gap in the walls of the calorimeter caused considerable difficulty during early tests, mainly because secondary air could not be excluded. Initially the calorimeter was mounted directly onto the base board so that air could not enter under the walls. In this position it was found that however much primary air was premixed with the methane, up to the onset of lift off, some air was being drawn in through the gap. Attempts to fill the gap above and below the pyrometer were not entirely successful and the nearer flame was distorted by the incoming air. A satisfactory solution was found by raising the calorimeter 4 cm from the base board and fixing the air flows at 50% stoichiometric. As a further safeguard a perspex shield was fitted beneath the pyrometer mounting jacket and this was sealed against the calorimeter lagging by strips of polyurethane foam.

In themselves these measures, allowing air under the calorimeter walls and reducing the suction through the gap, were not quite sufficient but due to draughts in the laboratory affecting the flames it was considered undesirable to raise the calorimeter further. In order to enable more air to pass under the walls the expanded polystyrene lagging was cut away from the lower edge of the calorimeter at 45°. The tops of the burners were level with the lower edge of the calorimeter. Viewed from above the flames showed a satisfactory circular section and there was no consistent tendency towards distortion.

The above modifications made the flames susceptible to draughts causing intermittant distortion. The gap between the outer surfaces

Figure 21 Front of test rig.

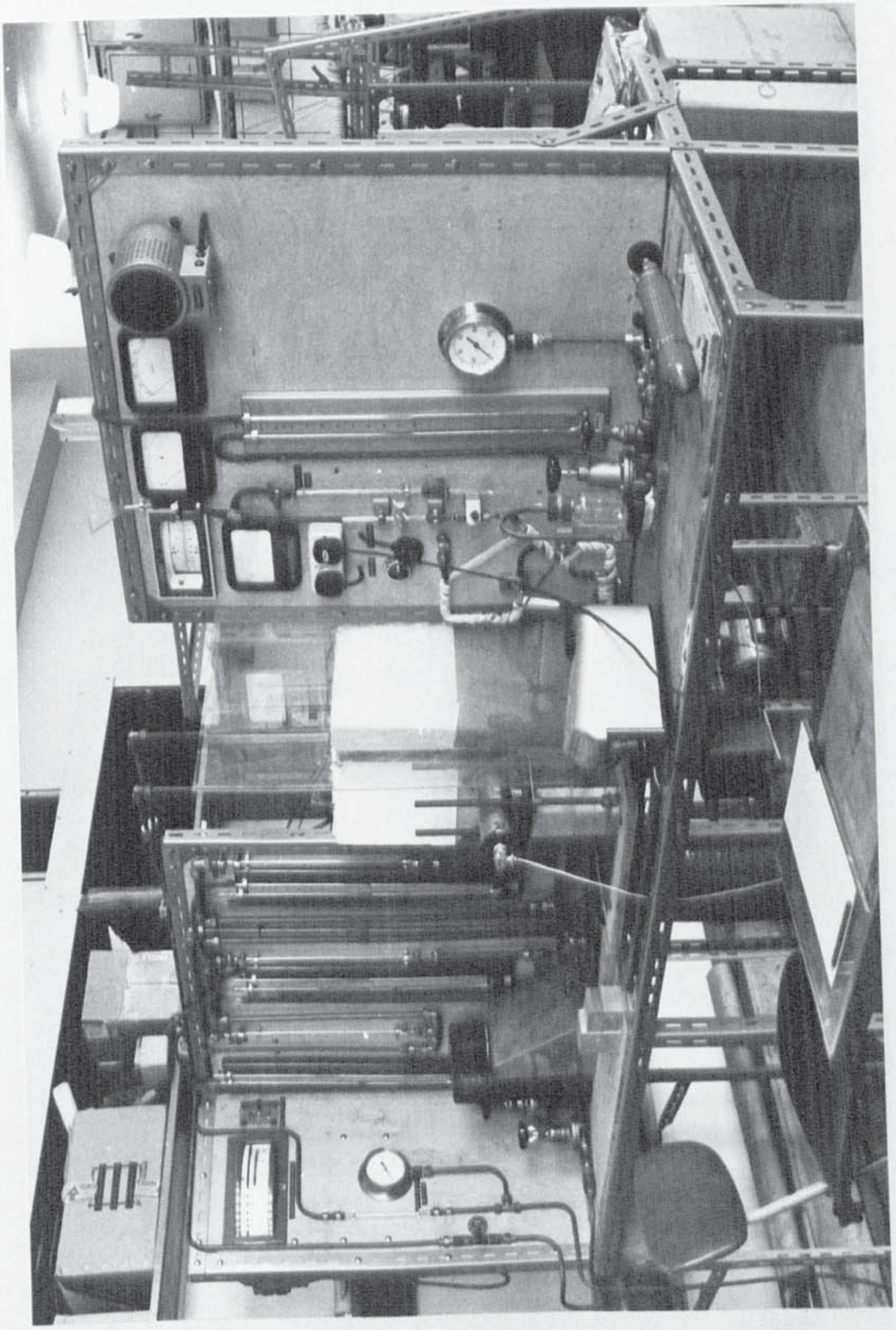


Figure 22 Rear of test rig.

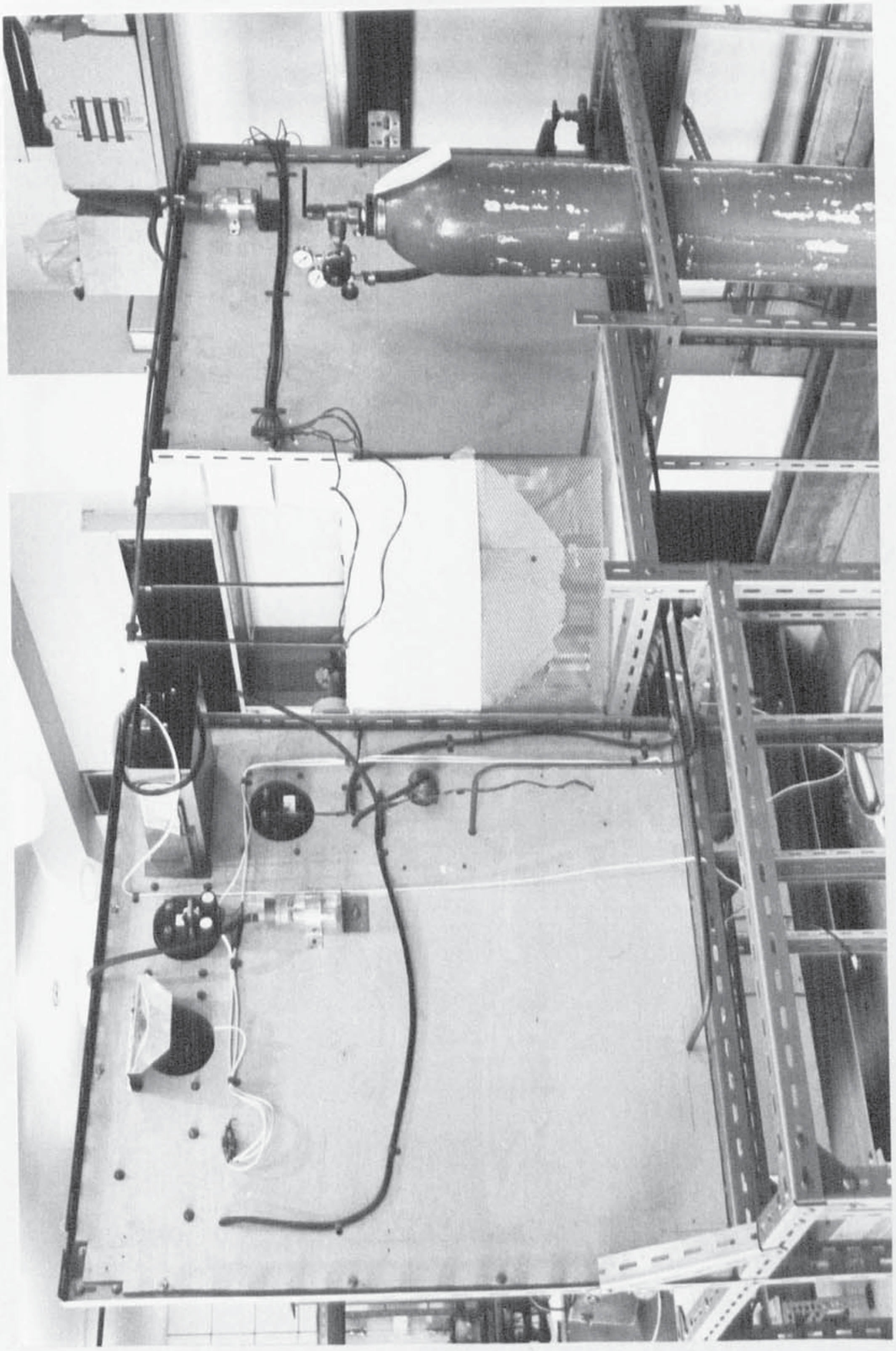
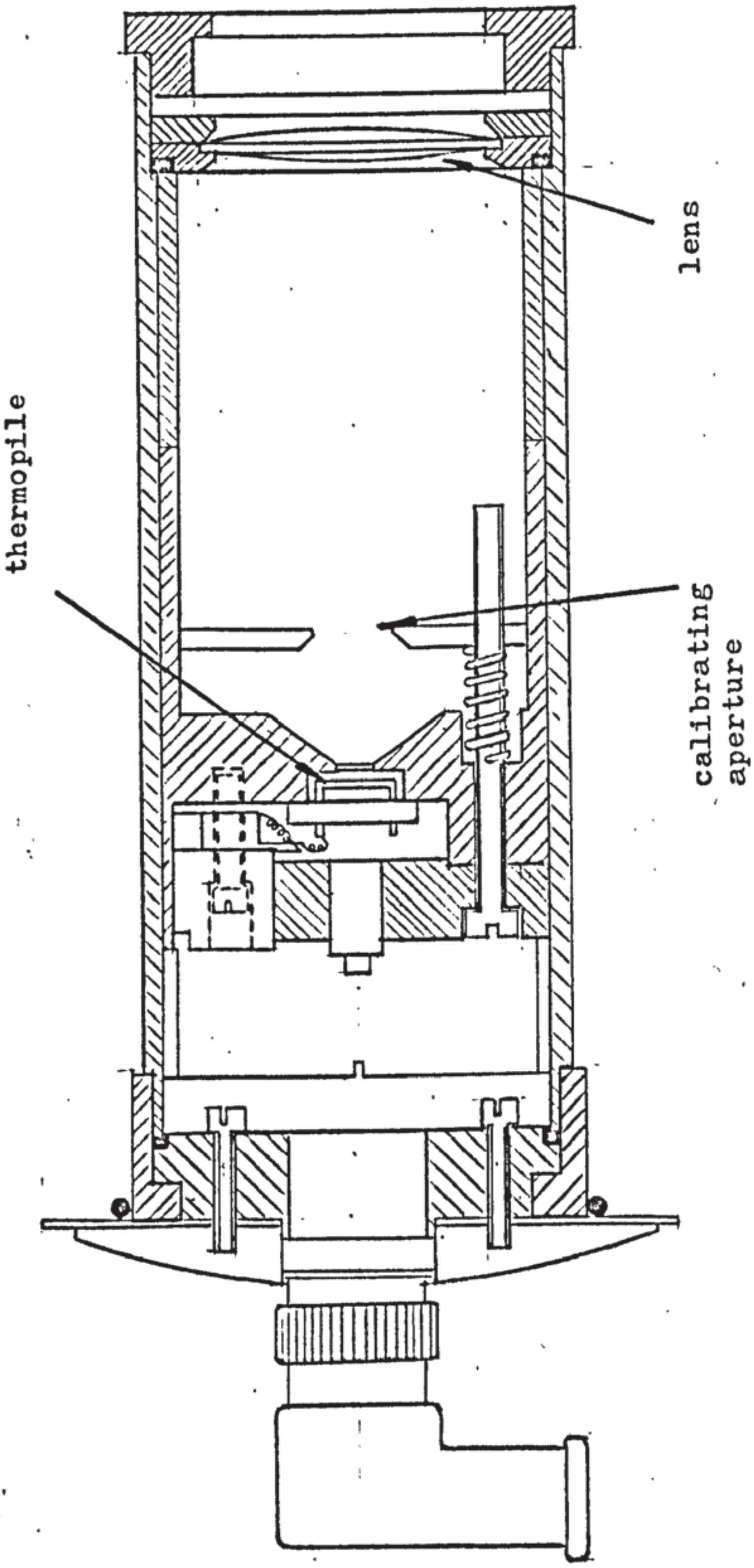


Figure 23 Pyrometer.



of the lagging and the base board were, therefore, filled using expanded aluminium mesh, as can be seen in figs. 21 and 22. This material has a large portion of its surface area available for air to pass through but, because of the twist imparted to the mesh as it was expanded most of the air was diverted from its original path and did not flow directly to the flame. The effects of draughts were thereby much reduced but as a further precaution one side of the rig was screened from the laboratory by hardboard panels.

7.3 The Pyrometer

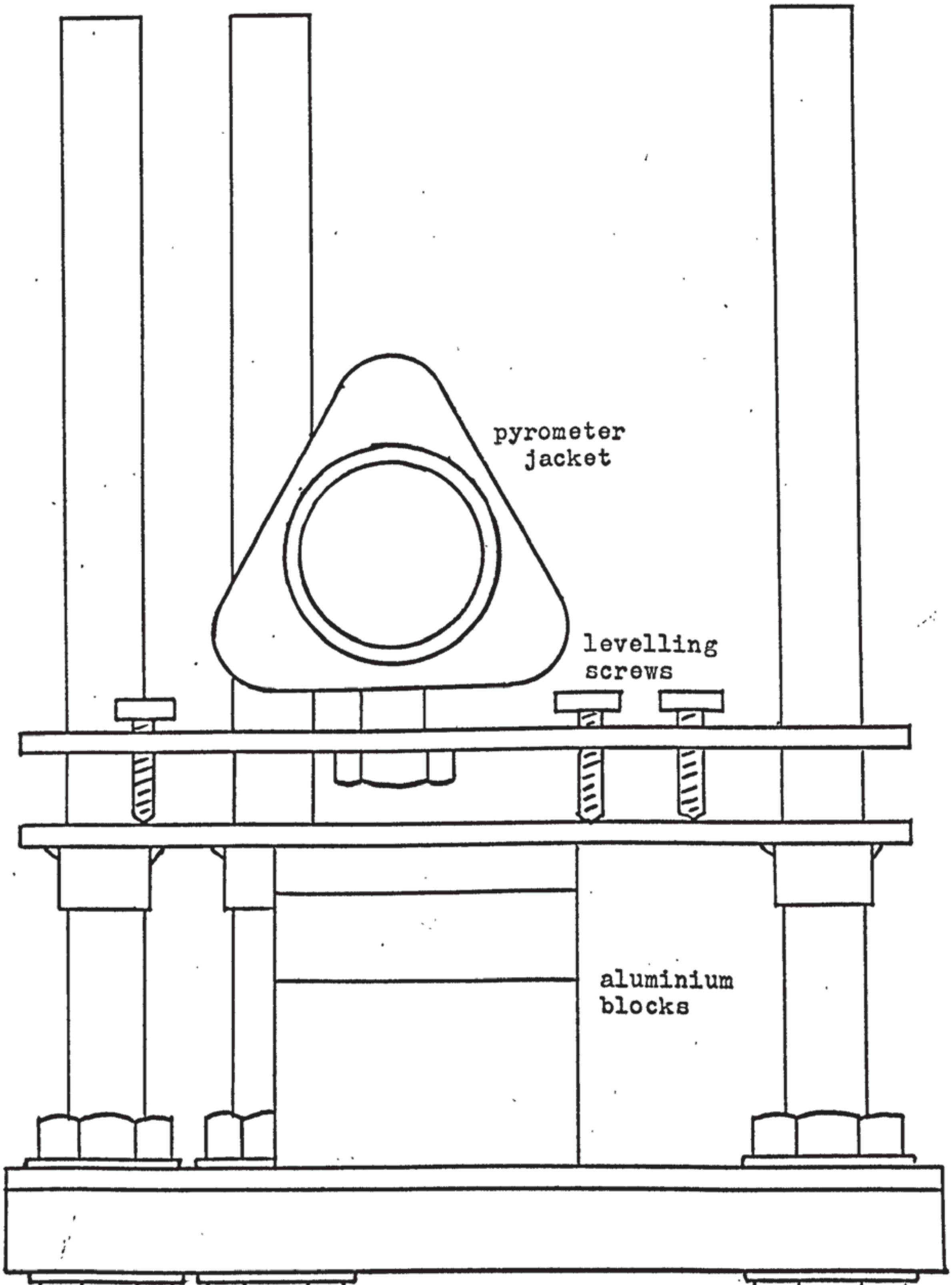
The pyrometer used was supplied by Land Pyrometers Ltd. Type ORF 35/20/6, see figs. 20 and 23. The lens was of arsenic trisulphide with an aperture of 35 mm, no protective window was used and the angular field of view was 0.05 radian. The response time was approximately 2 s to 98% of the final output. The pyrometer was compensated so that variations of its temperature in the range 0°C to 100°C had a negligible effect on the output. This was achieved by shunting the thermopile with a temperature sensitive resistor having a value of 60 ohm at 20°C. The resistance of the thermopile itself was approximately 30 ohm whence the effective internal resistance of the pyrometer was given by

$$\frac{1}{R_{pyro}} = \frac{1}{30} + \frac{1}{60}$$

$$\text{i.e.} \quad \underline{R_{pyro} = 20 \text{ ohm}}$$

Figure 24.

Arrangement of pyrometer support.

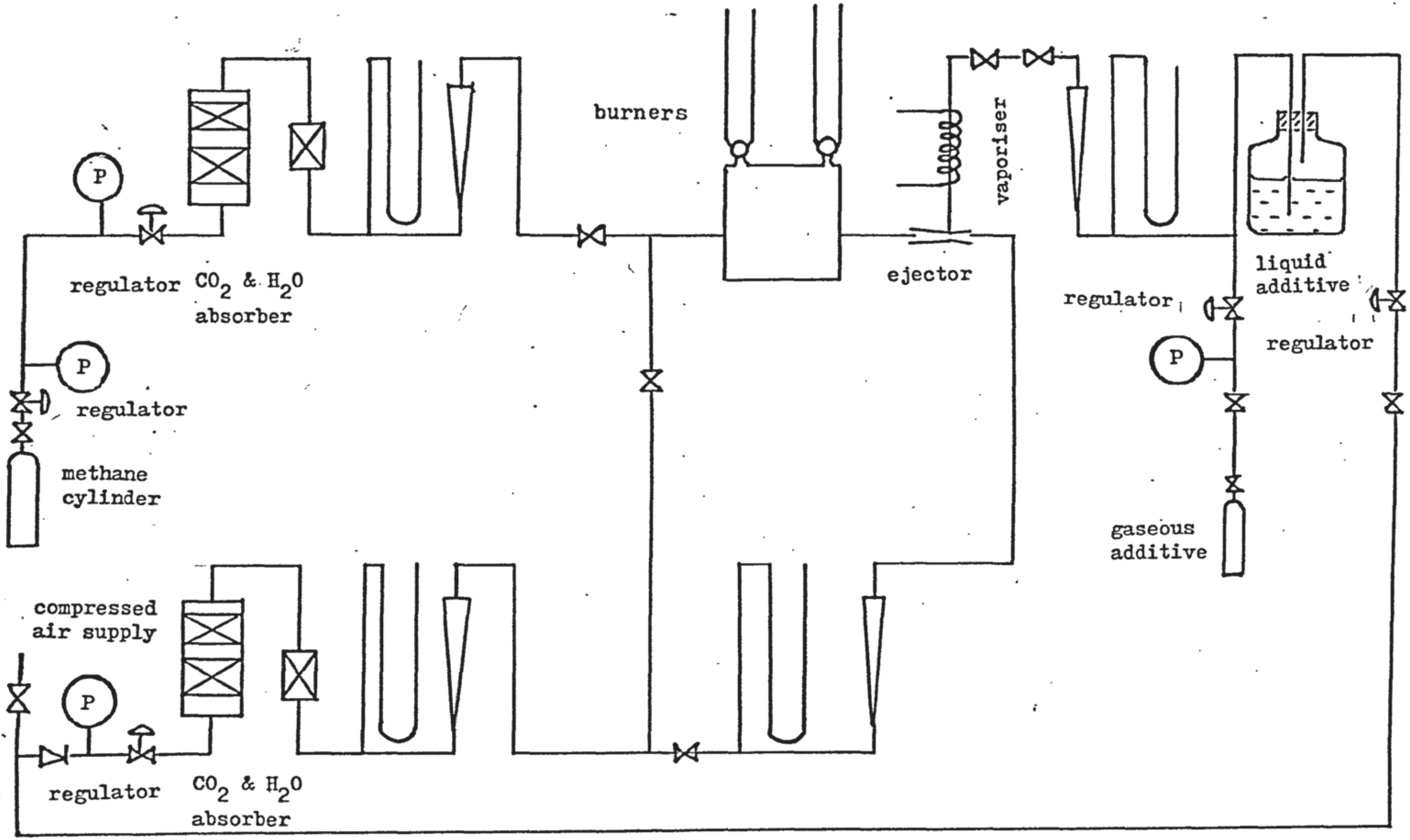


For the temperature compensation to be effective it was necessary to use a measuring instrument of resistance greater than 200 ohm. Otherwise the compensation would have been shunted and become less effective.

An Ether Type 1250 B potentiometric temperature indicator specifically calibrated for the pyrometer was available. Neither of the two ranges provided, 0°C to 1000°C and 0°C to 1800°C, was sufficiently accurate for the comparatively low brightness temperatures encountered, however. Instead a Pye Scalamp moving coil galvanometer was used. The meter was supplied with an arbitrary scale and was calibrated using a Cambridge potentiometer, see Appendix 3. The pyrometer was connected to the galvanometer by copper leads of resistance approximately 1 ohm.

The pyrometer was housed in a cast aluminium jacket which acted as a heat sink. The jacket was fixed by a single bolt to a horizontal plate supported on an identical plate by three set-screws, fig. 24. The pyrometer could be levelled by adjusting the screws. The two plates were free to slide up and down three steel columns firmly mounted on a wooden base board faced with a sheet of aluminium. The plates and pyrometer were supported at various heights by blocks of aluminium stacked on top of one another. The blocks were machined with parallel surfaces at thicknesses of 1, 2, 4, 6 and 8 cm to an accuracy of 1/1000 in. Suitable combinations of blocks enabled any desired height of the pyrometer above the burners to be obtained quickly and accurately. The height adjustment was zeroed, by altering the position of the

Figure 25 Schematic layout of the rig



calorimeter baseboard, such that using the 6 cm block alone placed the pyrometer axis level with the top of the burners. The baseboard was mounted so that it could be moved in both horizontal planes, towards and away from the burners and also laterally.

7.4 The methane supply

The layout of the various supplies is shown schematically in fig. 25. The methane cylinders were fitted with a Matheson No. 36 high purity gas regulator, the pressure of methane into the rig being maintained at 30 lbf. in^{-2}g. The pressure was further reduced by a Norgren E2A regulator before the methane passed into a combined moisture and carbon dioxide absorber. This was probably unnecessary for the grade of methane used but consisted of a 30 cm long, 7.5 cm diameter mild steel vessel containing two packed beds, one being 200 g of silica gel and the other being 200 g of 'Carbosorb', a mixture of soda and asbestos containing 63% w/w Na_2O. The beds were supported on copper mesh fixed to the walls of the vessel.

After the absorber the methane flowed through a fritted glass filter to stop any particles of Carbosorb being carried through the pipework which was a combination of 3/8 in. and ½ in. o.d. copper tubing.

Metering of the methane flow was by a Metric 7X Rotameter having a duralumin float. The pressure in the rotameter was measured by a mercury manometer and was maintained at 10 cm Hg g. by the regulator. The rotameter was calibrated using a Parkinson-Cowan wet-type gas meter having an accuracy of ± 0.25% at flows less than 12 $\text{sft.}^3\text{h}^{-1}$, see Appendix 3. The flow was controlled by a needle valve positioned after the rotameter before passing to the mixing chamber beneath the burners.

7.5 The air supply

Compressed air was available at a pressure of 80-120 lbf.in^{-2}g. from a main supply to the laboratory. The passage of methane into the main was prevented by a non-return valve after which the pressure was reduced from about 40 lbf.in^{-2}g. by a Norgren model 11400-2G regulator. The air was then passed through an absorber and filter similar to those described in the methane supply. It was found that the absorbents tended to agglomerate and the pressure drop across the absorber increased as progressively more air had been treated until replacement became necessary.

After the absorber the total air flow was measured by a Metric 10P Rotameter with a duralumin float and a mercury manometer. The pressure at the inlet of the rotameter was controlled at 10 cmHg g. by the regulator. Provision was made for splitting the air flow into two streams. One passed directly to mix with the methane just prior to entry to the mixing chamber, while the second was measured, using a Metric 7P Rotameter with duralumin float and a mercury manometer, before taking up the additive under investigation and then proceeding to the mixing chamber. In practice the former flow path was not used and all the air was utilised in transporting the additive. The air flow was again controlled by a needle valve and copper tubing was used throughout. The rotameters were calibrated with the wet-type gasmeter, Appendix 3.

7.6 The additive supply

Liquid additives were pumped from a 250 ml glass bottle by compressed air at a pressure of 10 cmHg g. The air was controlled by a Norgren model 2A regulator.

The gaseous additives were supplied under pressure in cylinders. The pressure of the gases was reduced to 10 cmHg g. by a Norgren model E2A regulator.

The pressure of the compressed air and thus the liquid additives or the pressure of the gaseous additives were measured with a mercury manometer. Additive flows were metered by Fischer and Porter Flowrators, FP - 1/16 - 10 - G - 5/36 tubes with sapphire floats were used for liquids and with tantulum floats for most of the gases. For hydrogen and helium it was necessary to use an FP - 1/8 - 16 - G - 5/36 tube with a tantulum float. The rotameters were calibrated for the liquids by collecting the liquid passed over a timed interval, see Appendix 3. Where suitable the rotameters were calibrated for the gases using a soap film meter. For dangerous gases a theoretical calibration was obtained using the Fischer and Porter Handbook which incorporates allowances for fluid density and viscosity.

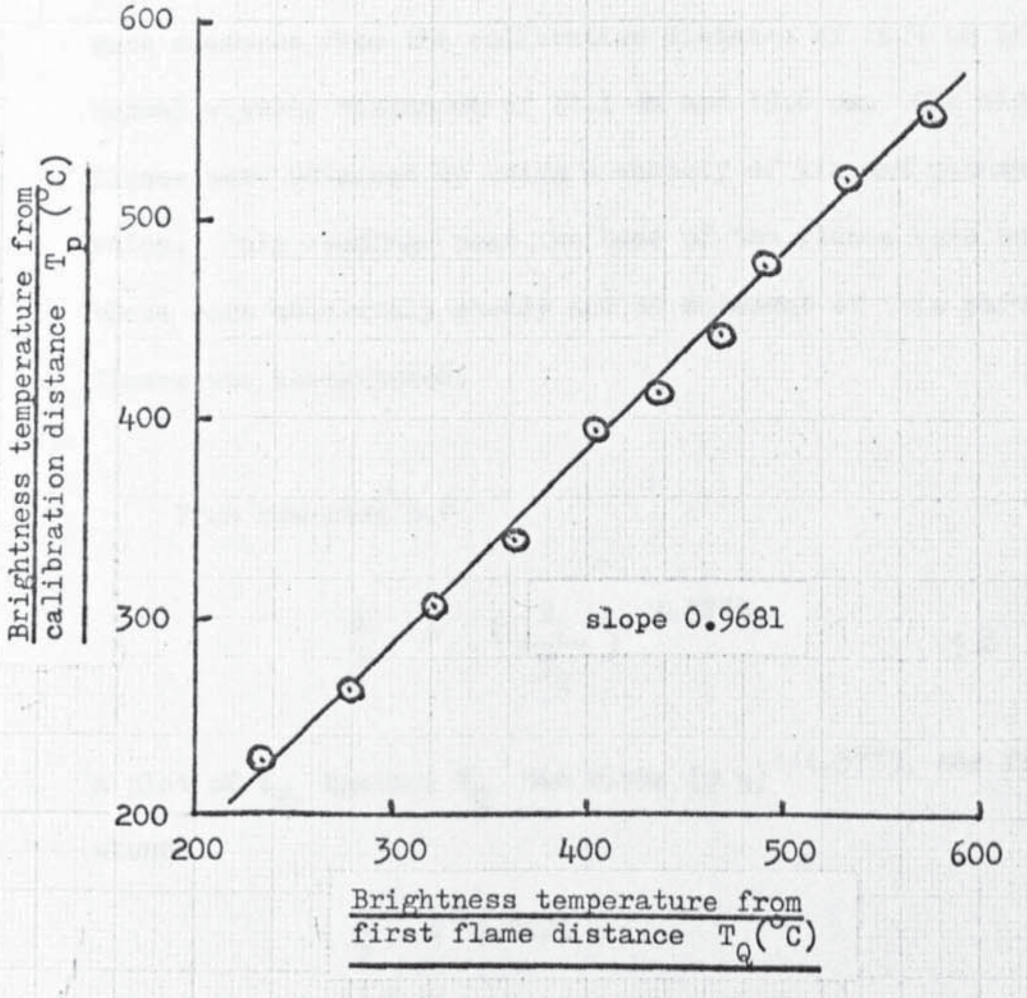
The additive flow was controlled by two needle valves. The first, a combined stopcock and needle valve manufactured from glass and P.T.F.E. was used to restrict the maximum additive flow to full scale on the rotameter. The second needle valve, in stainless steel, was fitted with a needle having a 1° taper and was used for fine control of the additive flow.

After the needle valves the liquid additives were vaporised in glass tubing heated externally by electrical heating tape. The heating rate could be controlled by a variable transformer and provision was made for measuring the voltage and current supplied. The outer surface temperature of the glass tubing was measured approximately by a chromel-alumel thermocouple. The output was measured by a 0 - 10 mV galvanometer recalibrated in °C according to B.S.1827.

The vaporised liquid additive or the gaseous additive was drawn into the suction tube of a glass ejector pump, see fig. 20, by the air passing into the mixing chamber. For liquid additives the air stream was heated by external tapes before the ejector, all subsequent tubing and the mixing chamber were similarly heated. As the preliminary tests detailed in section 8.3 show this heating did not itself significantly effect the radiative properties of the flames. Glass tubing was used throughout the additive supply. The purities of the additives used are listed in Appendix 4.

Figure 26.

Plot of brightness temperature measured at calibration distance against brightness temperature measured at first flame distance for identical sources



8. Preliminary Experiments

8.1 Corrections for the portions of the flames viewed and for atmospheric absorption

As has been mentioned in section 5.2.1., the pyrometer views slightly different portions of the two flames. The possibility of atmospheric absorption of radiation by water vapour was discussed in section 5.2.2. A simple preliminary experiment was performed to evaluate the ratios p/q and q/r which were used to correct for these sources of error.

The brightness temperatures of a series of different flames were measured from the calibration distance of 20.3 cm and the normal viewing distances of 14.1 cm and 19.6 cm. The different flames were obtained by using a variety of air and methane flow rates. Only readings near the base of the flames were used as these were absolutely steady and no movement of this part of the flames was encountered.

From equation 5.6

$$\frac{p}{q} = \left(\frac{T_P}{T_Q} \right)^{4.5773} \qquad 5.6$$

a plot of T_P against T_Q had slope $(p\ q)^{1/4.5773}$, see fig. 26, whence

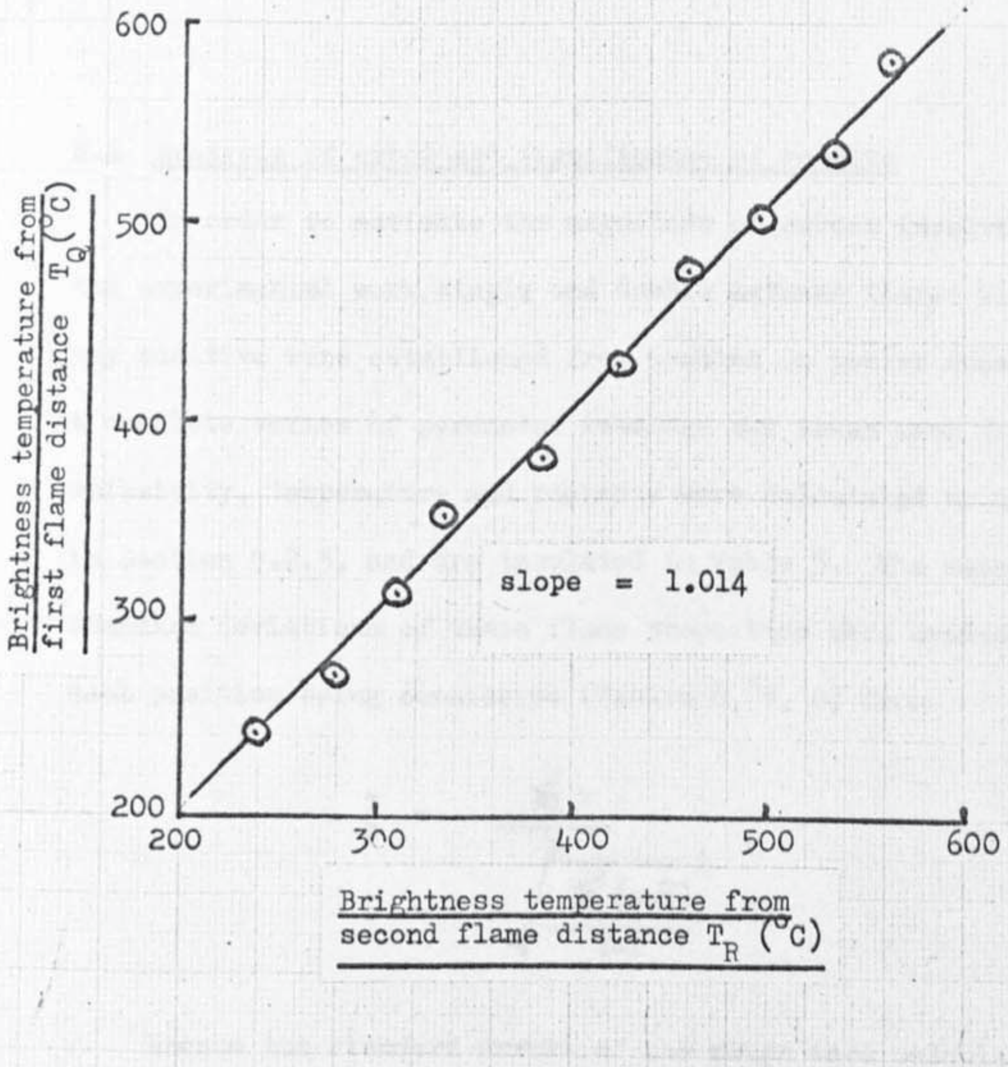
$$\frac{p}{q} = 0.8621$$

Similarly from equation 5.7,

$$\frac{q}{r} = \left(\frac{T_Q}{T_R} \right)^{4.5773} \qquad 5.7$$

Figure 27.

Plot of brightness temperature measured at first flame distance against brightness temperature measured at second flame distance for identical sources



a plot of T_Q against T_R had slope $(q/r)^{1/4.5773}$, see fig. 27, whence

$$\frac{q}{r} = 1.067 \ ,$$

The least mean squares curve fit, Appendix 2, was used to obtain the accurate values of the slopes for substitution in equations 5.12 and 5.13 :

$$= 2.067 - 1.067 \left(\frac{T_2}{T_1}\right)^{4.5773} \qquad 8.1$$

$$T = \left(\frac{0.8621}{\epsilon}\right)^{0.2185} \cdot T_1 \qquad 8.2$$

8.2 Analysis of error and significance of results

In order to estimate the magnitude of errors involved in the experimental work, single and double methane flames without any additive were established from scratch on twelve occasions. A complete series of pyrometer readings was taken each time. The emissivity, temperature and radiance were calculated as described in Section 9.2.3. and are tabulated in Table 5. The means and standard deviations of these flame properties were evaluated for each position being considered (Tables 6, 7, 8) from

$$\bar{x} = \frac{\sum x}{N}$$

$$s = \sqrt{\frac{\sum (x-\bar{x})^2}{N-1}}$$

Whence the standard errors of the means were calculated from

Figure 28.

Significance levels and confidence limits of means of emissivities.

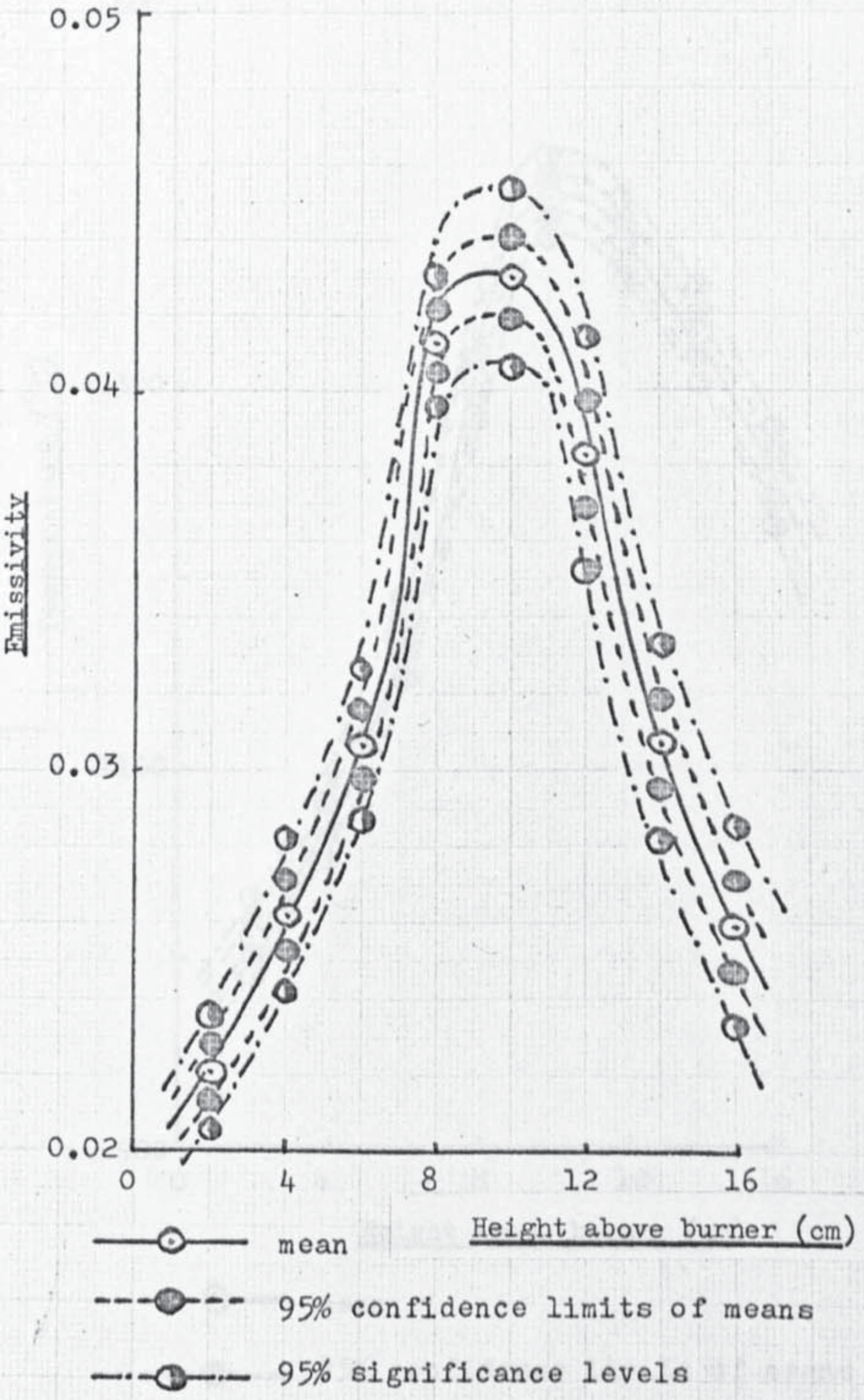


Figure 29.

Significance levels and confidence limits of means of temperatures.

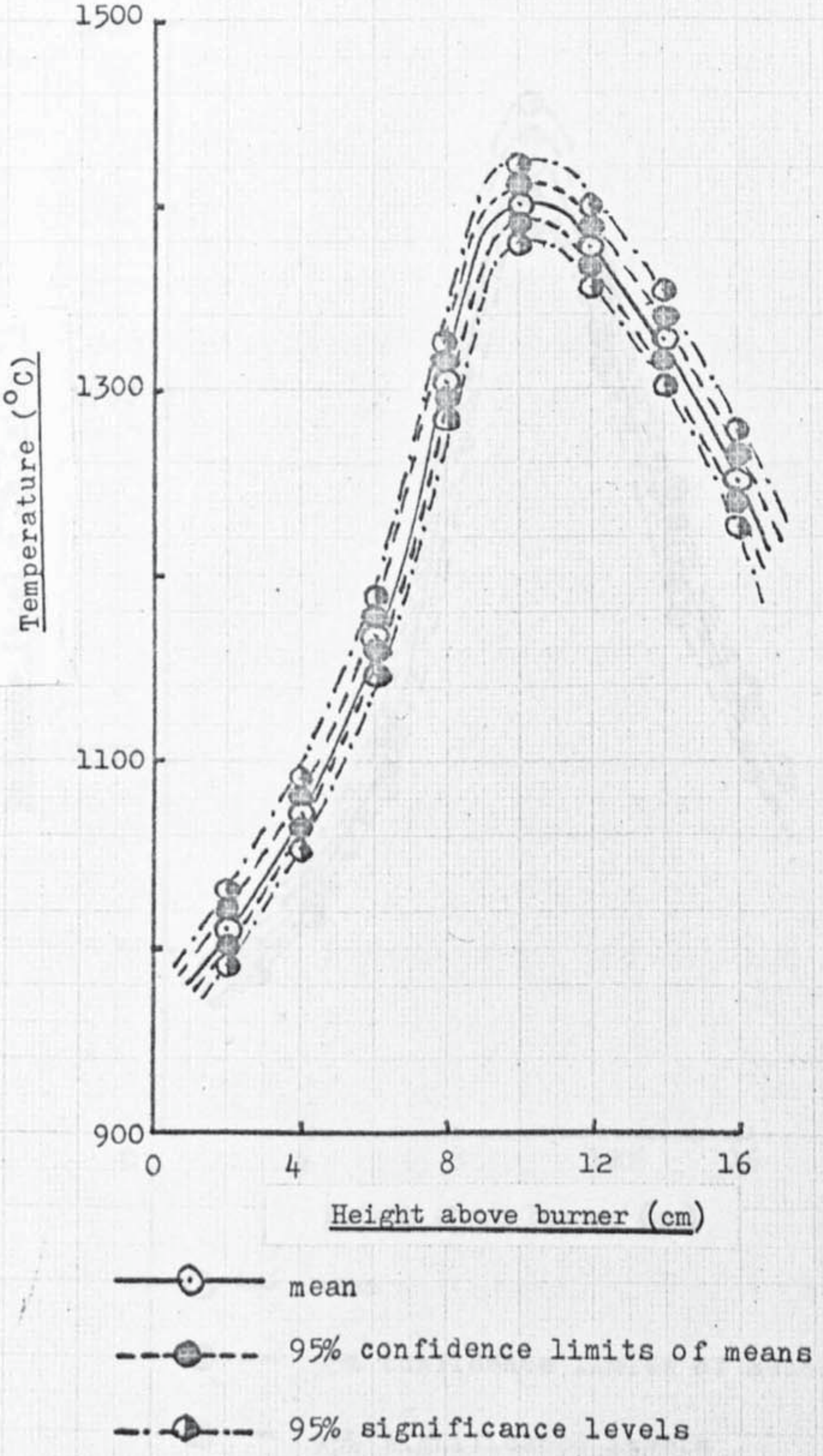
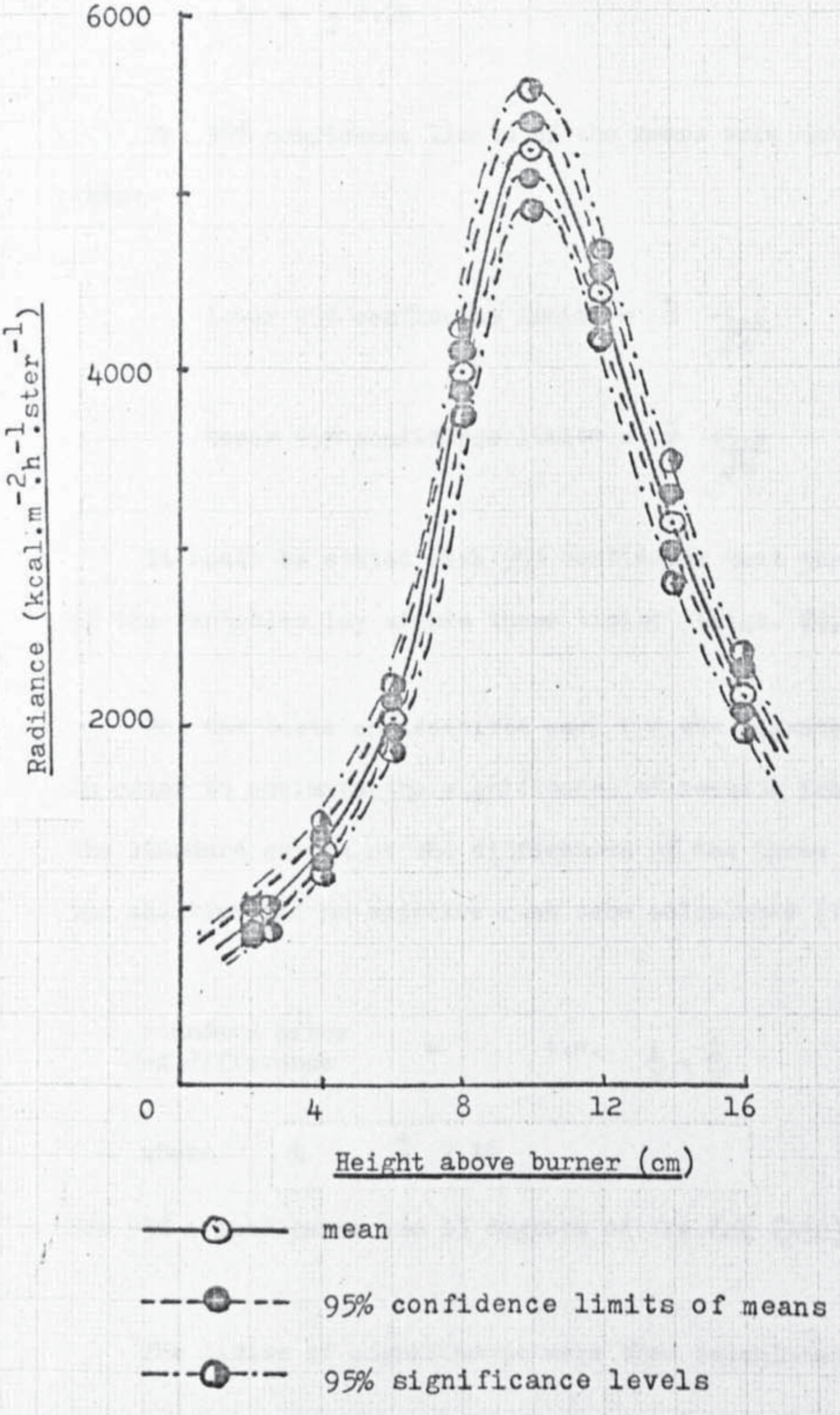


Figure 30.

Significance levels and confidence limits of means of radiances.



$$\text{standard error of mean} = \frac{t.s}{\sqrt{N}}$$

where from the literature (132) for a probability of 0.05 and 11 degrees of freedom

$$t = \pm 2.20$$

The 95% confidence limits of the means were obtained from:

$$\text{lower 95\% confidence limits} = \bar{x} - \frac{t.s}{\sqrt{N}}$$

$$\text{upper 95\% confidence limits} = \bar{x} + \frac{t.s}{\sqrt{N}}$$

It could be stated with 95% confidence that the true values of the variables lay within these limits (figs. 28, 29, 30).

For the tests on additives each run was repeated twice. In order to estimate the significance of results from these runs, the standard errors of the differences of the three variables for the additive and no-additive runs were calculated (Table 9) from:

$$\begin{array}{l}\text{standard error}\\ \text{of difference}\end{array} = t.s. \ \frac{1}{N} + \frac{1}{N'}$$

where $t = \pm 2.16$

for 95% significance and 13 degress of freedom (132).

The limits of significance were then calculated from:

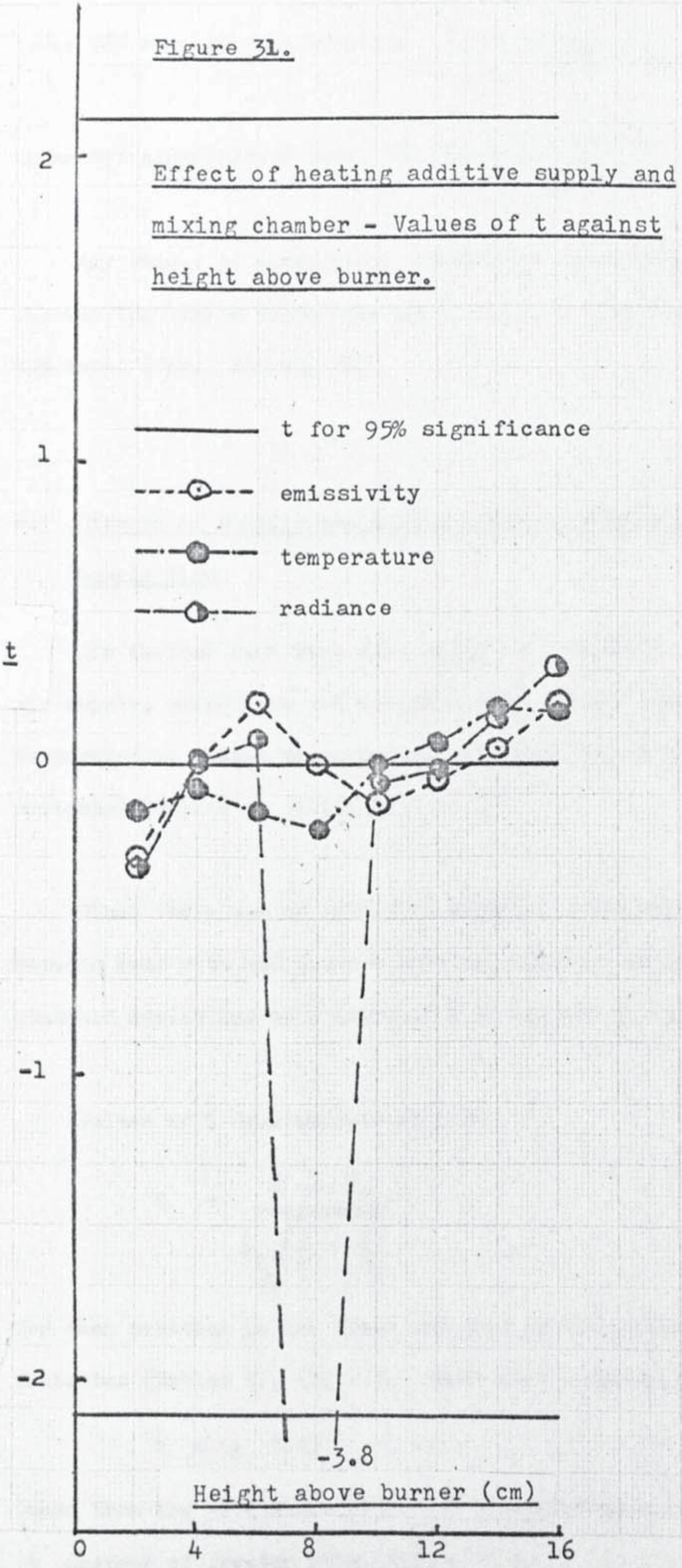


Figure 31.

Effect of heating additive supply and mixing chamber - Values of t against height above burner.

$$\text{lower 95\% significance level} = \bar{x} - t.s.\sqrt{\frac{1}{N} + \frac{1}{N'}}$$

$$\text{upper 95\% significance level} = \bar{x} + t.s.\sqrt{\frac{1}{N} + \frac{1}{N'}}$$

Any values of emissivity, temperature orradiance lying outside the limits calculated above would be significant at the 95% level (figs. 28, 29, 30).

8.3 Effects of heating the mixing chamber and additive supply line

Six further runs were made using the heating to the additive air supply, varporiser and mixing chamber (Table 10). Emissivities, temperatures, radiances, means and standard deviations were evaluated (Tables 11, 12, 13).

Since there was no reason to expect a difference in variance between runs with and without heating, combined estimates of the standard deviations were calculated to achieve greater accuracy.

Values of t were calculated from

$$t = \frac{\bar{x} - \bar{x}_H}{s_{H'}\sqrt{\frac{1}{N} + \frac{1}{N_H}}}$$

for each position in the flame and each of the three dependant variables (Tables 11, 12, 13). These were compared with

$$t = \pm\ 2.12$$

taken from the literature (132) for a significance of 95% and 16 degrees of freedom (fig. 31).

To be significant at the 95% level the experimentally determined value of t would have to be less than -2.12 or greater than +2.12. Since none of the values of t calculated for emissivity and temperature satisfied this condition there was no statistical evidence to suggest that these flame properties were influenced by the heating. In one case, at 8 cm above the burner, the value of t for radiance lay outside the limits of t and the heating was, therefore, statistically significant. Since, however, this was only one of eight and as the variation among the other values appeared to be random, e.g. the values were not consistently positive or negative and did not change regularly along the length of the flame, this was probably a freak result and could be discounted. The heating did not, therefore, have a significant effect on the radiance from the flame.

8.4 Efficiency of the mixing chamber

In order to assess the efficiency of the mixing chamber in supplying similar combustion mixtures to each of the two burners a preliminary experiment was carried out measuring single flame outputs only. The normal flames were set up together with the addition of 20% acetone. Pyrometer readings were taken for each flame at the near flame distance of 14.1 cm with radiation from the other flame being screened from the pyrometer. The experiment was repeated twelve times (Table 14). The means, standard deviations and differences of means for the two burners were evaluated (Table 15).

Values of t were calculated from

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s_M\sqrt{\frac{1}{N_1} + \frac{1}{N_2}}}$$

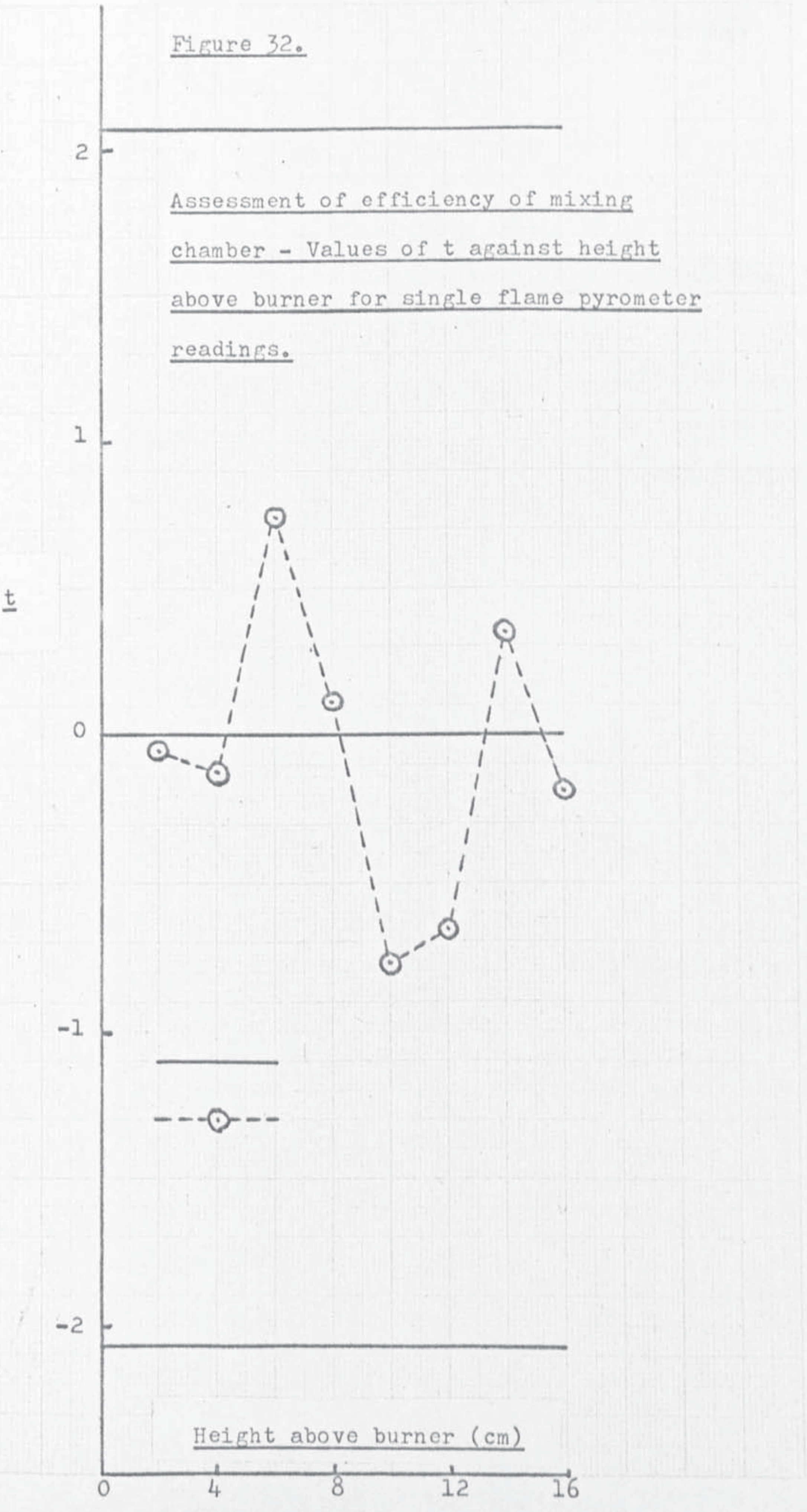


Figure 32.

Assessment of efficiency of mixing chamber - Values of t against height above burner for single flame pyrometer readings.

for each position in the flame (Table 15). These were compared with

$$t = \pm 2.07$$

for a significance of 95% and 22 degrees of freedom (fig. 32).

None of the experimental values of t were less than - 2.07 or greater than + 2.07 so there was no statistical evidence to suggest that the mixing chamber was significantly inefficient and that the two flames were not similar.

9. Procedure and calculation of results

9.1 Experimental procedure

At the beginning of each run the ambient temperature was measured and the calorimeter water temperature indicator was adjusted to this value. The zeroes of all the meters were checked, the pyrometer was levelled and burners were adjusted to be vertical.

The water to the calorimeter was turned on and adjusted to the required flow rate. A single flame was lit and the calorimeter was allowed to heat up until a constant outlet temperature was achieved, air was bled from the calorimeter by way of the vent on the top edge.

When the calorimeter had reached equilibrium, usually after about 30 minutes, the pyrometer outputs for single and double flames without additives were checked. If there were any discrepancies with previous values they were corrected by checking the alignment and level of the pyrometer and burners.

The additive under test was then supplied to the single flame, heating being switched on in the case of liquid additives, and several minutes allowed for the rig to settle down.

The lowest additive flow was tested first. The methane and additive flows were maintained constant while the air flow was adjusted to determine the critical flow for the smoke point, the luminosity just appearing and just disappearing readings being taken consecutively.

The single flame pyrometer output readings were taken next, one reading at flame height increments of 2 cm. These groups of readings were repeated twice and the mean values for the outputs at each height were calculated. The critical air flows for the smoke point were again determined before each group of pyrometer output readings were taken and mean values calculated. After all measurements had been made three times the calorimeter inlet and outlet temperatures were noted.

The additive flow rate was adjusted to the next value and the smoke points and output readings were measured three times. After all the additive rates had been tested on the single flame the second flame was lit and the calorimeter was again allowed to reach equilibrium.

Starting with the lowest additive flow rate the output readings were again taken three times but no smoke point determinations were made with the double flames. Calorimeter inlet and outlet temperatures were again taken after each group of output readings.

Whilst taking pyrometer output readings it was essential to ensure that the flames were stationary and not being distorted by draughts. Provided great care was taken it was possible to obtain consistent results. A small amount of trouble was experienced with the calorimeter due to air bubbles in the water supply. These were bled from the system at the calorimeter itself and the flow rate reset, this tended to drift slightly and required attention about every ten minutes.

The additive metering arrangements proved entirely satisfactory with gases but the rotameter float was prone to pulsation when used with liquids. Adjustment of the additive supply pressure reduced this to a minimum and as it also occurred during calibration of the rotameter it was considered tolerable.

After about twentyfive runs had been performed it was found that the coating of lampblack-water glass solution on the inner surface of the calorimeter had begun to blister. This was most severe where the coating had been applied thickly. It was necessary to scrape off the charred remains and apply a new coating.

The pressure drop through the carbon dioxide-moisture absorber in the air supply had increased to approximately 30 lbf.in^{-2} after forty runs when it was found that the carbosorb particles had become welded into a solid mass. Both beds were replaced, this difficulty was not encountered with the absorber in the methane supply however.

9.2 Calculation of results

9.2.1 Smoke point

The stoichiometric air flow was calculated from consideration of the following equation for the complete combination of methane, no account was taken of air required by the additive.

$$\underset{1\text{ vol.}}{CH_4} + \underbrace{2O_2 + 7.52N_2}_{9.52\text{ vol.}} \longrightarrow CO_2 + 2H_2O + 7.52N_2$$

i.e. for a methane flow of 0.0264 l.s^{-1}

stoichiometric air flow = 0.2515 l.s^{-1}

The actual air flow used was calculated from the air rotameter reading using the equation which had been fitted to the rotameter calibration curve, Appendix 3.

$$\text{Air flow} = 0.01271 + 0.01175\,(\text{rotam.rdg.}) + 0.0000954\,(\text{rotam.rdg.})^2\ \text{l.s}^{-1}$$

$$\text{Fraction of Stoichiometric Air} = \frac{\text{Actual air flow at smoke point}}{0.2515}$$

9.2.2 Calorimeter

The heat transferred to the calorimeter was calculated quite simply from the water flow rate and the temperature difference between the calorimeter inlet and outlet temperatures.

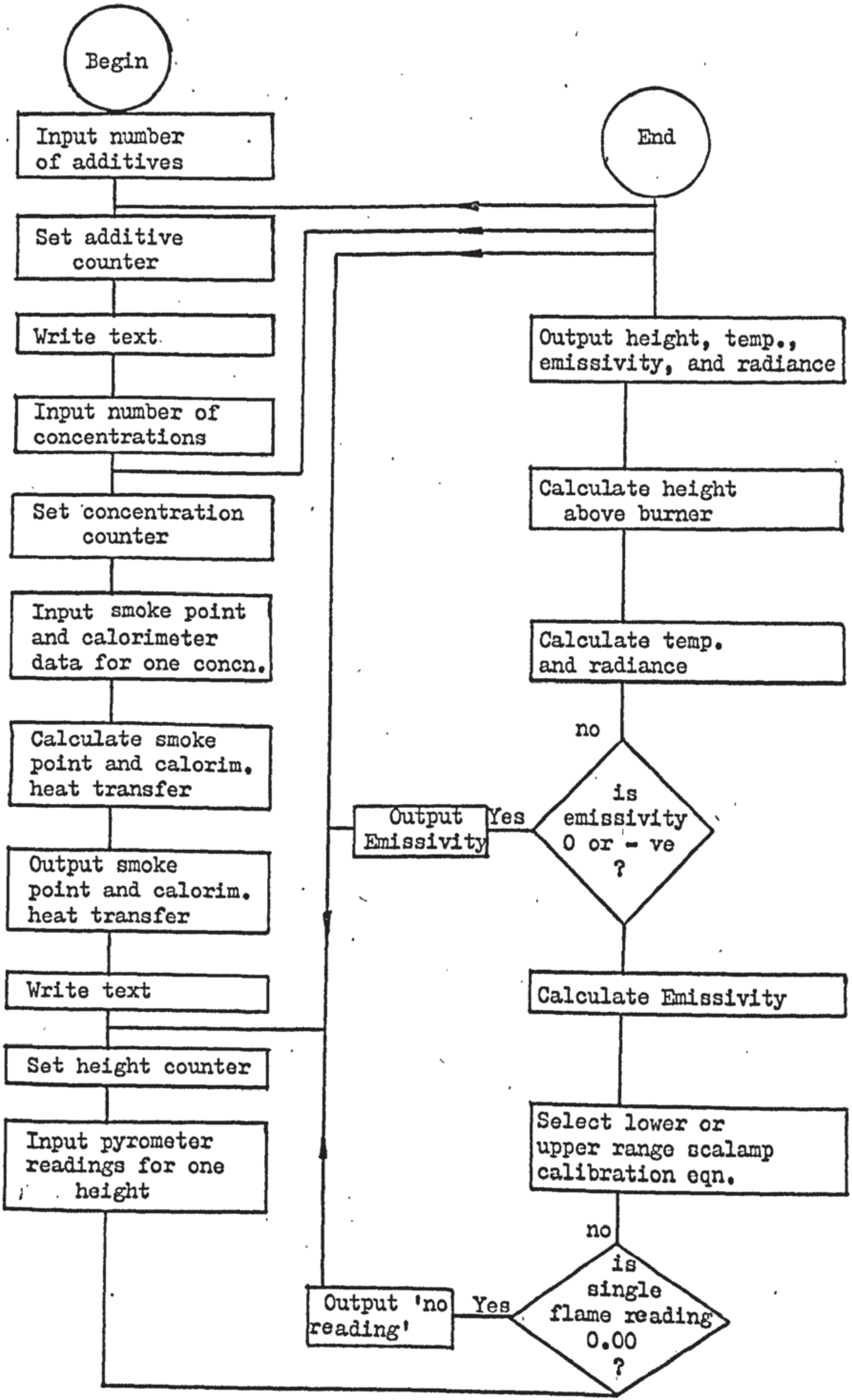
A fixed water flow rate at rotameter reading 18, corresponding to 1.916 ml.s^{-1}, was used.

$$\text{heat transferred to calorimeter} = 1.916\,(\text{outlet temp.}-\text{inlet temp})\ \text{cal.s}^{-1}$$

9.2.3 Emissivity, temperature and radiance

Mean values of the three readings of pyrometer output for each pyrometer position were evaluated during the run and entered on the log sheet. The first stage of the calculation of the emissivity, temperature and radiance was the evaluation of the two brightness temperatures using the equations of the galvanometer calibration curves, Appendix 3.

Figure 33. Flowsheet of computer program for calculating final results



lower range:

$$\text{brightness temp.} = 180.31 + 41.486\ (\text{galvo.rdg.}) - 1.3024\ (\text{galvo.rdg.})^2\ {}^{\circ}\text{C}$$

upper range:

$$\text{brightness temp.} = 384.12 + 111.37\ (\text{galvo.rdg.}) - 3.8219\ (\text{galvo.rdg.})^2\ {}^{\circ}\text{C}$$

The emissivity, temperature and radiance were then calculated from equations 8.1, 8.2 and 5.14,

$$\epsilon = 2.067 - 1.067\left(\frac{T_2}{T_1}\right)^{4.5773} \tag{8.1}$$

$$T = \left(\frac{0.8621}{\epsilon}\right)^{0.2185} . T_1 \quad {}^{\circ}\text{K} \tag{8.2}$$

$$W = 1.552.10^{-8}.\epsilon.\ T^4\ \text{kcal.m}^{-2}.\text{h}^{-1}.\text{ster}^{-1} \tag{5.14}$$

9.2.4. Computer Programme

In view of the large number of results to be handled the following computer program was written to perform the above calculations. It is summarised by the flowsheet shown in fig.33.

```
'BEGIN' 'COMMENT' THE INFLUENCE OF ADDITIVES ON THE
                  RADIATIVE PROPERTIES OF A PREMIXED
                  METHANE AIR FLAME:
        'REAL'    ROTAM, SINLETT, SOUTLETT, DINLETT, DOUTLETT,
                  AIRFLO, FRASTO, SHEATTR, DHEATTR, RDG 1,
                  RDG 2, CT1, T1, CT2, T2, EMISSIVITY, CT,
                  RADIANCE;
```

```
'INTEGER' NOADDS, NOCONCNS, HEIGHT, M, N, J;
'REAL' 'ARRAY'  CONCN  1:5  ;
CONCN  1 : = 2.5;
CONCN  2 : = 5.0;
CONCN  3 : = 10.0;
CONCN  4 : = 15.0;
CONCN  5 : = 20.0;
NOADDS : =  READ:
'FOR' M := 1 'STEP' 1 'UNTIL' NOADDS 'DO'
'BEGIN'   WRITE TEXT ('("('3C')'RUN'('S')'NO'('S')")');
          COPYTEXT ('('ZZ')');
          WRITE TEXT ('(''('20S')'ADDITIVE'('25')'')');
          COPYTEXT ('(' ZZ')');
          NOCONCNS := READ;
          'FOR' N := 1 'STEP' 1 'UNTIL' NOCONCNS 'DO'
'BEGIN'   ROTAM := READ;
          SINLETT := READ;
          SOUTLETT := READ;
          DINLETT := READ;
          DOUTLETT := READ;
          AIRFLO := 0.01271 + 0.01175*ROTAM + 0.0000954*
                        ROTAM '**'2;
          FRASTO := AIRFLO/0.2515;
          SHEATTR := 1.916* (SOUTLETT-SINLETT);
          DHEATTR := 1.916* (DOUTLETT-DINLETT);
          NEWLINE (4);
          SPACE (9);
          PRINT(CONCN  N  ,2,1);
          WRITE TEXT ('('%'('S')'CONCENTRATION'('3C,16S
          ')'SMOKE'('S')'POINT'('(2C,22S')'MEAN'('S')'AIR'('S')'
          ROTAMETER '('S')'READING'('16S')'')');
          PRINT(ROTAM,2,1);
          WRITE TEXT ('(''('C,22S')'FRACTION'('S')'OF'('S')'
          STOICHIOMETRIC '('S')'AIR'('S')'FLOW'('8S')'')');
          PRINT (FRASTO, 1,3);
          WRITE TEXT ('(''('2C,16S')'CALORIMETER'('2C,40S')'
          INLET '('S')'TEMP'('55')'OUTLET'('S')'TEMP'('6S')'HEAT
          '('S')'TRANSFER'('C,42S')'(DEG.C)'('7S')'(DEG.C)'
          ('10S')'(CAL/S)'('C,22S')'SINGLE'('S')'FLAME'('9S')
          '')');
          PRINT (SINLETT,2,1);
          SPACE (7);
          PRINT(SOUTLETT,2,1);
          SPACE (9);
          PRINT (SHEATTR,2,1);
          WRITE TEXT ('(''('C,22S')'DOUBLE'('S')'
          FLAME'('9S')'')');
          PRINT (DINLETT,2,1);
          SPACE (7);
          PRINT (DOUTLETT,2,1);
          SPACE (9);
          PRINT (DHEATTR, 2,1);
          WRITE TEXT ('('3C,16S')'EMISSIVITY'('S')'
          TEMPERATURE'('S')'RADIANCE'('2C,22S')'
          HEIGHT'('S')'ABOVE'('3S')'PYROMETER'('S')'
          READINGS'('3S')'BRIGHTNESS'('S')'TEMP'('
          3S')'EMISSIVITY'('3S')'TEMPERATURE'('5S')'
```

```
                  RADIANCE'('C,22S')'BURNER'('S')'(CM)'('4S')'
                  SINGLE'('6S')'DOUBLE'('3S')'SINGLE'('3S')'
                  DOUBLE'('18S')'(DEG.C)'('5S')'(KCAL/SQ.M.STER)
                  '('C')'')');
                  HEIGHT := 0;
                  'FOR' J := 1 'STEP' 1 'UNTIL' 8 'DO'
        'BEGIN'   RDG1 := READ;
                  RDG2 := READ:
                  'IF' RDG1 'EQ' 0.00 'THEN' 'GOTO' NORDG;
                  'IF' RDG2 'GE' 20.00 'THEN' 'GOTO' RANGE 2;
        RANGE 1:  CT1 := 180.31+41.486*RDG1 - 1.3024*RDG1'**'2;
                  'GOTO' CONT 1;
        RANGE 2:  RDG1 := RDG1 - 20.00;
                  CT1 := 384.12 + 111.37*RDG1 - 3.8219*RDG1'**'2;
        CONT1:    T1 := CT1 + 273.16;
                  'IF' RDG2 'GE' 20.00 'THEN' 'GOTO' RANGE 4;
        RANGE 3:  CT2 := 180.31+41.486*RDG2-1.3024*RDG2'**'2;
                  'GOTO' CONT 2;
        RANGE 4:  RDG2 := RDG2-20.00;
                  CT2 := 384.12+111.37*RDG1-3.8219*RDG2'**'2;
        CONT2:    T2 = CT2 + 273.16;
                  EMISSIVITY := 2.067-1.067*(T2/T1)'**'4.5773;
                  'IF'EMISSIVITY'LE'0.000'THEN''GOTO'FAILURE;
                  CT := T1*(0.8621/EMISSIVITY)'**'0.2185-273.16;
                  RADIANCE := 1.552*10'**'(-8)*EMISSIVITY*
                                     (CT+273.16)'**'4;
                  HEIGHT := HEIGHT + 1;
                  SPACE (26);
                  PRINT (HEIGHT,2,0);
                  SPACE (6);
                  PRINT (RDG1,2,2);
                  SPACE (4);
                  PRINT (RDG2,2,2);
                  SPACE (1);
                  PRINT (CT1,3,1);
                  SPACE (2);
                  PRINT (EMISSIVITY,1,3);
                  SPACE (6);
                  PRINT (CT,4,0);
                  SPACE (7);
                  PRINT (RADIANCE,5,1);
                  'GOTO' AGAIN;
        NORDG:    WRITE TEXT ('(''('10S')' NO'('S')'READING ')');
                  'GOTO' AGAIN;
        FAILURE:  WRITE TEXT ('(''('10S')'NEGATIVE'('S')'
                           EMISSIVITY'('4S')'')');
                  PRINT (EMISSIVITY,1,3);
        AGAIN:    NEWLINE (1);
        'END';
        'END';
        'END';
'END';
```

The programe was run on an ICL 1905 computer.

10. Discussion of results

The full results from the research are listed in Appendices 6 and 7. To facilitate comparisons between the effects of the different additives they have been classified into eight groups. These are paraffins; aromatics; acetylene, ethylene and cyclohexane; halogenated compounds; organic compounds containing oxygen; flame reactants and products of combustion; miscellaneous additives, and, finally, sulphur trioxide.

10.1 Calorimeter

The results obtained for heat transferred to the calorimeter were largely insignificant (Appendix 5).

Those additives which could be considered as fuels usually gave increased heat transfer rates as the additive flow was increased but the effects observed within groups of similar additives were random. It has not been possible to correlate the heat transfer rates with either emissivity, flame temperature or radiance. The influence of these factors on the heat transfer was so slight that changing conditions within the laboratory such as room temperature and the presence of draughts rendered them insignificant. It was not considered worthwhile expending further effort on improving the rig as the data of this type available on such a small scale would be of rather limited value. It was decided to concentrate on measuring the other properties of the flame.

Significant overall heat transfer could only be effectively measured in a model furnace using water-cooled loads on a scale many times larger e.g. as in the experimental furnaces at Ijmuiden. This would be facilitated by the bulk supplies of natural gas now more readily available.

Figure 34.

Smoke points with paraffins as additives.

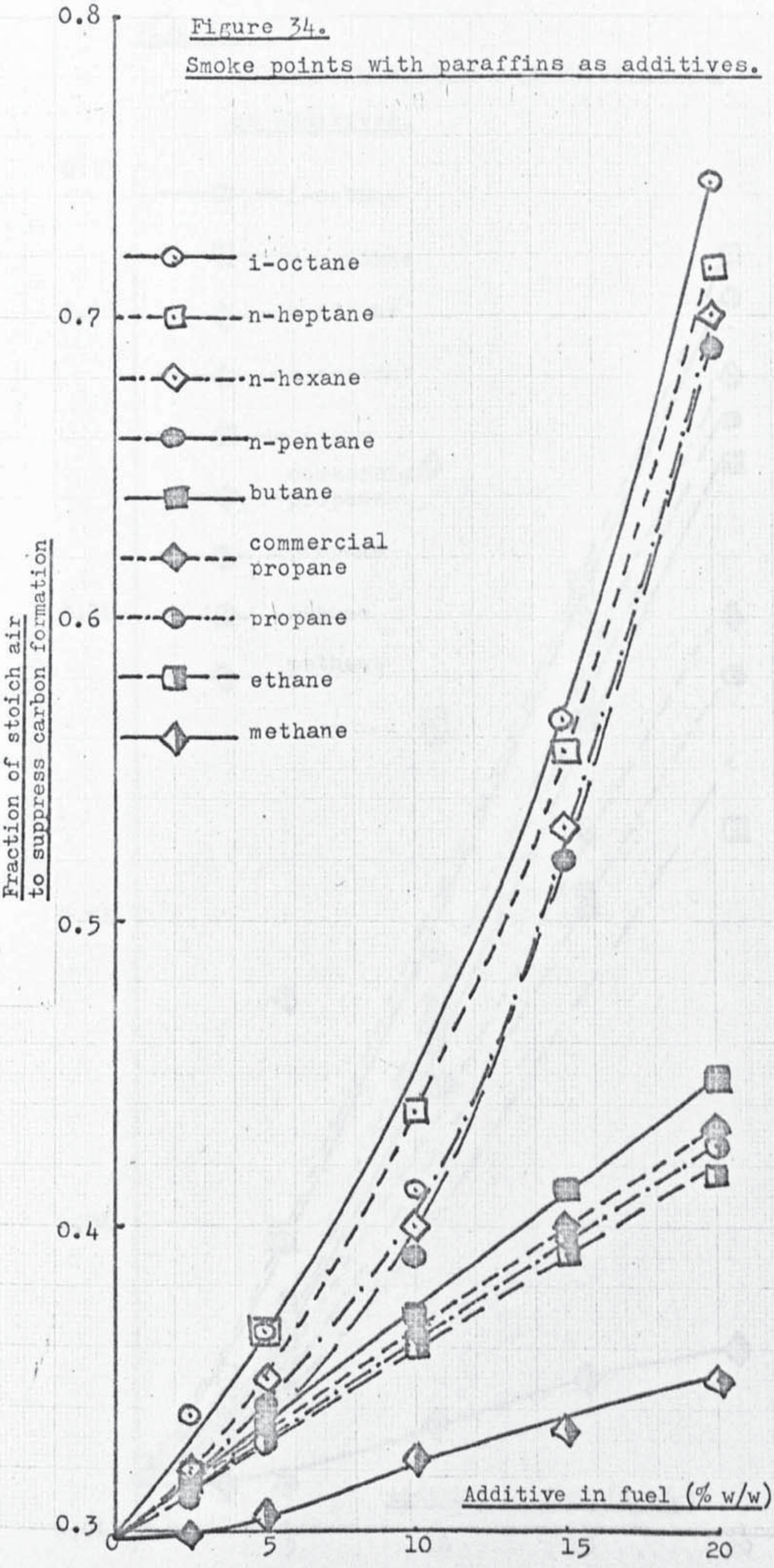


Figure 35.

Maximum emissivities with paraffins as additives.

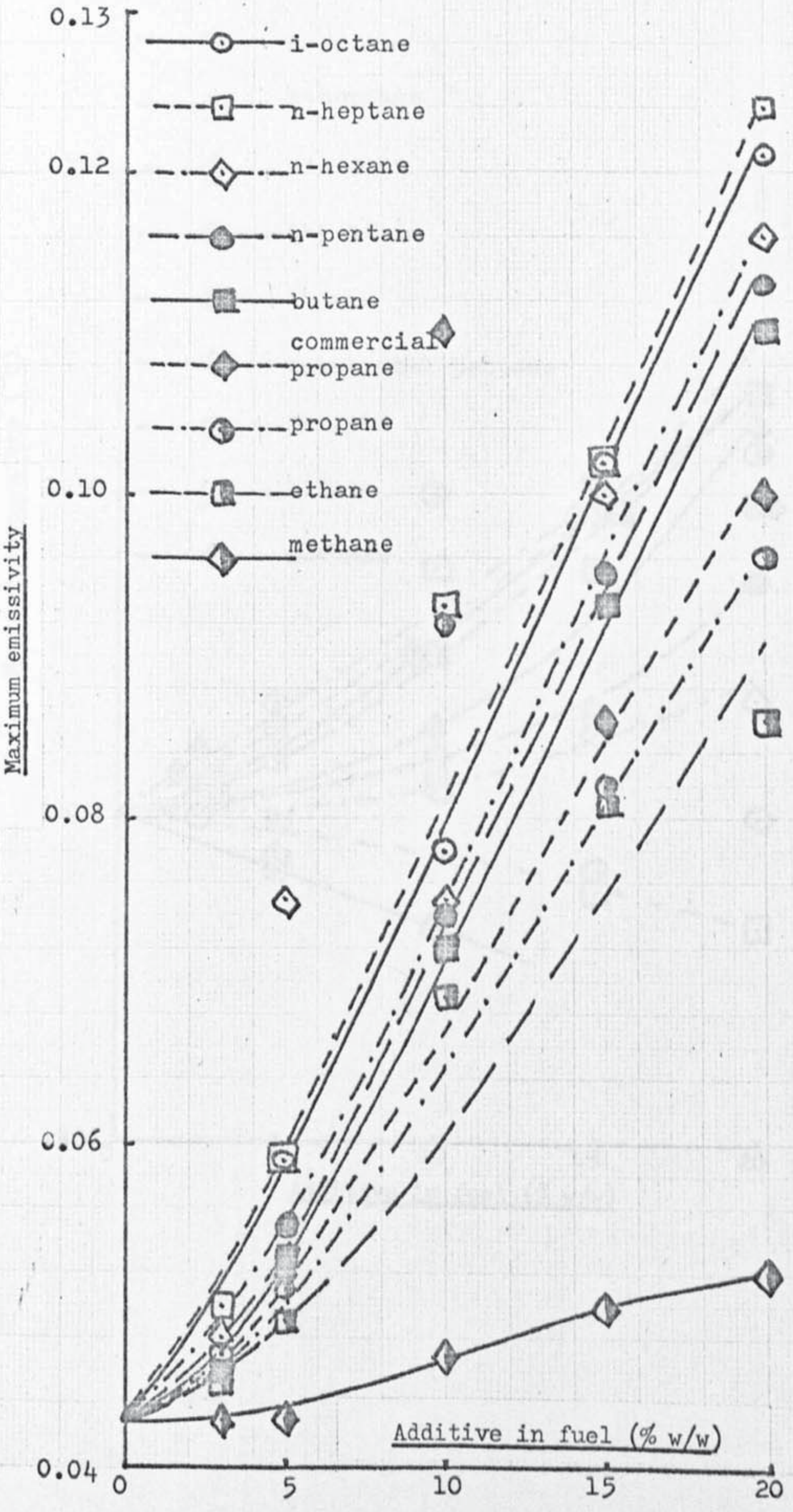


Figure 36.

Maximum temperatures with paraffins as additives.

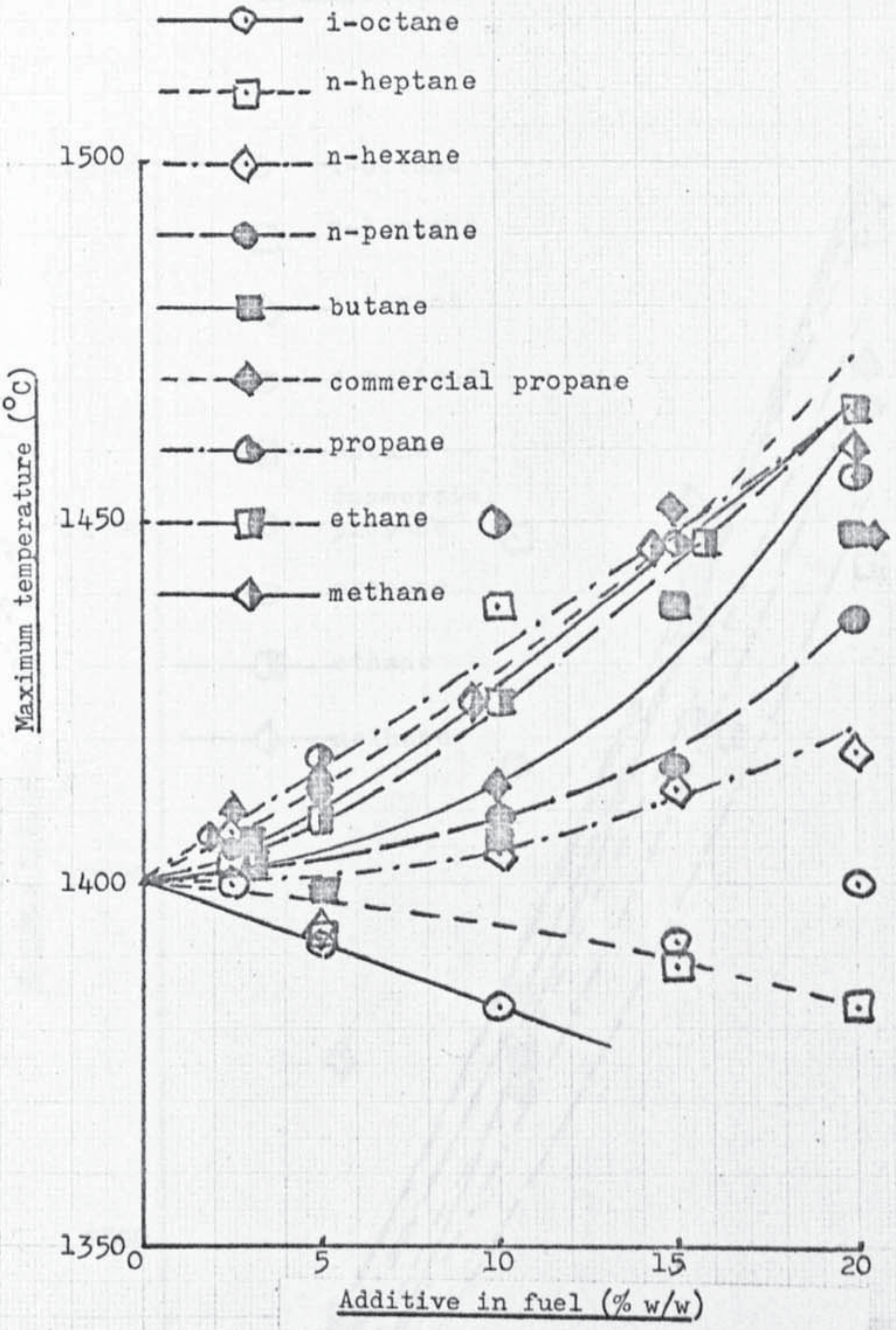


Figure 37.

Maximum radiances with paraffins as additives.

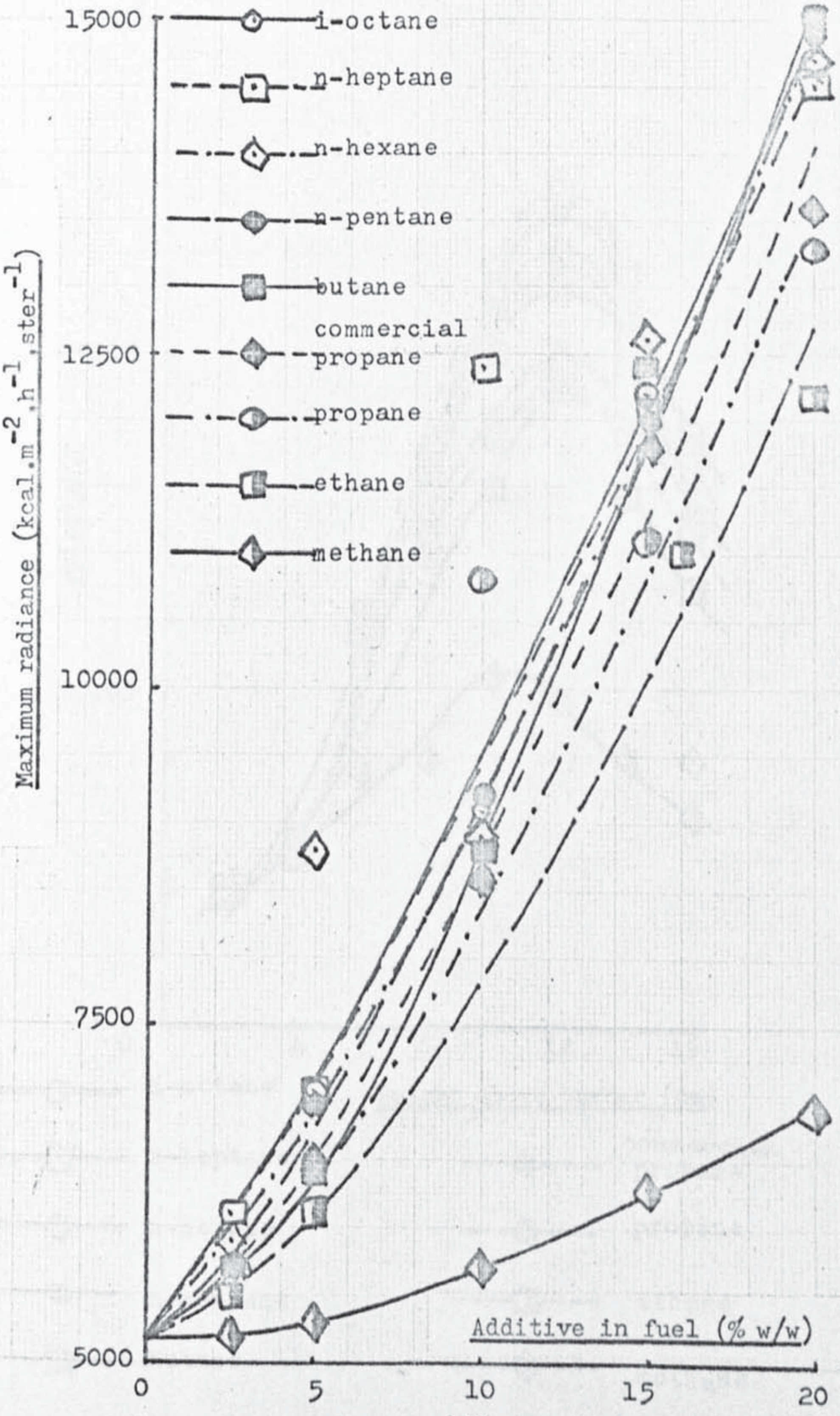


Figure 38.

Variation of emissivity with height above burner for 20% w/w paraffin additives.

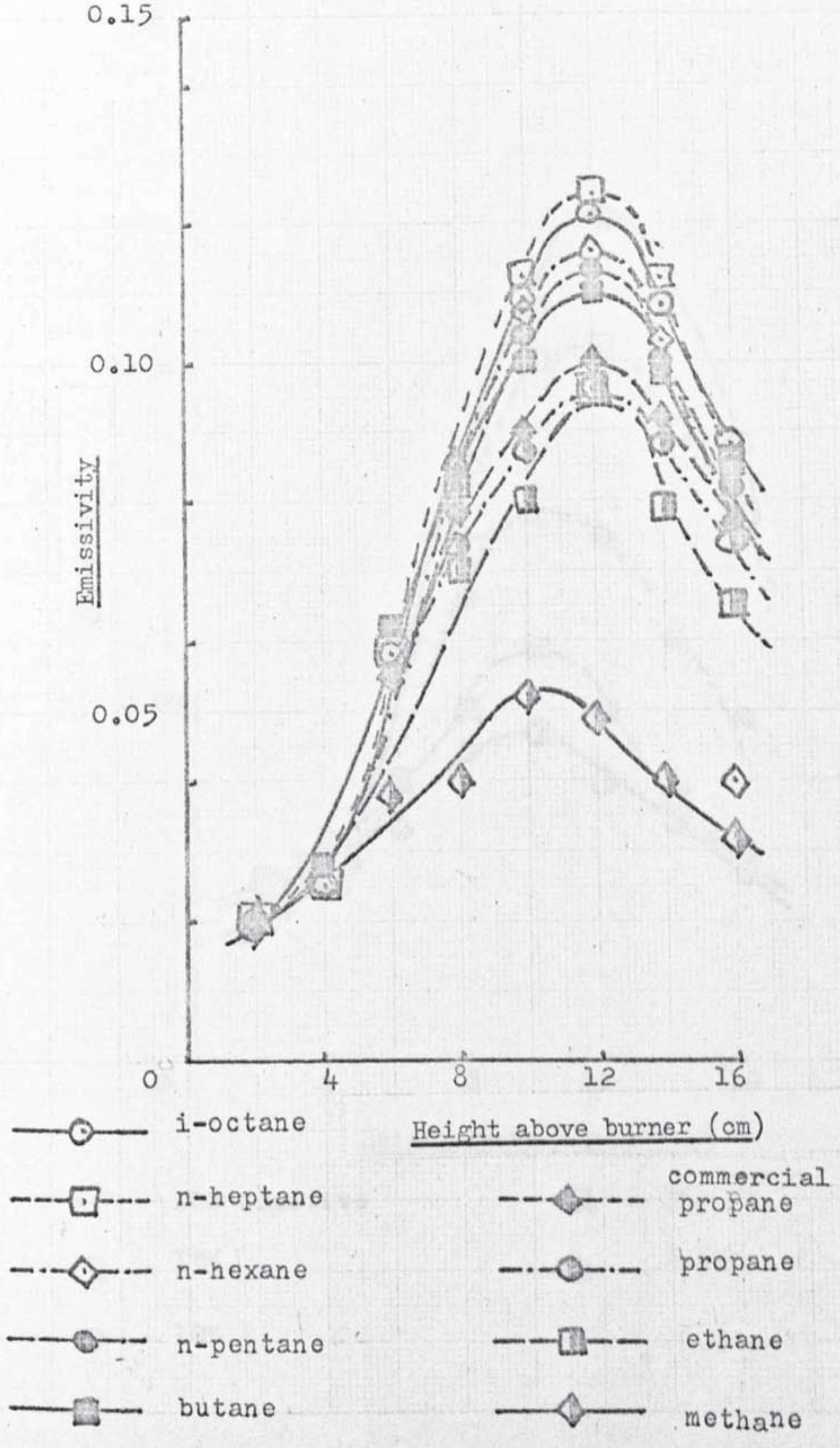


Figure 39.

Variation of emissivity with height above burner for i-octane as additive.

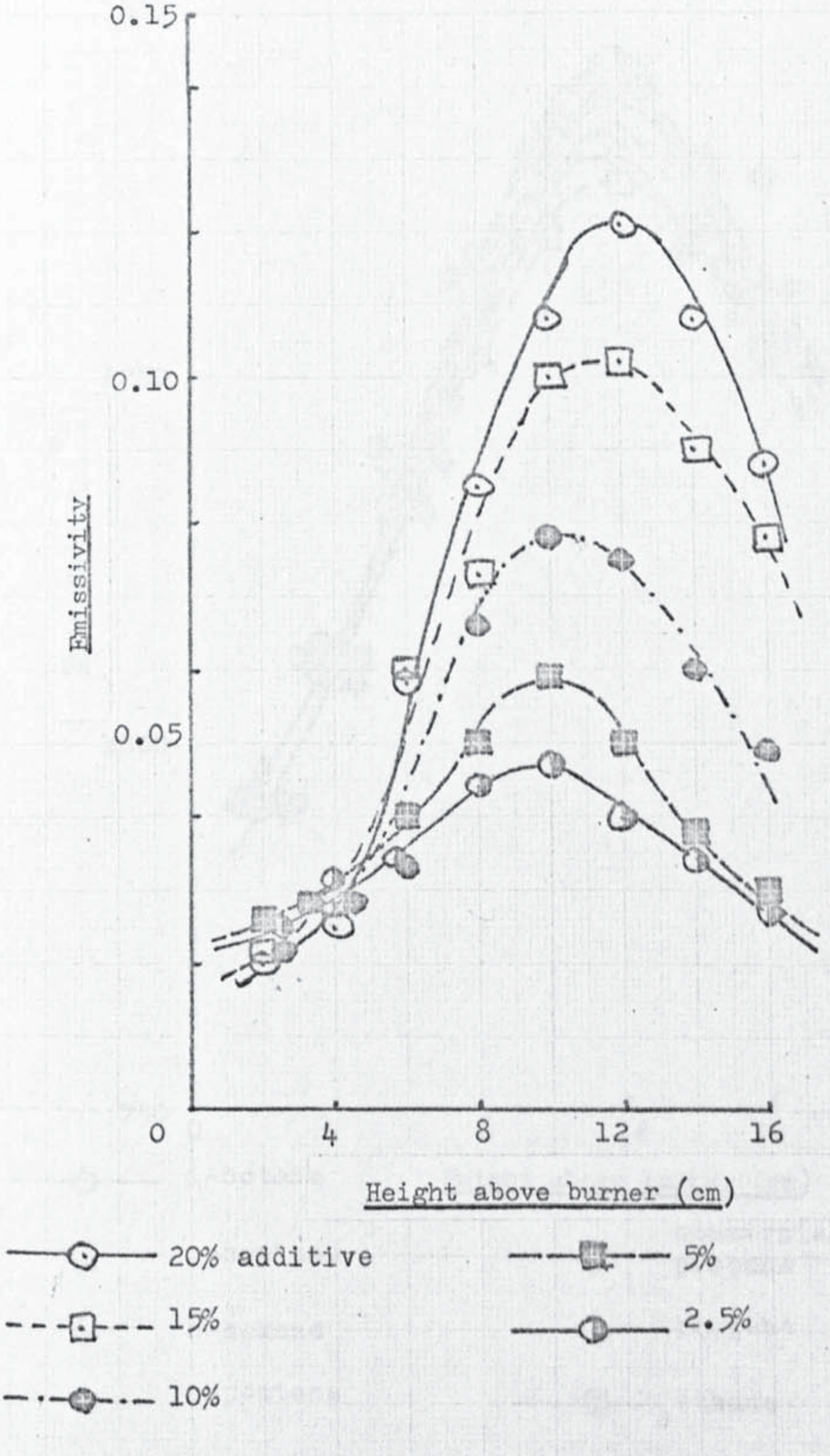


Figure 40.

Variation of temperature with height above burner for 20% w/w paraffin additives.

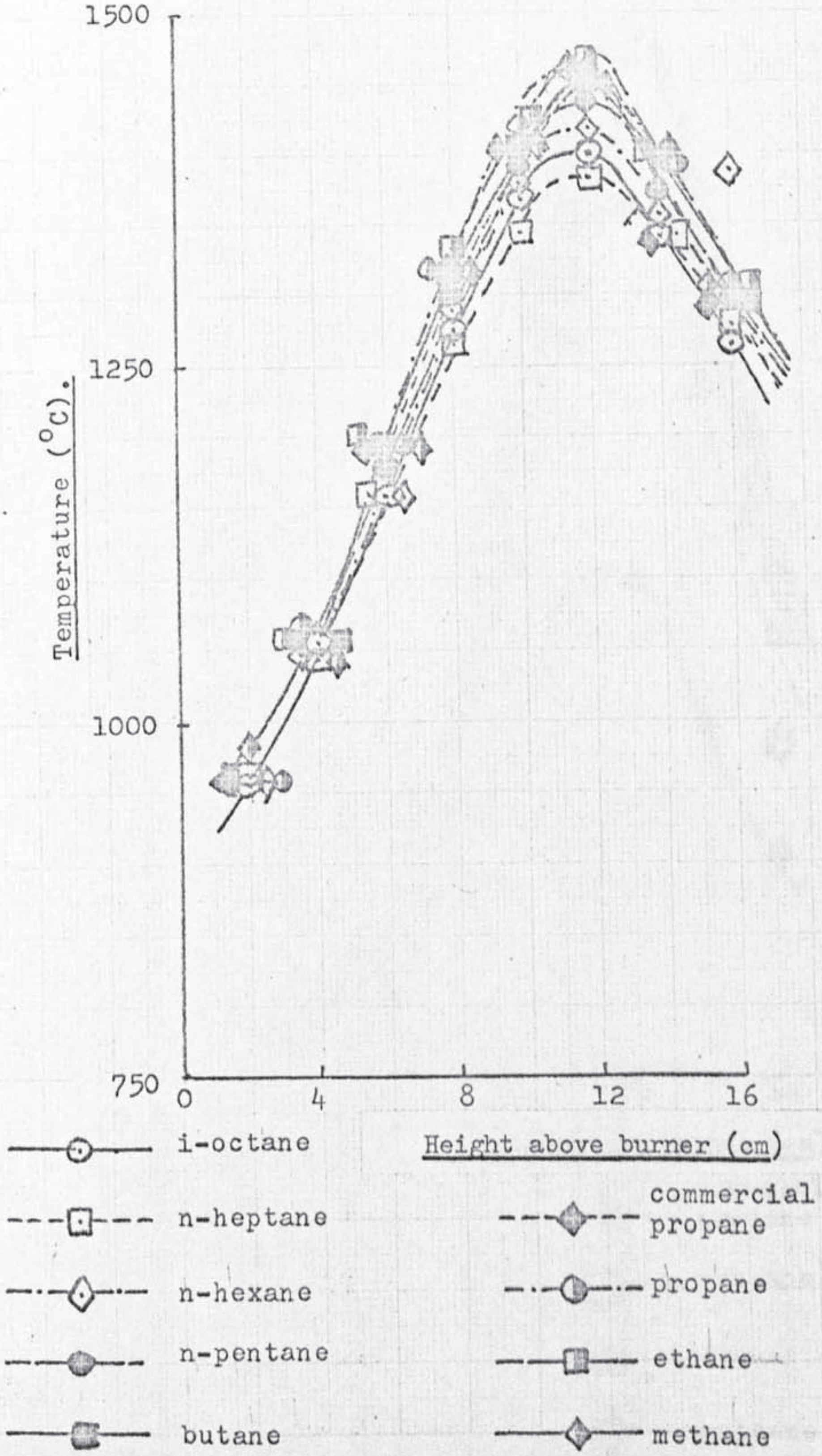
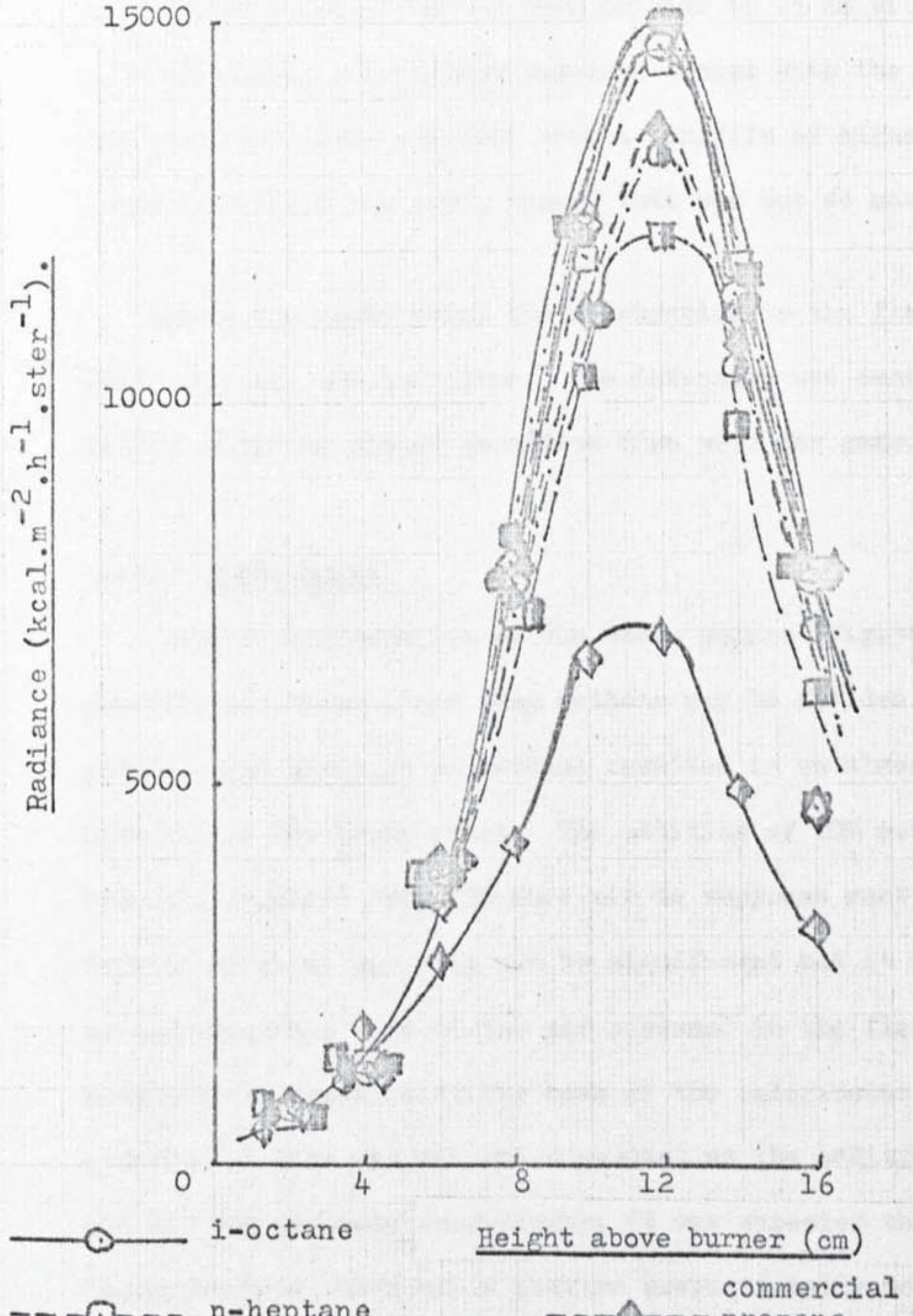


Figure 41.

Variation of radiance with height above burner for 20% w/w paraffin additives.



10.2 Paraffins as additives

All the flames with paraffins added had the same basic appearance. The main body of the flame was deep blue with a pale blue inner cone of height approximately 6 cm. The maximum width was approximately 2.5 cm and the visible height ranged from about 10 cm for pure methane to 15 cm with 20% i-octane added. The flames appeared longer with the higher additive flow rates and also when a paraffin of higher molecular weight was used, though this was not so marked.

Above the smoke point the colouration in the flame was yellow for all the paraffins. The intensity was considerably greater with the liquid paraffins than with the gaseous paraffins.

10.2.1 Smoke Point

From a consideration of the smoke points (fig.34) the paraffin additives other than methane may be divided into two groups. The addition of methane resulted in an almost linear increase in the smoke point. The addition of 20% methane, however, required only 17% more air to suppress soot formation. This discrepancy may well not be significant but it is surprising since some of the air consumed in the flame was not premixed but drawn in at the base of the calorimeter. As the quantity of this air was not dependant on the additive flow rate and did not increase accordingly, it was expected that the higher methane rates would require proportionally more premixed air. The Reynold's Number increased from 642 to 856 which would have resulted in greater turbulence and better mixing as the gases left the burner leading to more efficient combustion and, therefore, a lower smoke point.

The gaseous paraffins, ethane, propane, butane and the commercial propane, which contained a high proportion of butane, also caused a linear increase in the smoke point. The commercial propane was tested because it represented a quality of liquified petroleum gas readily available to industry. The differences between the four were quite small, although the smoke point was undoubtedly higher for the higher molecular weights. The differences between these paraffins and methane were much more marked, the smoke point of the latter being considerably lower. This is due to the variety of C_1 and C_2 radicals which can result from the dehydrogenation and breakdown of the higher paraffins, whereas the methane can only be dehydrogenated to C_1 radicals. It is thus possible for the former to build up more quickly into polyacetylenes, polyacetylene radicals and eventually into soot.

The liquid paraffin additives showed quite different effects, proportionally more air being required to prevent soot formation as the concentration of the additive was increased. The four liquids behaved similarly, though the higher molecular weights corresponded to the higher smoke points as with the gaseous paraffins. The differences between the smoke points decreased at concentrations above 10%. The shape of the curves and the difference in behaviour between the liquid and the gaseous paraffins suggest there was some condensation of the liquid additive vapour in the burner tubes. Small droplets would have been formed, carried into the flame and thermally cracked to relatively large soot particles. These would have had a lower emissivity than a larger number of smaller particles formed by a synthesis mechanism.

10.2.2. Emissivity, temperature and radiance

Plots of the maximum emissivity, temperature and radiance against concentration for each additive are shown in figs. 35, 36, 37. All the paraffins caused an increase in the maximum emissivity of the flames. There is some scatter among the points on these curves but above a concentration of 5% they can reasonably be approximated to straight lines. In general the higher molecular weights favoured the higher emissivities, the only exception being i-octane. When studying paraffins as the fuels of pre-mixed flames, Street and Thomas showed that the branched chain isomers had lower smoke points than the straight chain isomers (85). In this research the flames with i-octane added had lower emissivities even than those with n-heptane; the smoke points, however, did not show similar behaviour, the smoke point with i-octane being greater than that with n-heptane. It should be noted that the differences were very small in each case.

The increasesin emissivity caused by adding higher paraffins were much greater than those achieved by adding methane itself, presumably for the same reasons as were discussed in the previous section. The differences, however, were even more noticeable than with the smoke points. The soot particles formed by thermal cracking of the liquid in the droplets would have been larger but much fewer in number than those formed by a polymerisation process so that a large increase in emissivity need not necessarily occur. It can be shown that for a cloud of particles with a constant particle mass concentration the emissivity is inversely proportional to the particle diameter (Appendix 1).

The maximum emissivity of the flames could be raised to 0.11 - 0.125 by adding 20% of n-pentane, n-hexane, n-heptane or i-octane, corresponding to flames 1m thick with maximum emissivities in the range 0.9 - 0.99. The proportion of the flames at this high emissivity, however, was relatively small (figs. 38, 39). For all the paraffins except methane the maximum emissivity occurred at the same position above the burner; this height was a function of the additive concentration and ranged from about 9 cm at 2.5% concentration to 12 cm at 20% concentration. The shift was gradual as the concentration was increased. The fall off in emissivity on both sides of the maximum emissivity position was rapid and the high level was not sustained along the length of the flame as would be desirable in an industrial furnace. The position of maximum emissivity with methane added to the flame moved only from 9 cm to just over 10 cm above the burner as the concentration was increased.

The flame temperature was also dependent on the molecular weight of the additive, but inversely on this occasion. The i-octane was again an exception, its flame being hotter than that containing n-heptane. The flames with the higher emissivities lost more heat by radiation to the calorimeter than the others and were consequently slightly cooler.

The variation in temperature between the different flames was low. The maximum temperature occurred in almost the same position for all the additives at all concentrations, approximately 12 cm above the burner (fig. 40). This coincided with the position of maximum emissivity when 20% additive concentrations were used and gave rise to very high radiances under these conditions.

As the plot of radiance against height above the burner at 20% additive concentration shows (fig. 41), increases in emissivity were sufficient to offset the losses in temperature for all the additives. This was the case at all concentrations and it can be seen that all the additives gave a considerable improvement over methane, a high molecular weight additive favoured a high radiance. It is interesting to note that butane and i-pentane both yielded a higher radiance than n-hexane, n-heptane and i-octane. Although the latter had higher emissivities than the former, there was so much cooling of the flames that there was a resultant decrease in radiance. This may not occur in larger flames but it is an important factor when considering the use of additives to enhance the radiating properties of flames.

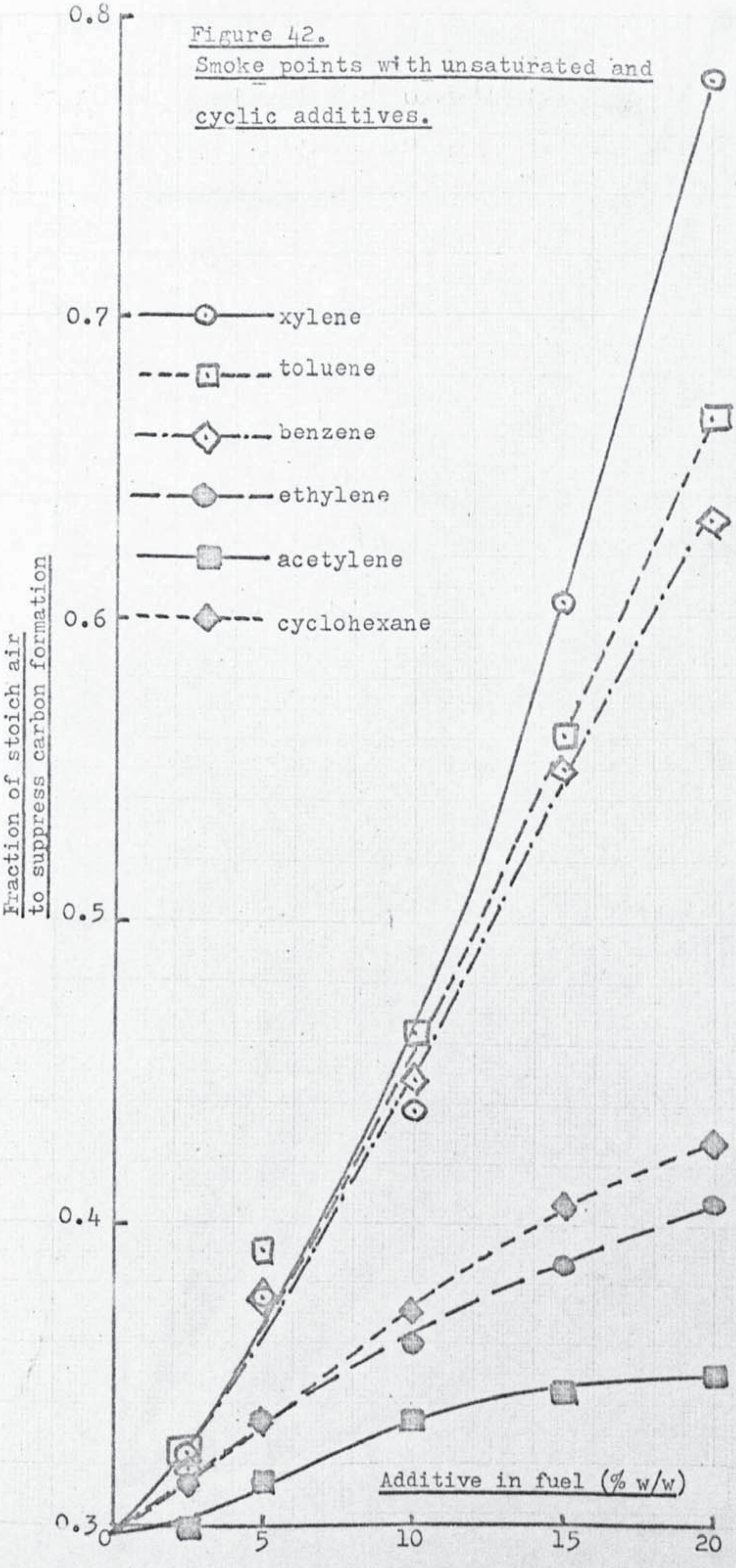


Figure 42.
Smoke points with unsaturated and cyclic additives.

Figure 43.

Maximum emissivities with unsaturated and cyclic additives.

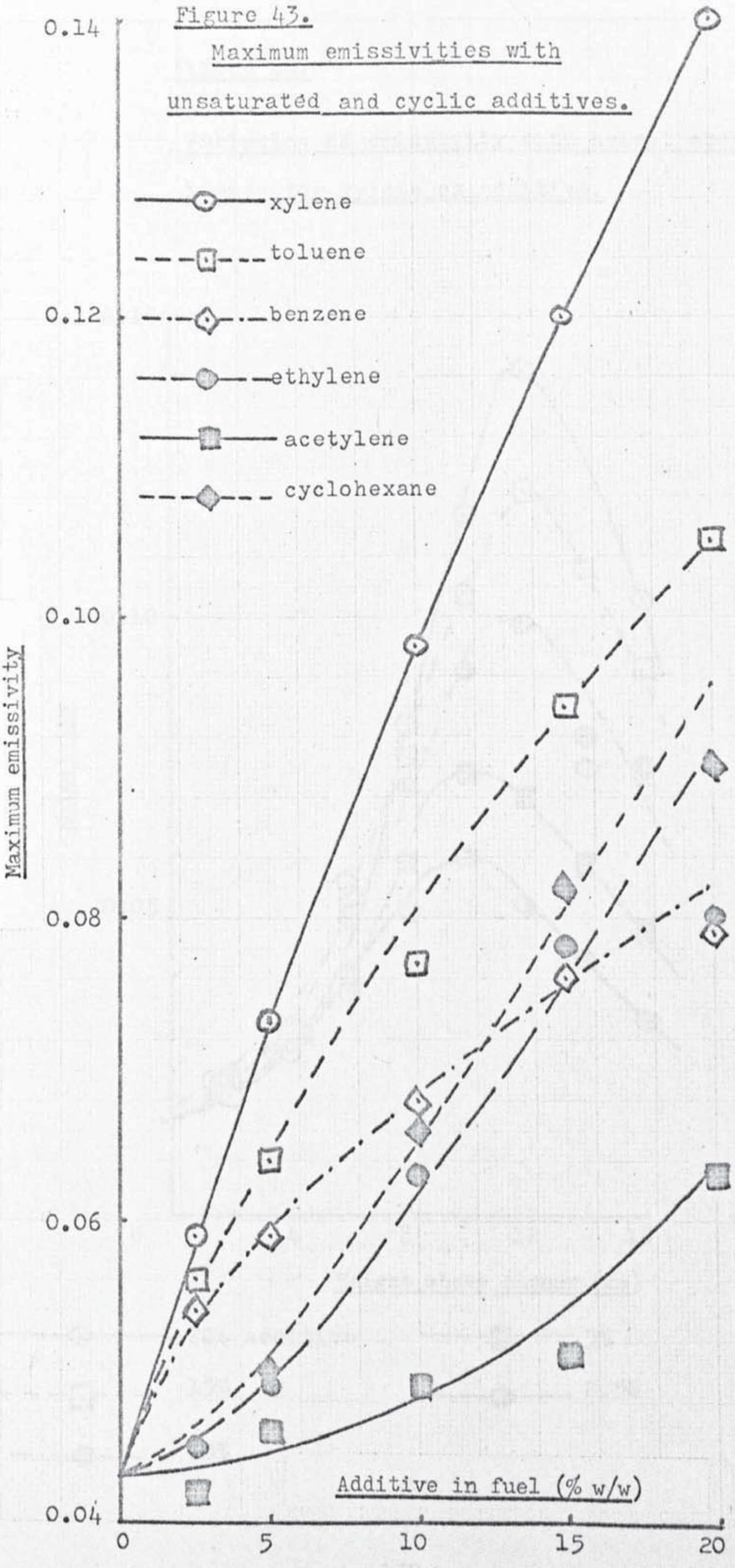


Figure 44.

Variation of emissivity with height above burner for xylene as additive.

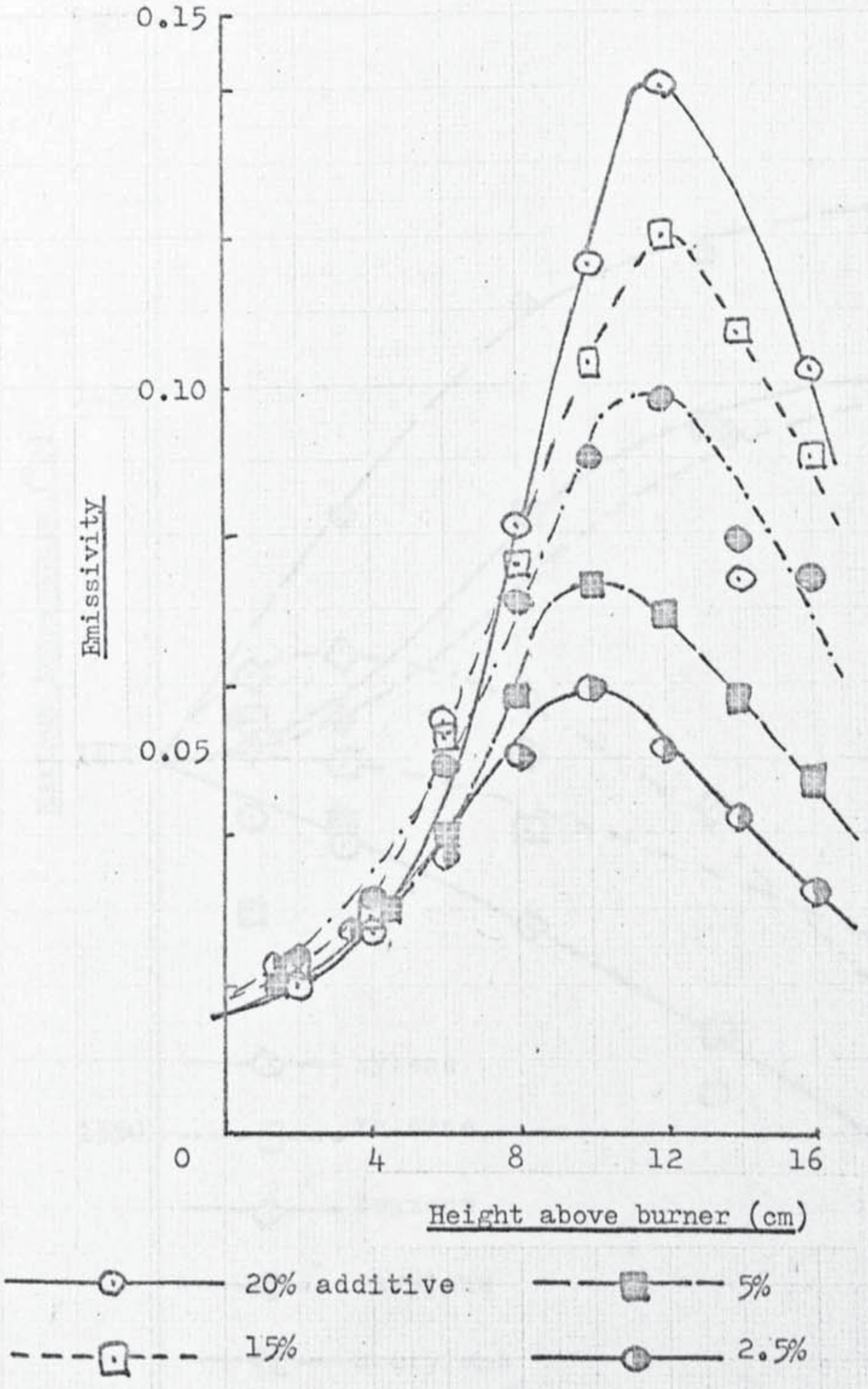
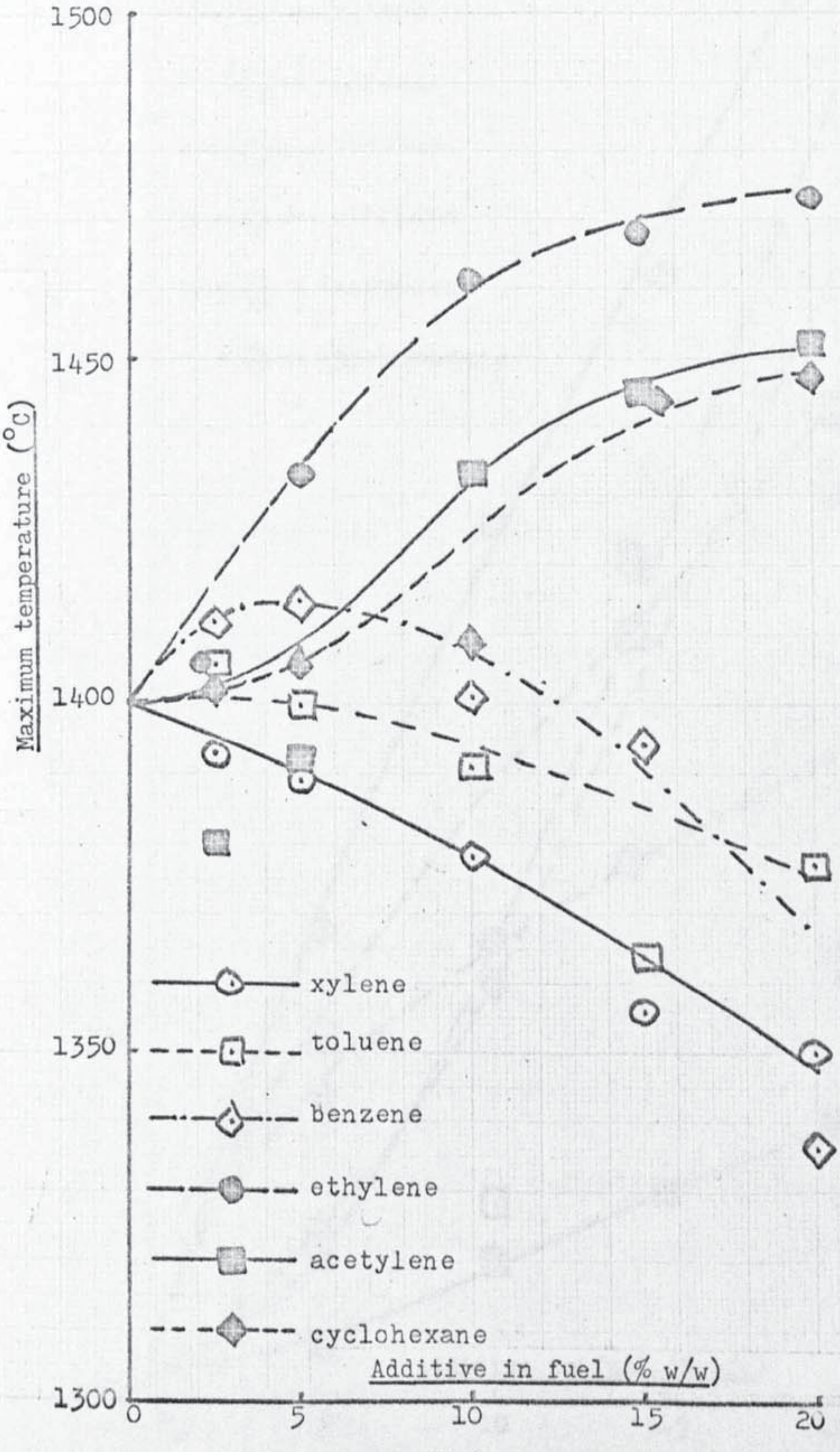


Figure 45.

Maximum temperatures with unsaturated and cyclic additives.



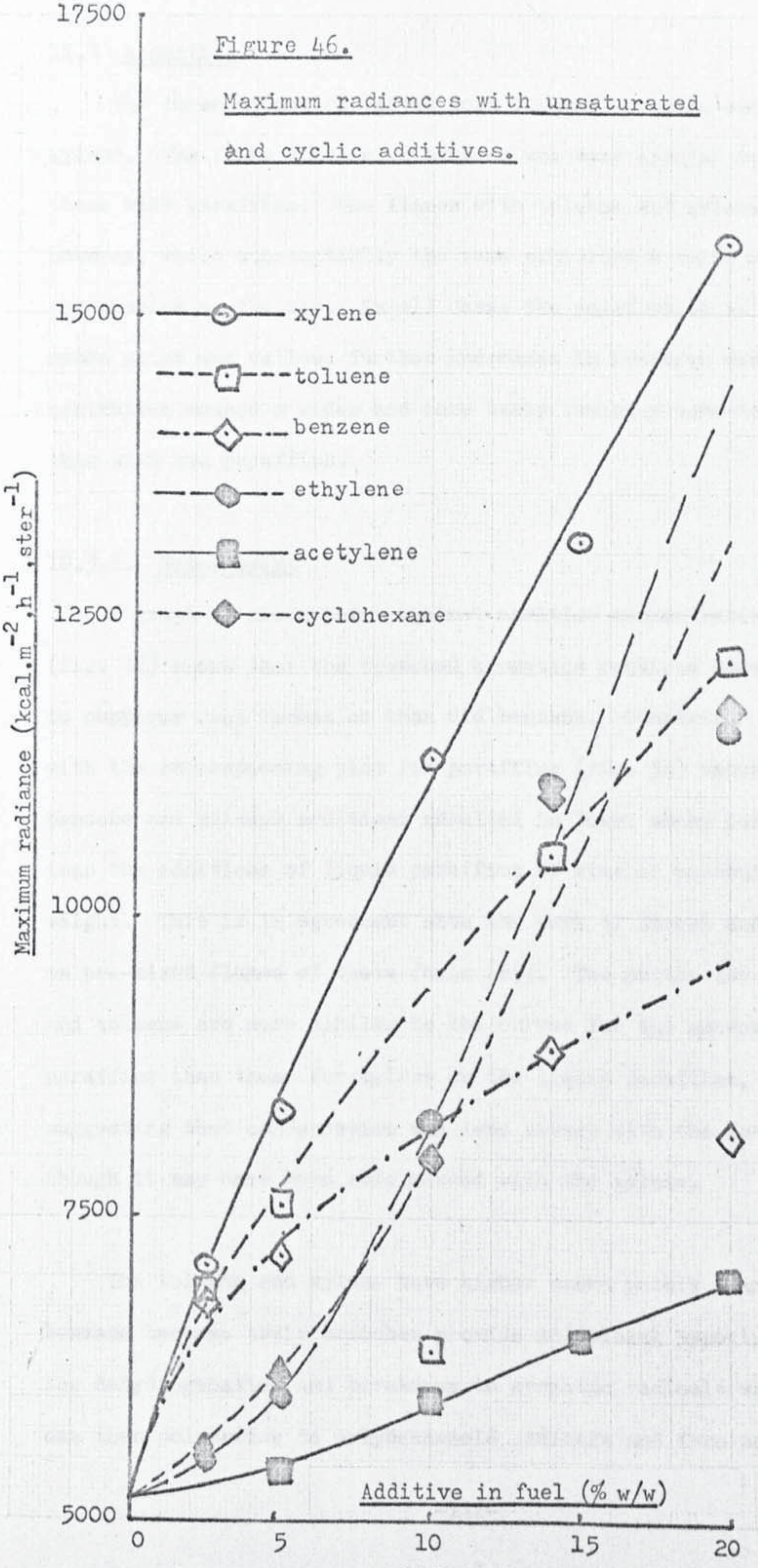


Figure 46.

Maximum radiances with unsaturated and cyclic additives.

10.3 Aromatics

The three aromatics tested were benzene, toluene and xylene. The flame containing benzene was very similar to those with paraffins. The flames with toluene and xylene, however, while substantially the same exhibited a faint white colouration at the tip. In all cases the colouration at the smoke point was yellow, further increases in additive concentration caused a wider and more bushy luminous zone to form than with the paraffins.

10.3.1. Smoke point

A graph of smoke point against additive concentration (fig. 42) shows that the branched aromatics required more air to suppress soot formation than did benzene. Comparison with the corresponding plot for paraffins (fig. 34) shows that benzene and toluene additions resulted in lower smoke points than the additions of liquid paraffins of similar molecular weight. This is in agreement with the work of Street and Thomas on pre-mixed flames of these fuels (85). The curves for benzene and toluene are more similar to the curves for the gaseous paraffins than those for xylene or the liquid paraffins, suggesting that condensation was less severe with the former, though it may have been more marked with the xylene.

The toluene and xylene have higher smoke points than benzene because their branches provide additional opportunities for dehydrogenation and breakdown to aromatic radicals which can then polymerise to polybenzenoid radicals and form soot.

10.3.2. Emissivity, temperature and radiance

The lower concentrations of the aromatic additives produced much greater increases in maximum emissivity of the flames when compared with the paraffins (figs. 35, 43). The highest emissivity recorded during all the experimental runs was 0.14 for 20% xylene but as with the smoke points the toluene and benzene emissivities at the higher concentrations fell slightly below those of the liquid paraffins, The range of emissivities of the aromatics at any particular concentration was much greater than for the liquid paraffins, exphasising that in respect of soot formation the significant features of their molecular structures are the branches. The branches provide the opportunities for soot formation to occur and the benzene rings provide the bulk of the deposit.

As little as 10% xylene gave a maximum emissivity of 0.098 which corresponds to an emissivity of almost 0.9 on an industrial scale. Unfortunately, as with the paraffins, this high level was not sustained over a significant length of the flame (fig. 44). 20% xylene gave an emissivity of 0.1 over approximately one third of the flame's length which is a marked improvement but a high emissivity over almost the entire flame length is desired. The position of maximum emissivity was dependent on the additive concentration as it was with the paraffins, though the lower regions of the flame, up to 5 cm, showed rather lower emissivities with the aromatics and the fall off at higher levels in the flame was not quite so rapid.

Whereas the addition of up to 10% benzene resulted in an increase in the maximum flame temperature, toluene and xylene cooled the flame at all addition rates. Compared with the liquid paraffins the cooling effect of xylene was even more severe due to the higher emissivities which occurred (fig. 45).

The maximum radiance of the flames with xylene added was greater than with any other additive at any concentration, the high addition rates yielding diminishing benefits, however (fig. 46). Toluene and benzene were more effective than the paraffins for producing a high radiance at low rates of addition but at increased levels their efficiency deteriorated and the radiance was considerably lower than when using liquid paraffins. This was particularly noticeable in the case of benzene.

10.4. Acetylene, ethylene, cyclohexane

The flames with acetylene added were rather different from those with other hydrocarbon additives in that at the smoke point, the yellow colouration appeared at the tip of the inner cone rather than at some distance above this point. This is in contrast to 100% acetylene flames in which the luminous zone occurs over the whole of the flame front at a position well above the inner cone, similarly to a 100% methane flame (71, 72, 73). The presence of the additive acetylene and thence radicals such as C_2H, CH, C_2 at an earlier position than could be achieved in a pure methane flame enables the polymerisation to polyacetylenes and polyacetylene radicals to be initiated and completed near to the reaction zone.

10.4.1 Smoke point

The plot ofsmoke point against concentration for acetylene is very similar to that for methane (figs. 34, 42). Only slightly more air was necessary with the acetylene and this was much less than with ethane and the other paraffins. Although acetylene promoted soot formation earlier in the flame it did not significantly increase the tendency of the flame to soot.

The ethylene flames were very similar in appearance to those of pure methane and the effect of ethylene on the smoke point was akin to that of ethane (fig. 42). When comparising the flames of 100% ethane and 100% ethylene, Street and Thomas found that ethane caused a more marked increase in the smoke point than ethylene (85).

The ring structure of cyclohexane made the formation of radicals more difficult than with the other paraffins of similar molecular weight, and it behaved in the same way as propane. In flames richer than at the smoke point the yellow colouration was generally paler than with other paraffins. At the higher concentrations the flames were noticeably longer.

10.4.2 Emissivity, temperature and radiance

Acetylene had little influence on the maximum flame emissivity below 5% concentration (fig. 43). At 10% and above it became more effective than methane itself but was still inferior to ethane. The point of maximum emissivity was slightly nearer to the burner than with the paraffins due to the earlier formation of soot. The shape of the emissivity-concentration curves for ethylene and cyclohexane also followed the pattern of the paraffins rather than the aromatics (figs. 35, 43). The cyclohexane flames had slightly higher emissivities than the ethylene flames but they were both very similar to ethane and propane flames. At 15% concentration and above they had greater emissivities than benzene flames; however, none of these additives gave a worthwhile increase in the flame emissivity.

Even at low concentrations the ethylene flames were much hotter than the acetylene or cyclohexane flames which were more closely related to the paraffin flames although the 20% additions did not achieve quite such high temperatures (fig. 45).

The radiance of the ethylene and cyclohexane flames were similar, due to the relatively low emissivity and high temperature of the former and the higher emissivity and lower temperature of the latter. In both cases at the higher additive concentrations the effect on the radiance was proportionally greater than at low concentrations. The readiances of those flames with acetylene added were only a little more than those with methane (fig. 46).

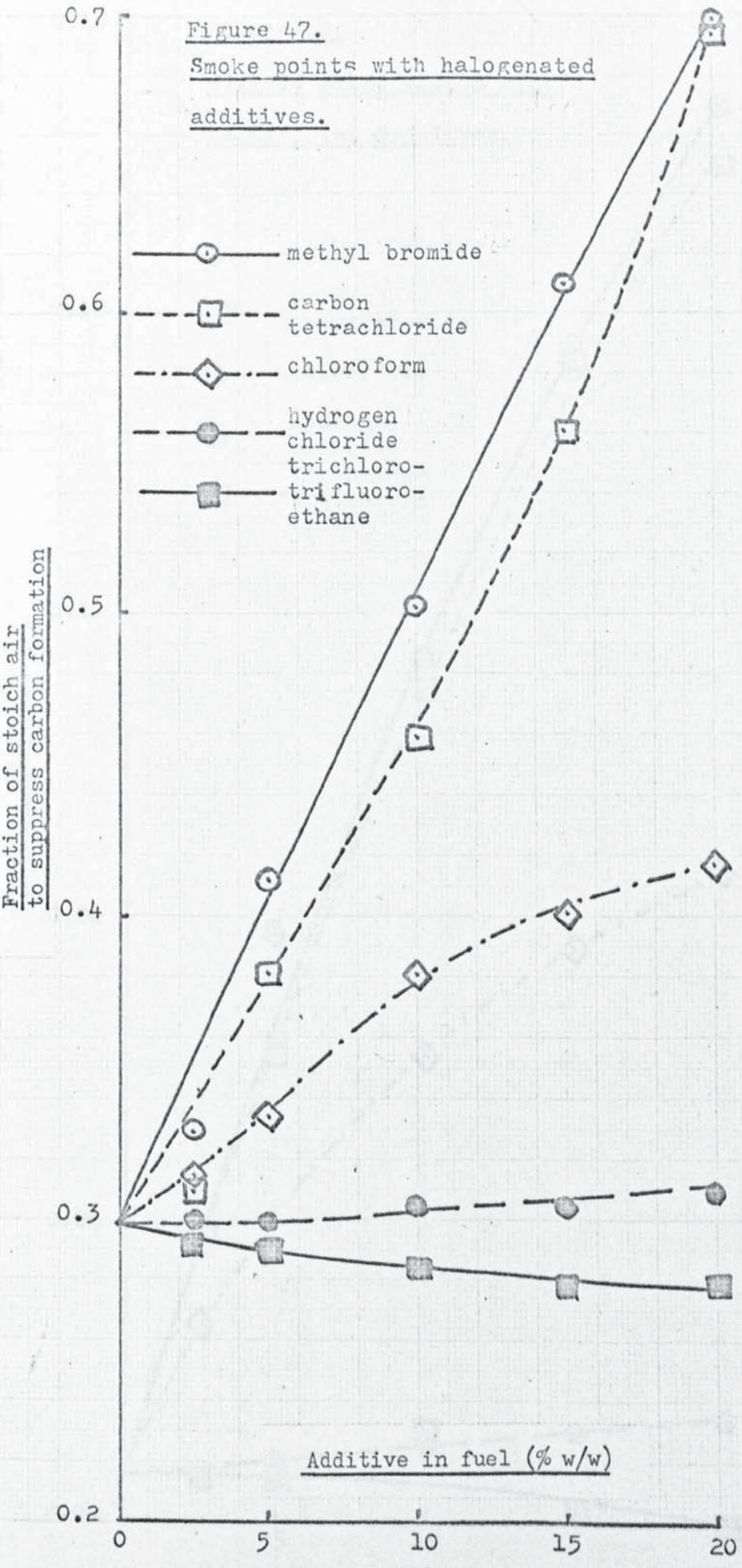


Figure 47.

Smoke points with halogenated additives.

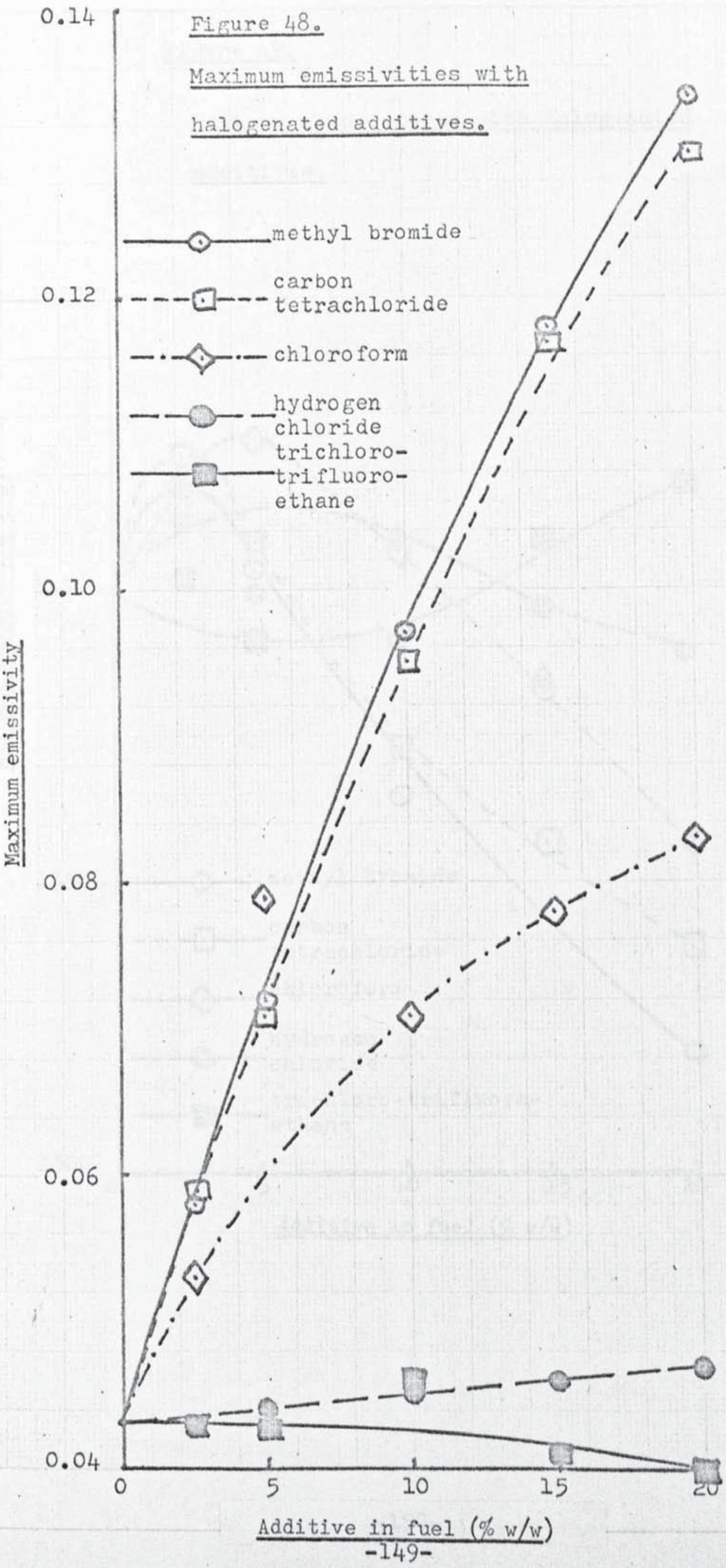


Figure 48.

Maximum emissivities with halogenated additives.

Figure 49.

Maximum temperatures with halogenated additives.

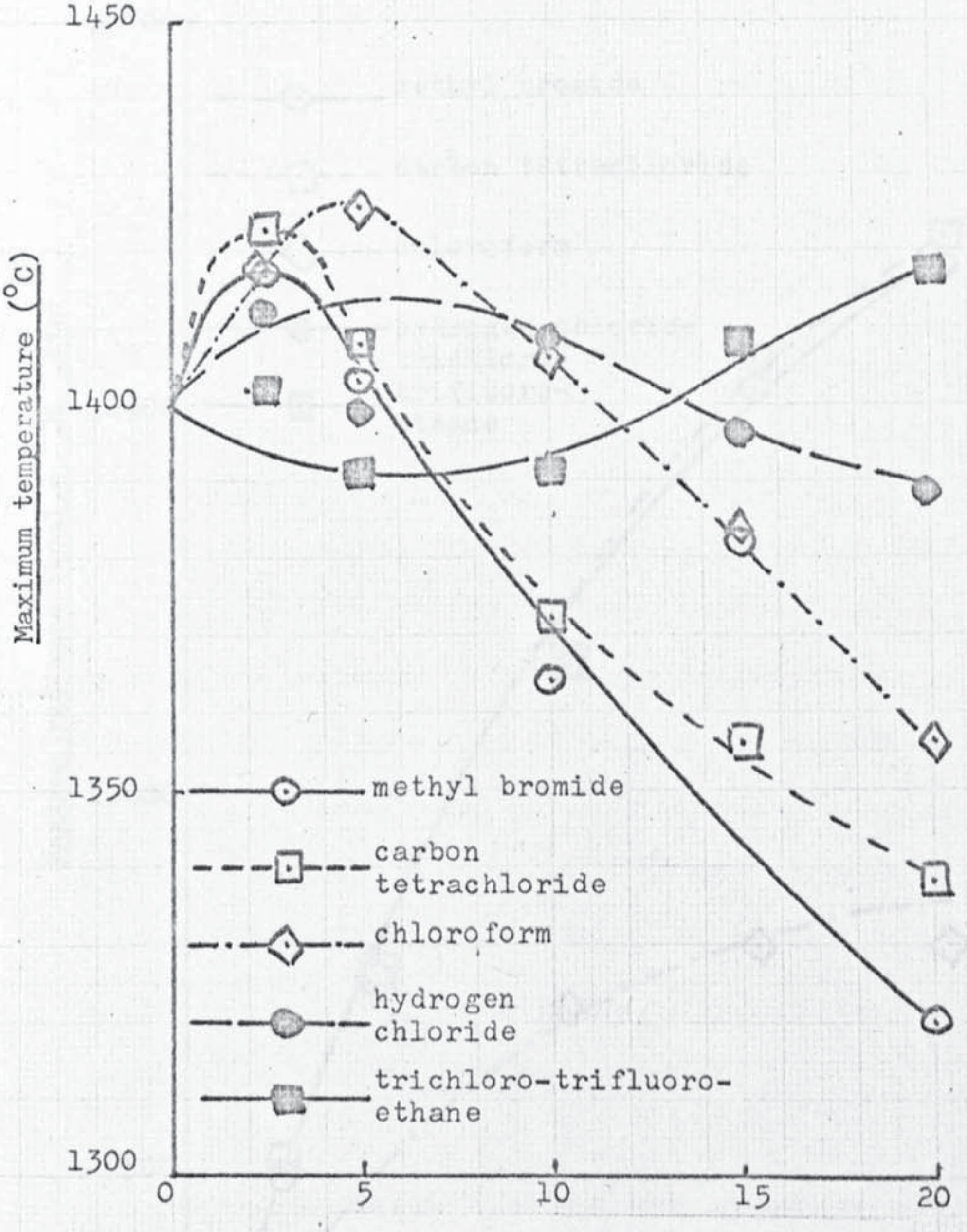
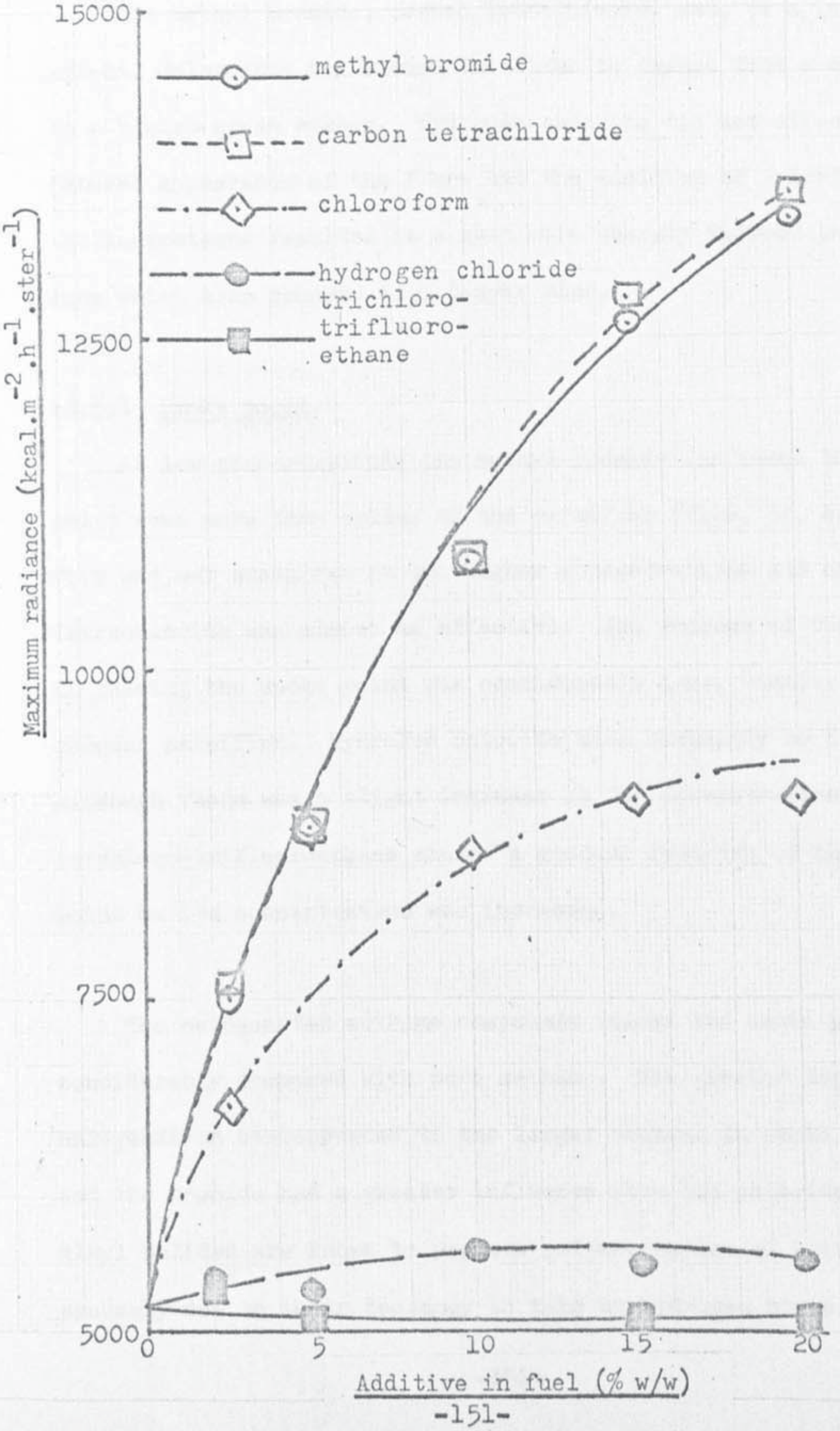


Figure 50.

Maximum radiances with halogenated additives.



10.5 Halogenated compounds

The five halogenated compounds tested were methyl bromide and carbon tetrachloride, both known flame retardants, chloroform, hydrogen chloride and trichloro-trifluoroethane.

The methyl bromide, carbon tetrachloride and, to a lesser extent, chloroform all caused the flame to change from a blue to a bluish-green colour. Hydrogen chloride did not affect the general appearance of the flame but the addition of trichloro-trifluoroethane resulted in a much more sharply defined inner cone which also changed to a deeper blue.

10.5.1 Smoke point

At low concentrations the methyl bromide increased the smoke point even more than xylene or the paraffins (figs. 34, 42, 47). This was not sustained at the higher concentrations and carbon tetrachloride was almost as effective. The success of the chloroform in raising the smoke point was considerably less, similar to the gaseous paraffins. Hydrogen chloride made virtually no difference although there was a slight increase at 20% concentration. The trichloro-trifluoroethane caused a gradual lowering of the smoke point as its concentration was increased.

The halogenated methane compounds raised the smoke point considerably compared with pure methane. The greater degree of halogenation corresponded to the larger changes in smoke point and the bromide had a greater influence than the chloride. These alkyl halides are known to promote polymerisation of hydrocarbons, probably due to their tendency to take up hydrogen atoms, and when used as an additive in this way they are able to increase the rate of polymerisation of the acetylene radicals.

10.5.2 Emissivity, temperature and radiance

The plots of maximum emissivity against concentration for methyl bromide and carbon tetrachloride are very similar to that for xylene (figs. 43, 48). The methyl bromide has a slightly greater influence than the carbon tetrachloride and the xylene is a little more effective than both. As in the case of xylene the maximum emissivity which can be achieved with as little as 10% addition is acceptably high at 0.096, corresponding to almost 0.9 on an industrial scale, but again this level is maintained along only a small proportion of the flame. The fall off in emissivity on both sides of the maximum is quite rapid.

The carbon tetrachloride is less effective than the other alkyl halides, the shape of the emissivity-concentration curve and the maximum emissivity of 0.083 at 20% concentration are very similar to those for benzene.

Hydrogen chloride addition resulted in a slight increase in emissivity and trichloro-trifluoroethane addition had the opposite effect, neither being very marked.

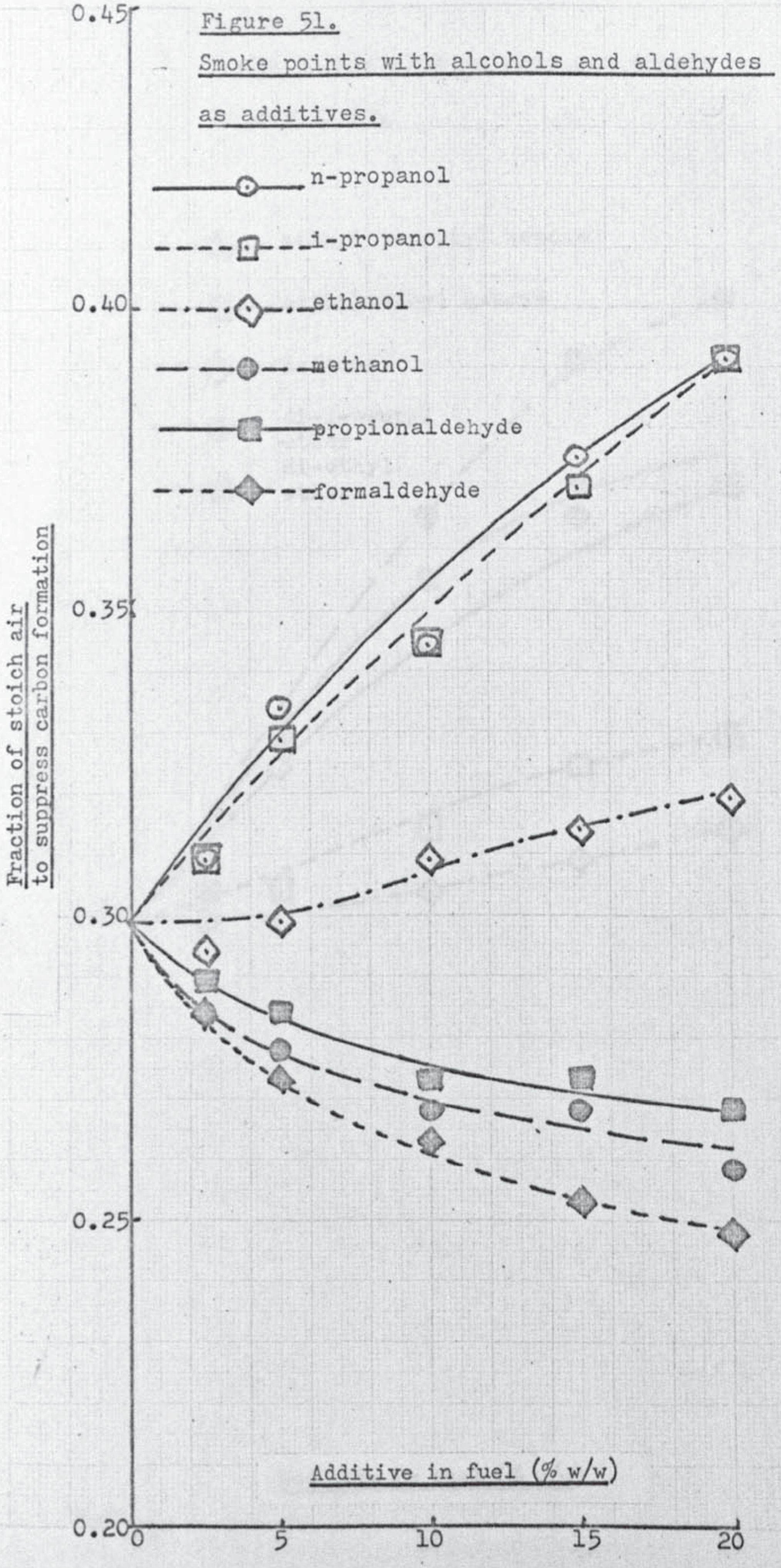
Methyl bromide, carbon tetrachloride, chloroform, and, to a lesser extent, hydrogen chloride all had similar maximum temperature-concentration profiles (fig. 49). Low addition levels increased whereas higher levels decreased the maximum flame temperature.

In the cases of the halogenated hydrocarbons the increase in the calorific input to the flame resulted in the higher temperatures at low addition rates. At the higher rates the calorific value of the extra fuel being supplied was outweighed by the consequent increase in the emissivity. The nett result was more heat being radiated from the flame which was, therefore, cooled, quite considerably in the cases of methyl bromide and carbon tetrachloride, which produced flames which were even cooler than those with added aromatics. The trichloro-trifluoroethane had little effect on the temperature of the flame.

The severe cooling at high addition rates resulted in the maximum radiances of the flames with methyl bromide and carbon tetrachloride being well below the maximum radiance of the xylene flames (fig. 50). The carbon tetrachloride flames were again similar to the benzene flames when considering the maximum radiance. Neither hydrogen chloride nor trichloro-trifluoroethane had a marked effect on the radiance.

Figure 51.

Smoke points with alcohols and aldehydes as additives.



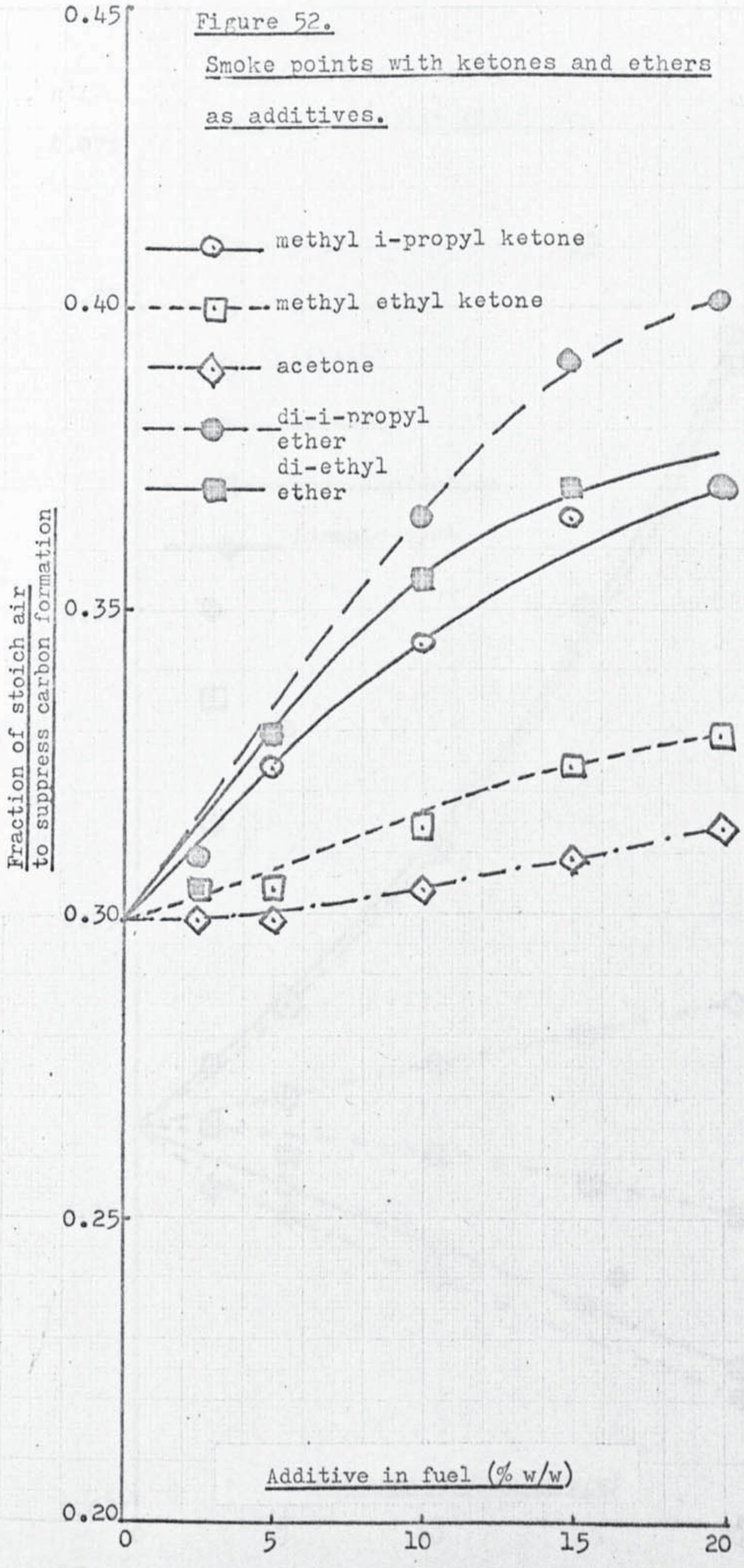
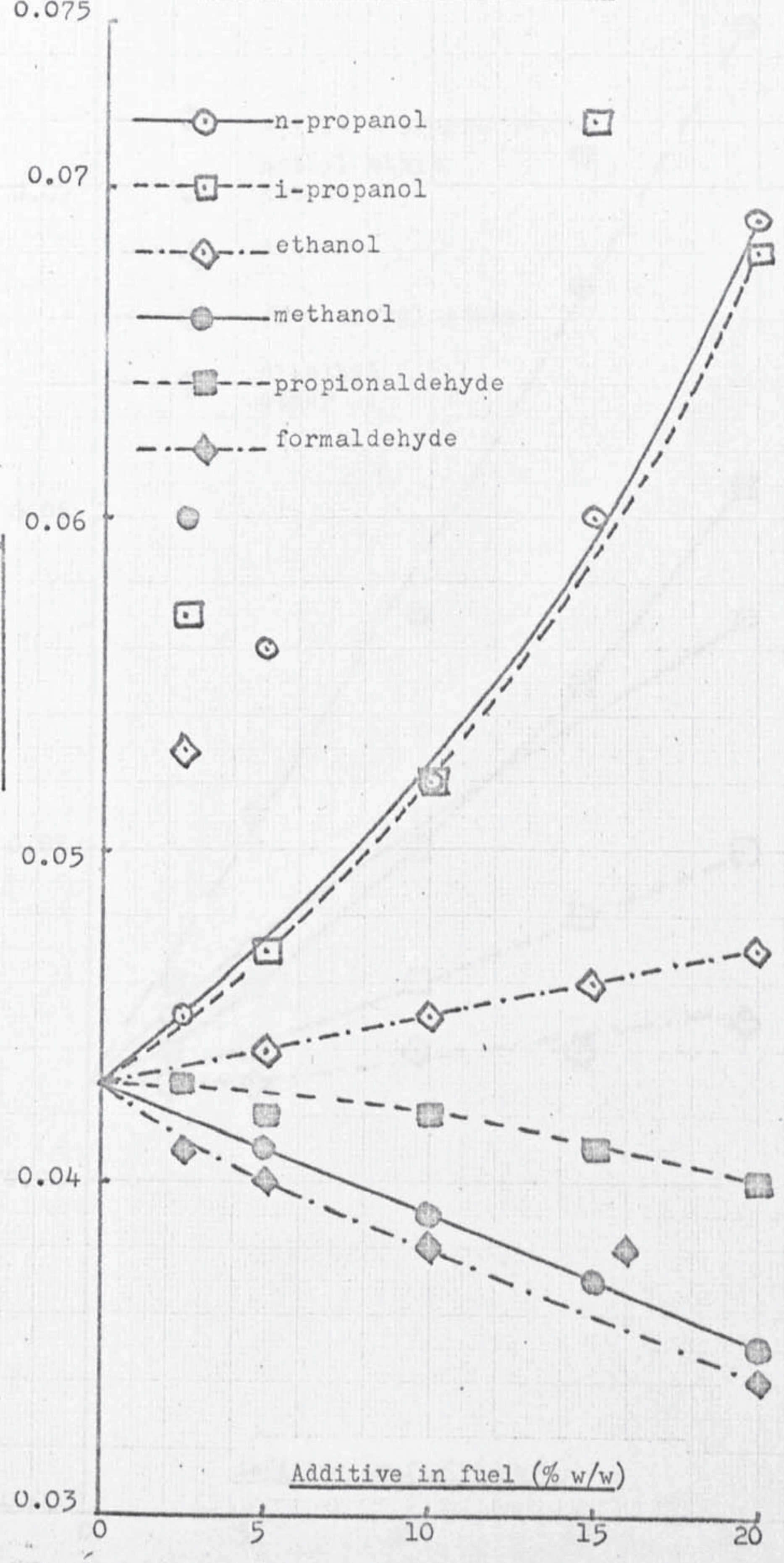


Figure 52.

Smoke points with ketones and ethers as additives.

Figure 53.

Maximum emissivities with alcohols and aldehydes as additives.



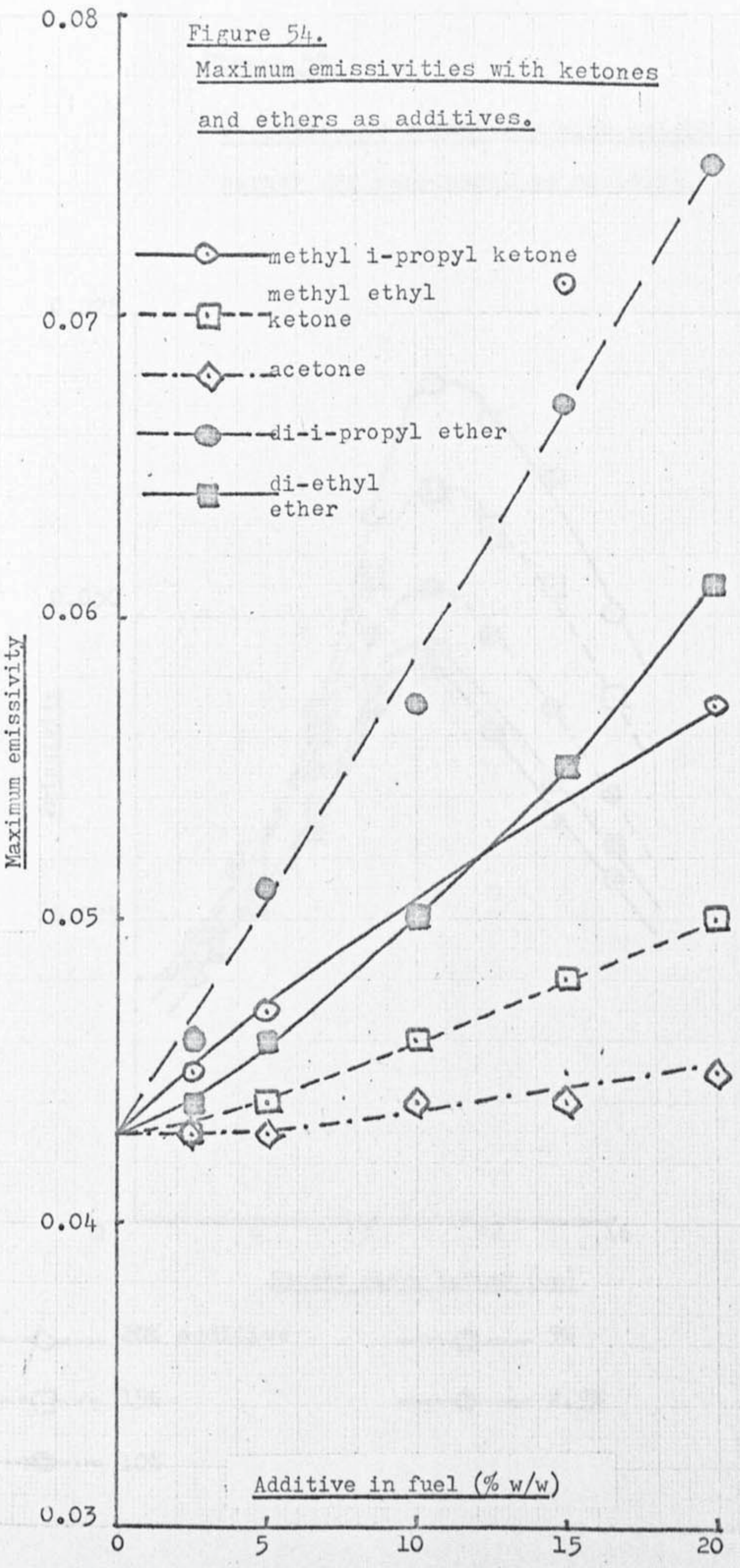


Figure 54.

Maximum emissivities with ketones and ethers as additives.

Figure 55.

Variation of emissivity with height above burner for n-propanol as additive.

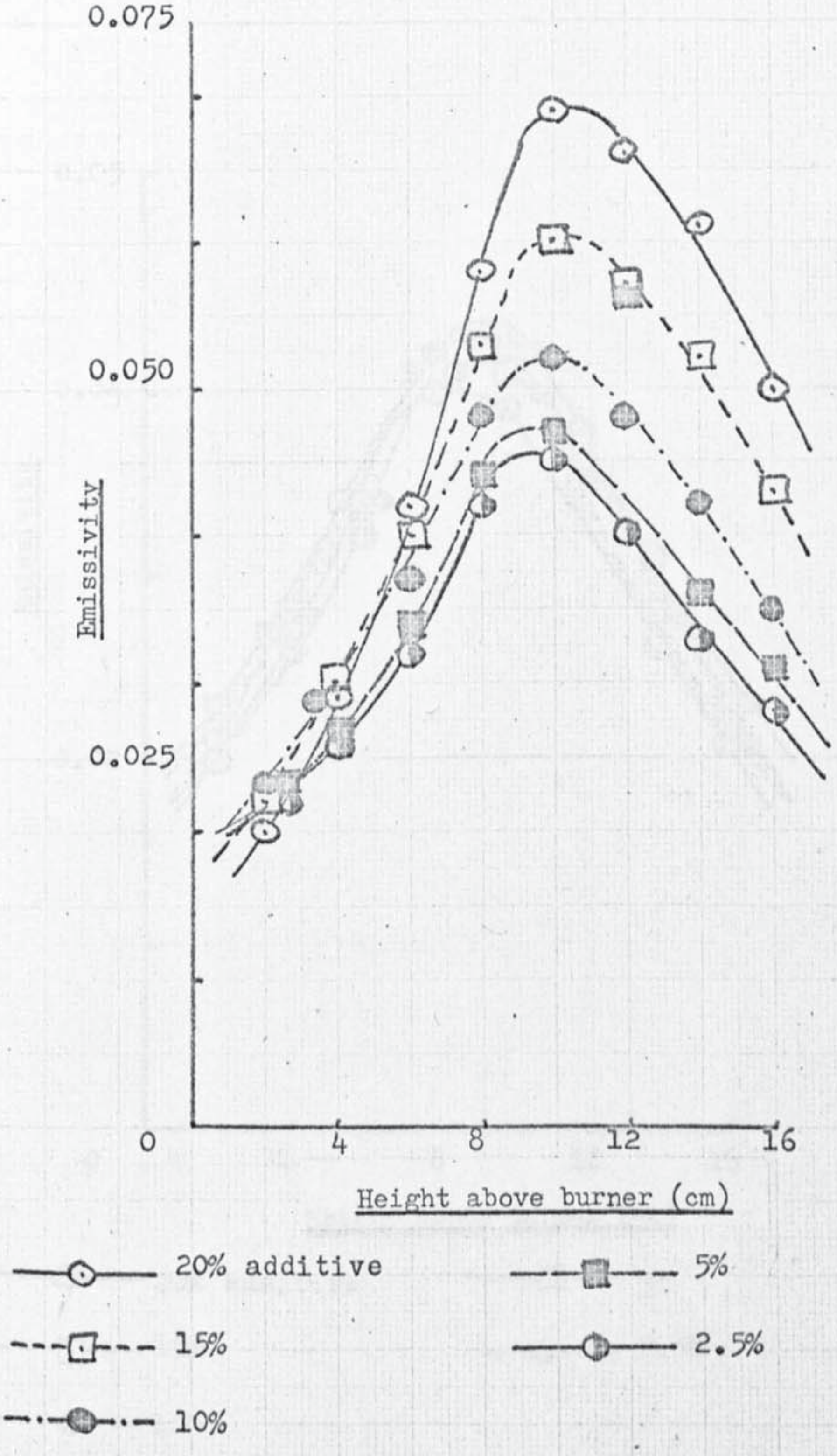


Figure 56.

Variation of emissivity with height above burner for propionaldehyde as additive.

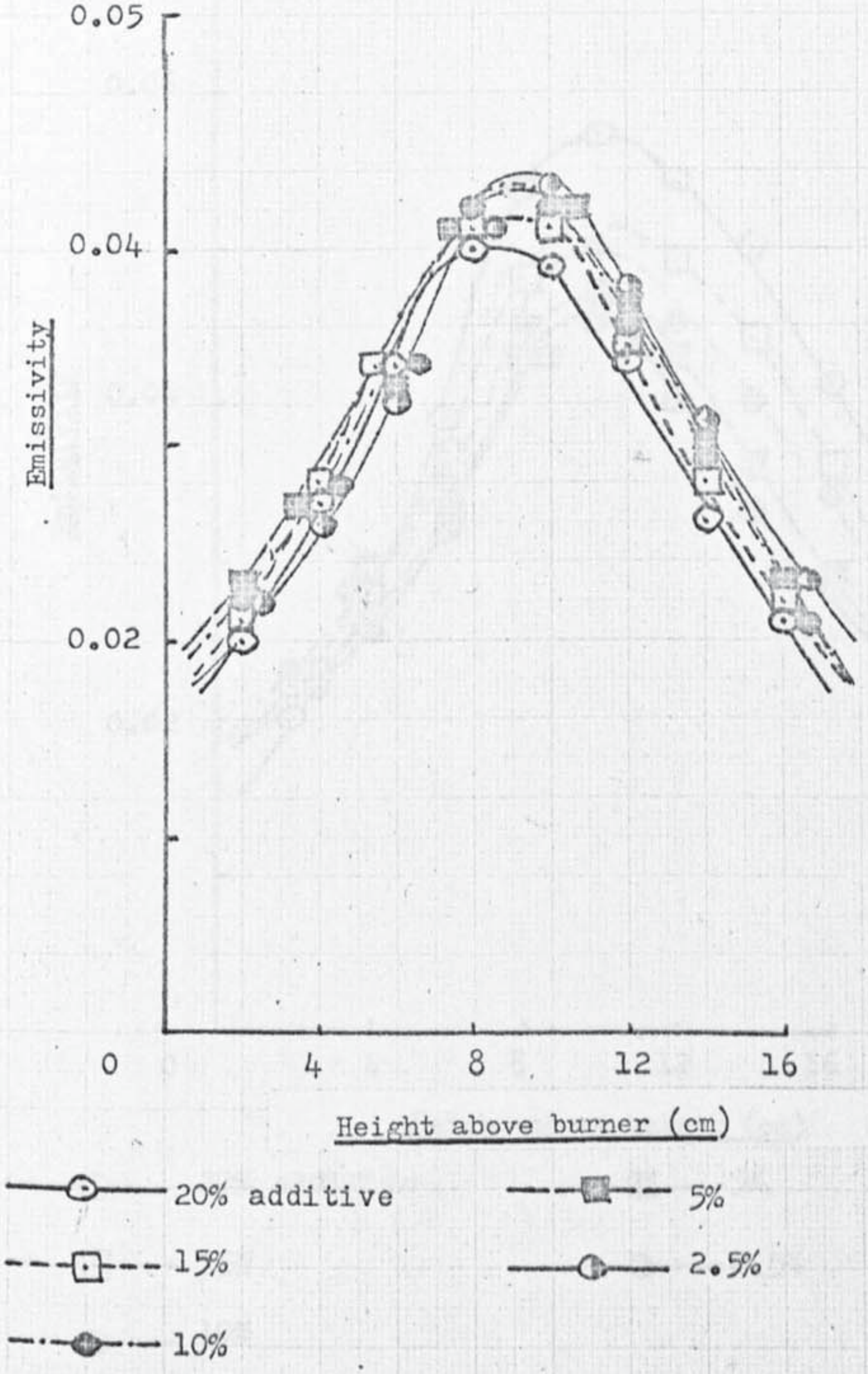


Figure 57.

Variation of emissivity with height above burner for methyl i-propyl ketone as additive.

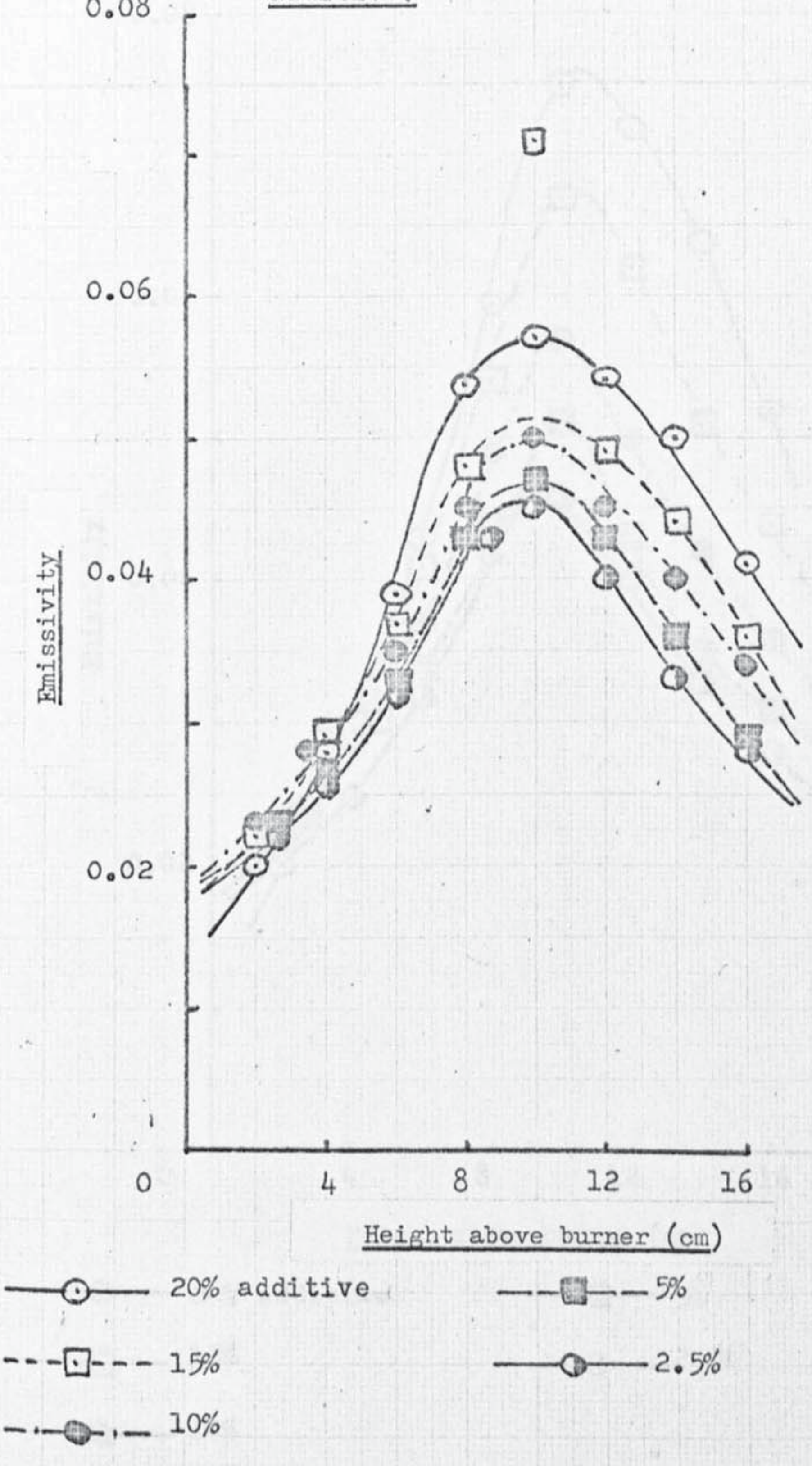


Figure 58.

Variation of emissivity with height above burner for di-i-propyl ether as additive.

Figure 59.

Variation of emissivity with height above burner for methanol as additive.

Figure 60.

Variation of emissivity with height above burner for formaldehyde as additive.

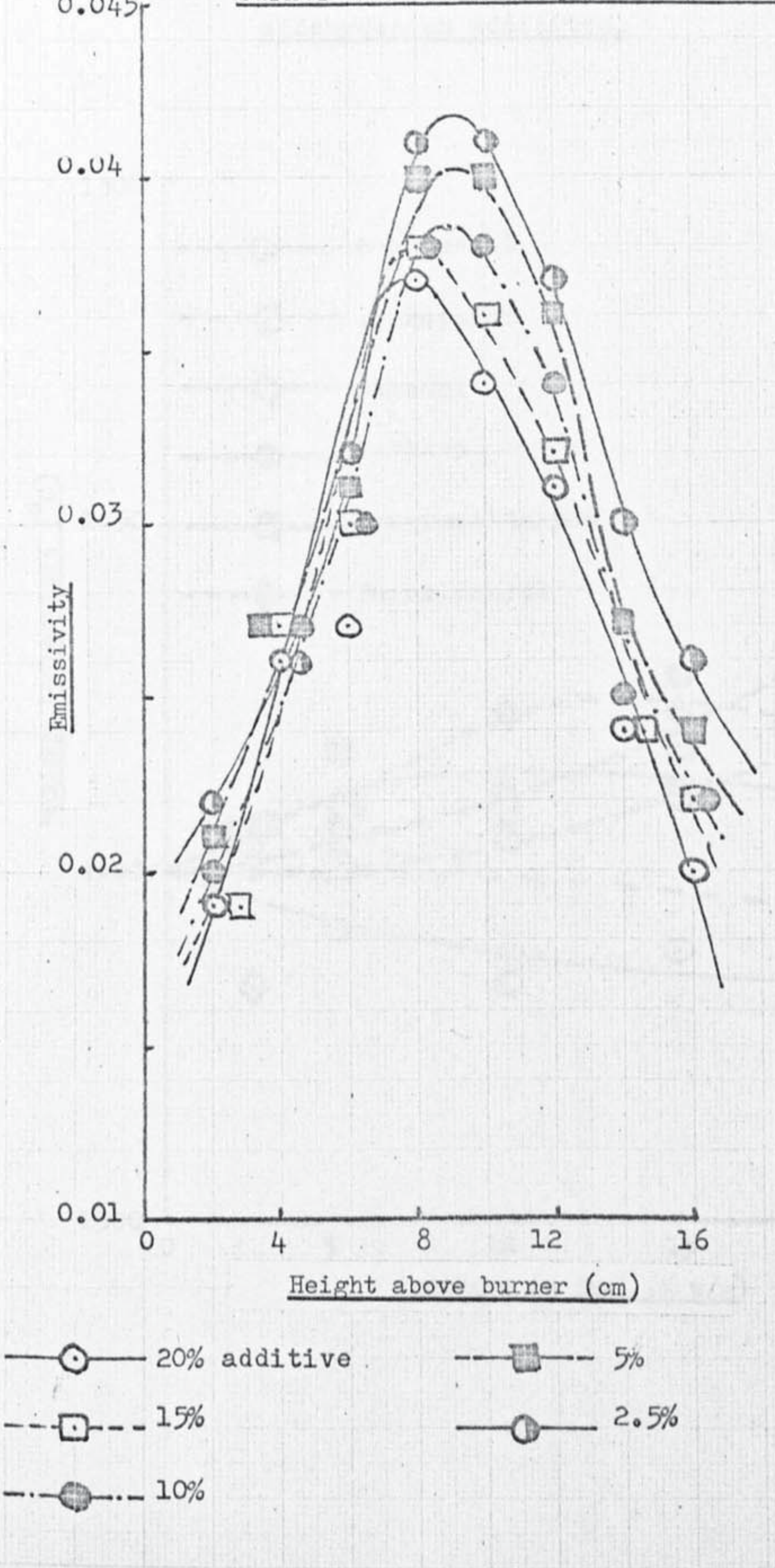


Figure 61.

Maximum temperatures with alcohols and aldehydes as additives.

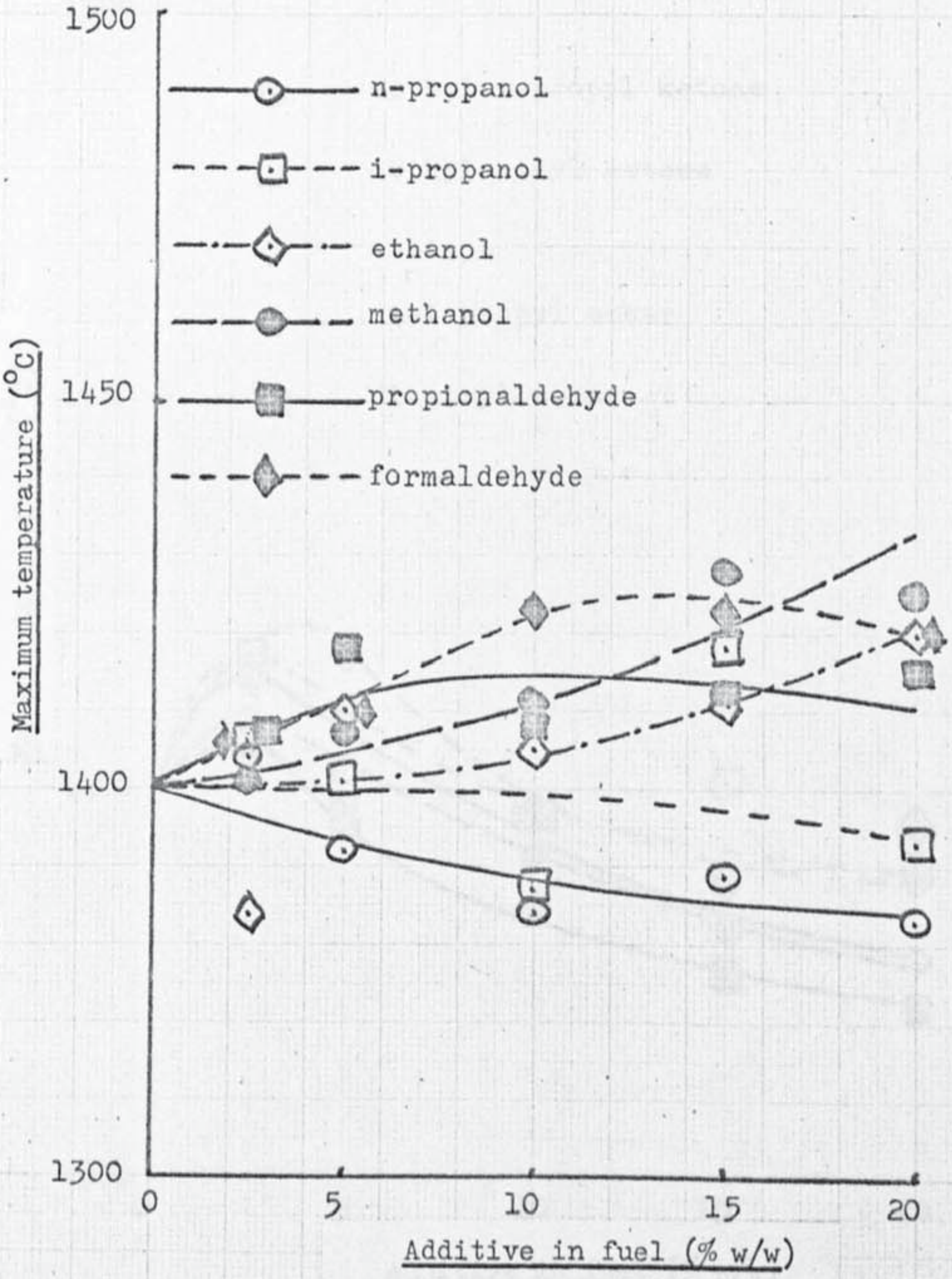


Figure 62.

Maximum temperatures with ketones and ethers as additives.

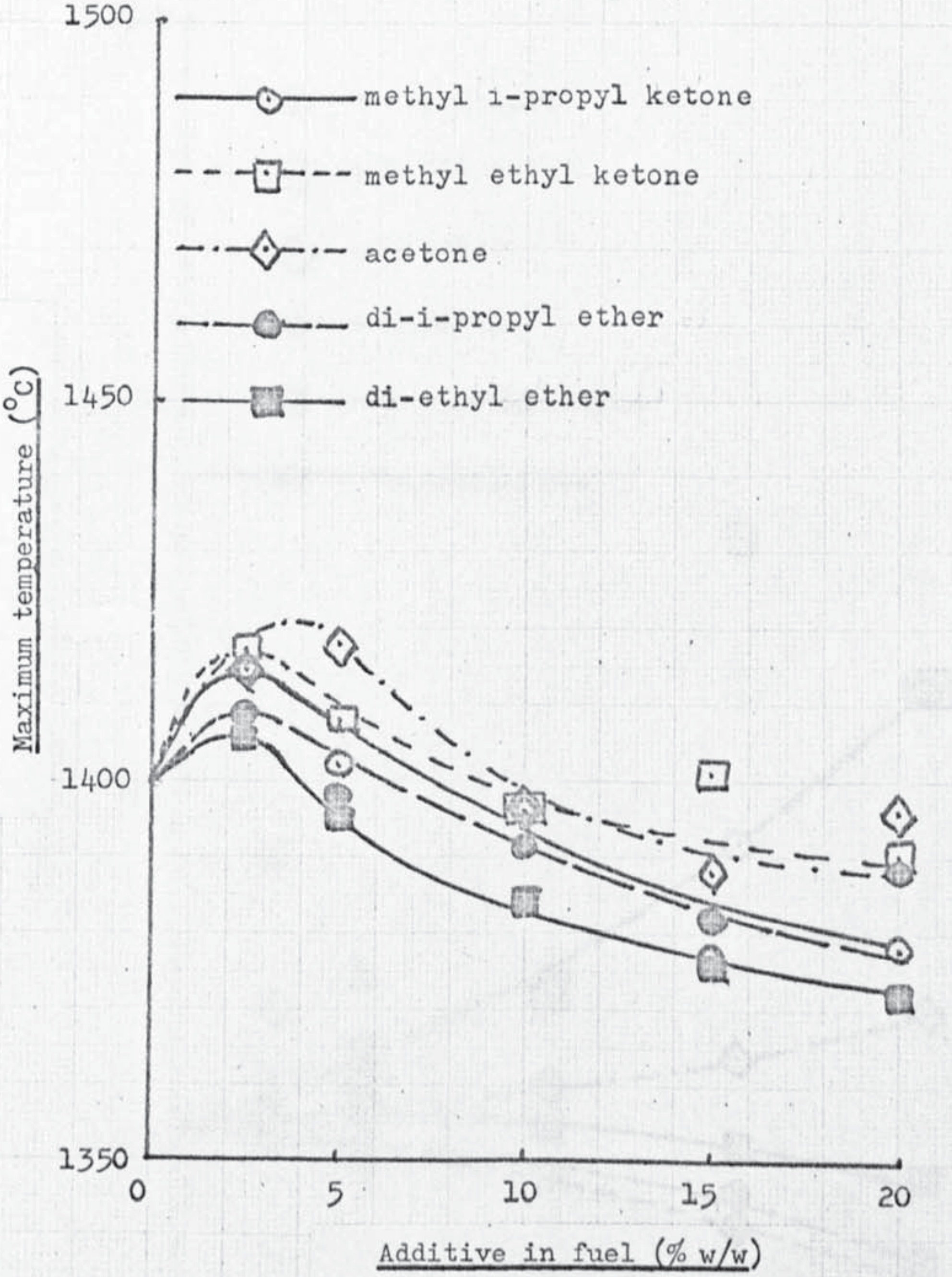


Figure 63.

Maximum radiances with alcohols and aldehydes as additives.

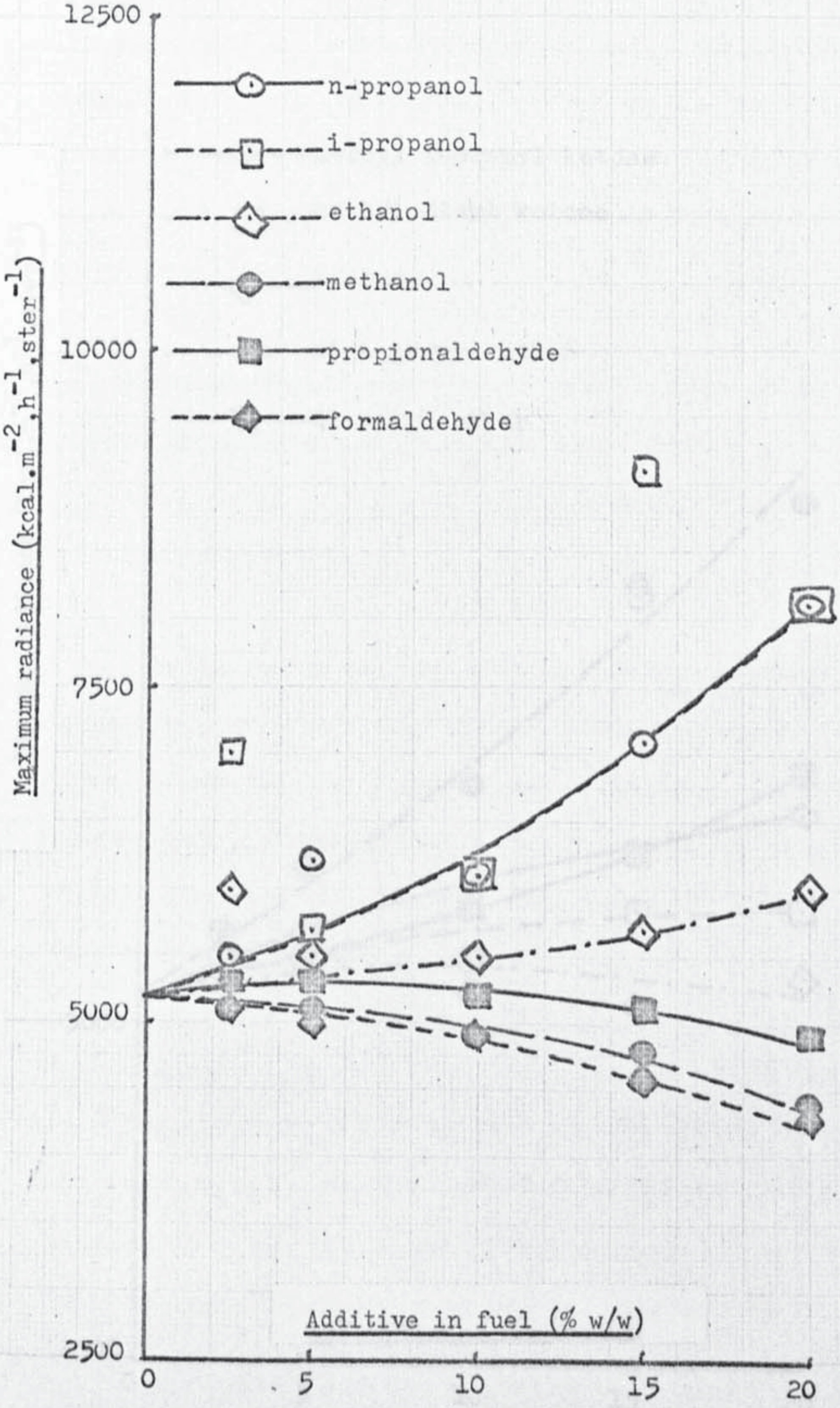
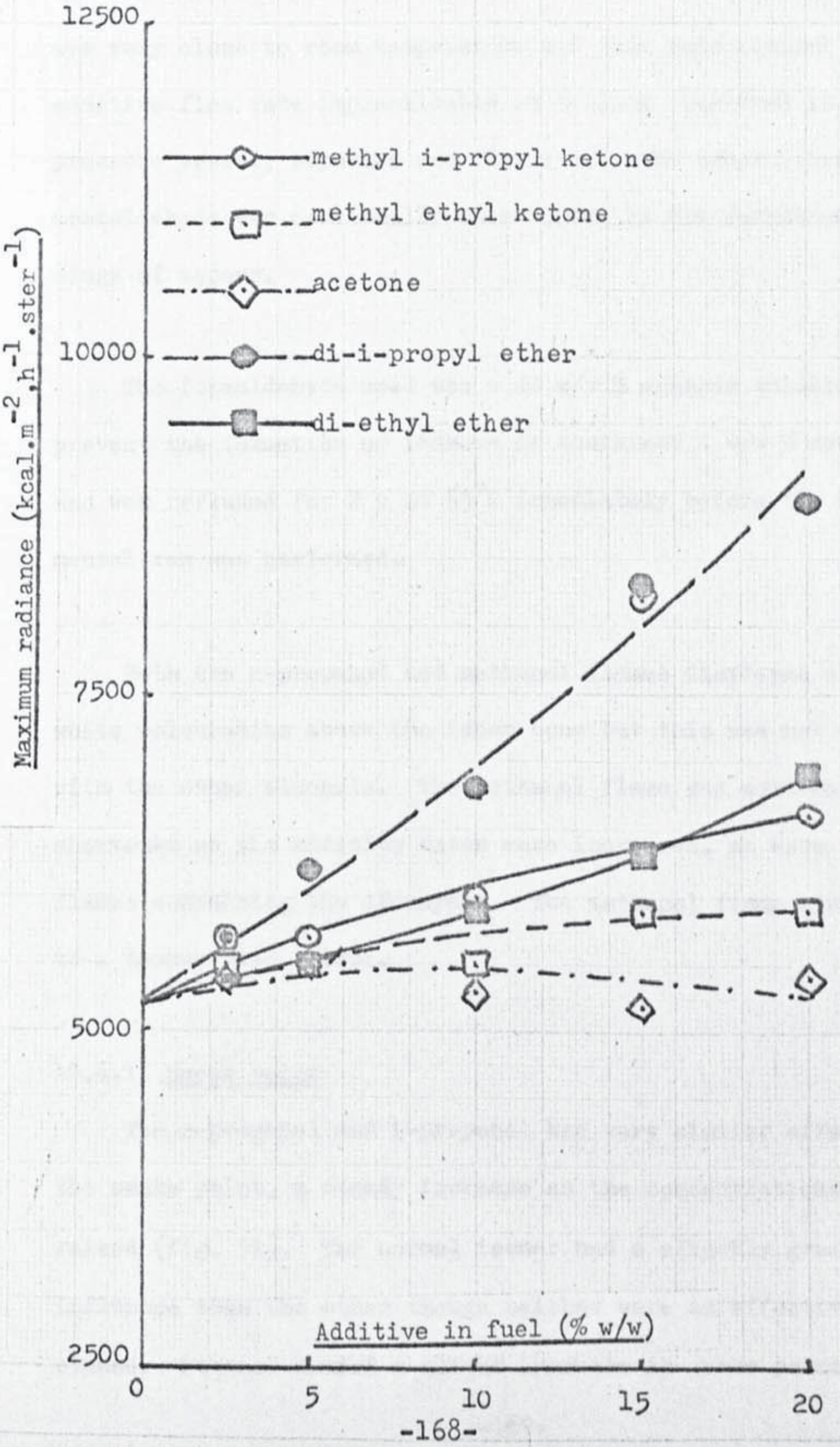


Figure 64.

Maximum radiances with ketones and ethers as additives.



10.6 Organic compounds containing oxygen

Eleven additives were evaluated under the above heading. They were n-propanol, i-propanol, ethanol, methanol, propionaldehyde, formaldehyde, methyl i-propyl ketone, methyl ethyl ketone, acetone, di-i-propyl ether and di-ethyl ether. Attempts were also made to test acetaldehyde as an additive. Its boiling point of 20°C was very close to room temperature and this made control of the additive flow rate impracticable as boiling occurred in the pressure vessel, pipework and flowmeter. The smooth flow of the acetaldehyde was continually interrupted by the formation of slugs of vapour.

The formaldehyde used was a 40 w/v % aqueous solution. To prevent the formation of isomers it contained 1 w/w % methanol and was refluxed for 2 h at 65°C immediately before the experimental run was performed.

Both the n-propanol and methanol flames displayed a faint white colouration above the inner cone but this was not observed with the other alcohols. The methanol flame was noticeably shortened as the additive rates were increased, as were the flames containing the aldehydes. The methanol flame also changed to a deeper blue colour.

10.6.1 Smoke point

The n-propanol and i-propanol had very similar effects on the smoke point, a steady increase as the concentrations were raised (fig. 51). The normal isomer had a slightly greater influence than the other though neither were as effective as ethane. Ethanol caused a slight increase in smoke point, at 10%

concentration and above. With the presence of the hydroxyl group being more significant in the lower molecular weight alcohol, methanol reduced the smoke point quite considerably, the effect being proportionally less as the concentration was increased.

The behaviour of the aldehydes was very similar to that of the methanol (fig. 51). Propionaldehyde reduced the smoke point slightly less and formaldehyde slightly more than methanol. Within each homologous series the higher molecular weights corresponded to the higher smoke points, as with the paraffins. With these compounds containing oxygen, however, the lower members of the series could actually decrease the tendency of the flame to form soot.

The methyl i-propyl ketone raised the smoke point rather less than the propanols though the shape of the smoke point-concentration curve was very similar (fig. 52). The other ketones were must less effective and were similar to ethanol, again the largest increases in smoke point corresponded to the highest molecular weights.

Di-ethyl ether increased the smoke point slightly more than methyl i-propyl ketone and di-i-propyl ether even more so than the propanols (fig. 52). None of these additives were as effective as the gaseous paraffins, however.

10.6.2 Emissivity, temperature and radiance

The influences of the alcohols, aldehydes, ketones and ethers on the smoke points and maximum emissivities of the flames were similar (figs. 53, 54). The isomers of propanol were again very much alike and caused a slightly accelerating rise in the emissivity as their concentrations were increased whereas their effect on the smoke point tended to tail off at high concentrations, however. Ethanol wrought a small increase in the emissivity in contrast to methanol which had the opposite effect. Methanol again lay between the two aldehydes, although closer to formaldehyde than on the smoke point plot. The ketones had a relatively small influence on the maximum emissivity. Di-ethyl-ether was even less effective at low concentrations and only at 15% and above did its emissivities exceed those with methyl i-propyl ketone. Di-i-propyl ketone had the greatest effect, reaching 0.075 at 20% concentration but this was still inferior to the gaseous paraffins. The position of maximum emissivity varied only slightly with the changes in concentration of the propanols, ethanol, propionaldehyde, ketones and ethers (figs. 55, 56, 57, 58). Methanol and formaldehyde, however, both caused the position of maximum emissivity to move nearer to the burner as their concentrations were increased (figs. 59, 60).

The maximum flame temperatures were little affected by the additives (figs. 61, 62). The aldehyde flames tended to be slightly hotter than the others and the additives with the higher molecular weights were cooler but the general variation from methane was small. The ketones and ethers had an overall cooling effect at 10% concentration and above.

The radiances of the flames containing the propanols and di-i-propyl ether were raised in increasing proportion as the additive flows were increased (figs. 63, 64). The effectiveness of the propanols and di-i-propyl ether as additives lay between methane and ethane. The other alcohols, aldehydes, ketones and ethers had only a small influence on the radiance.

Figure 65.

Smoke points with reactants and products of combustion as additives.

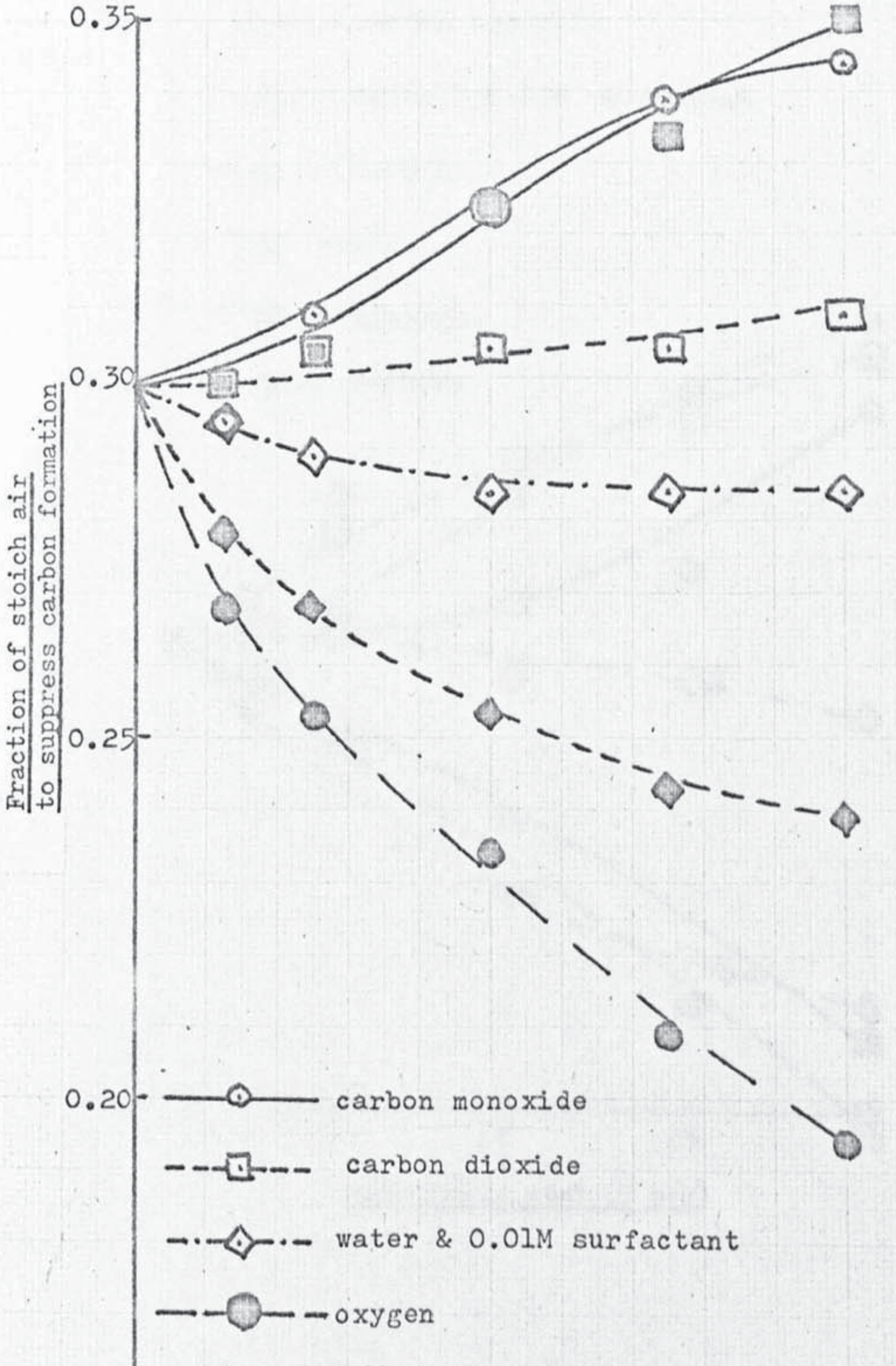


Figure 66.

Maximum emissivities with reactants and products of combustion as additives.

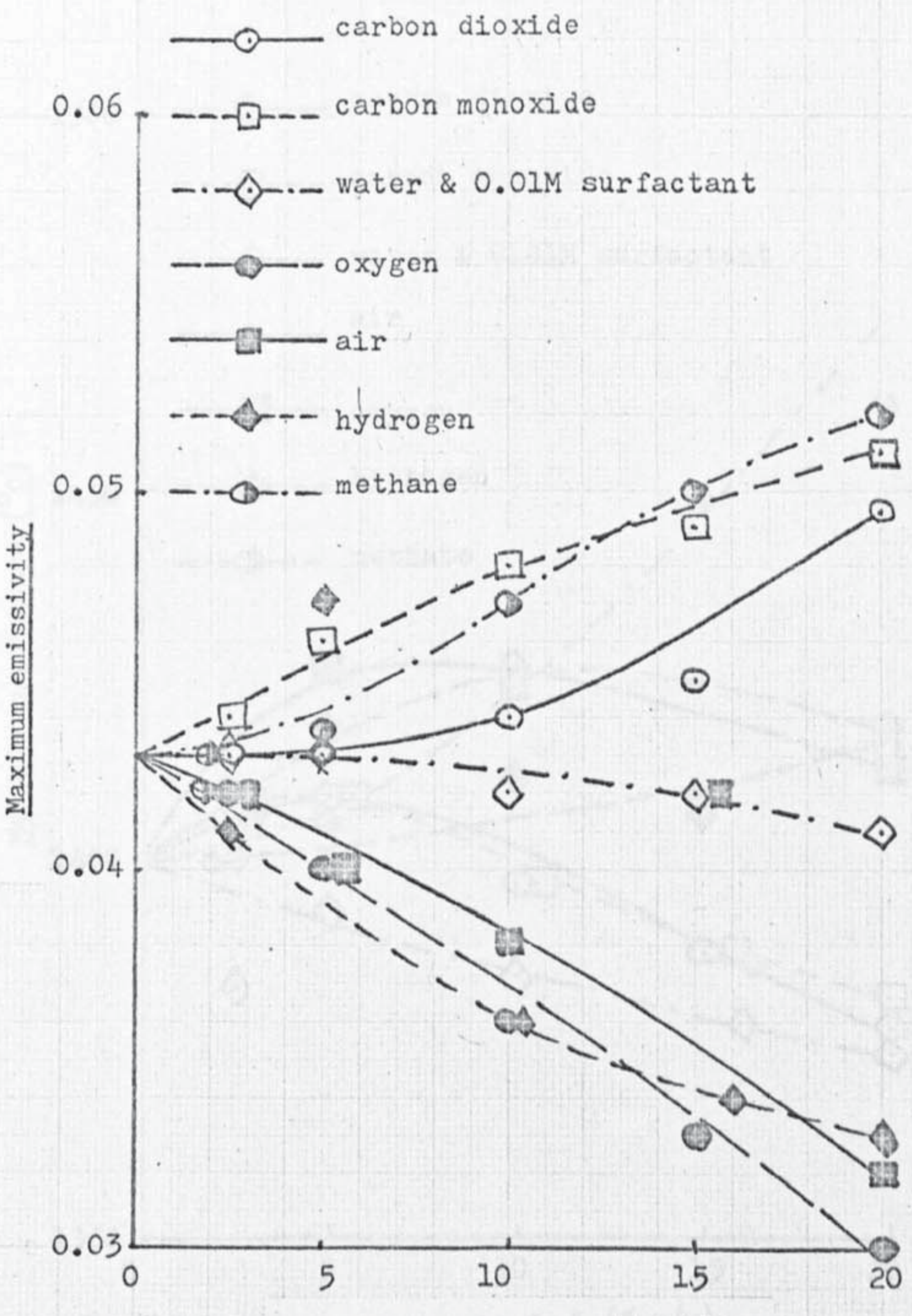


Figure 67.

Maximum temperatures with reactants and products of combustion as additives.

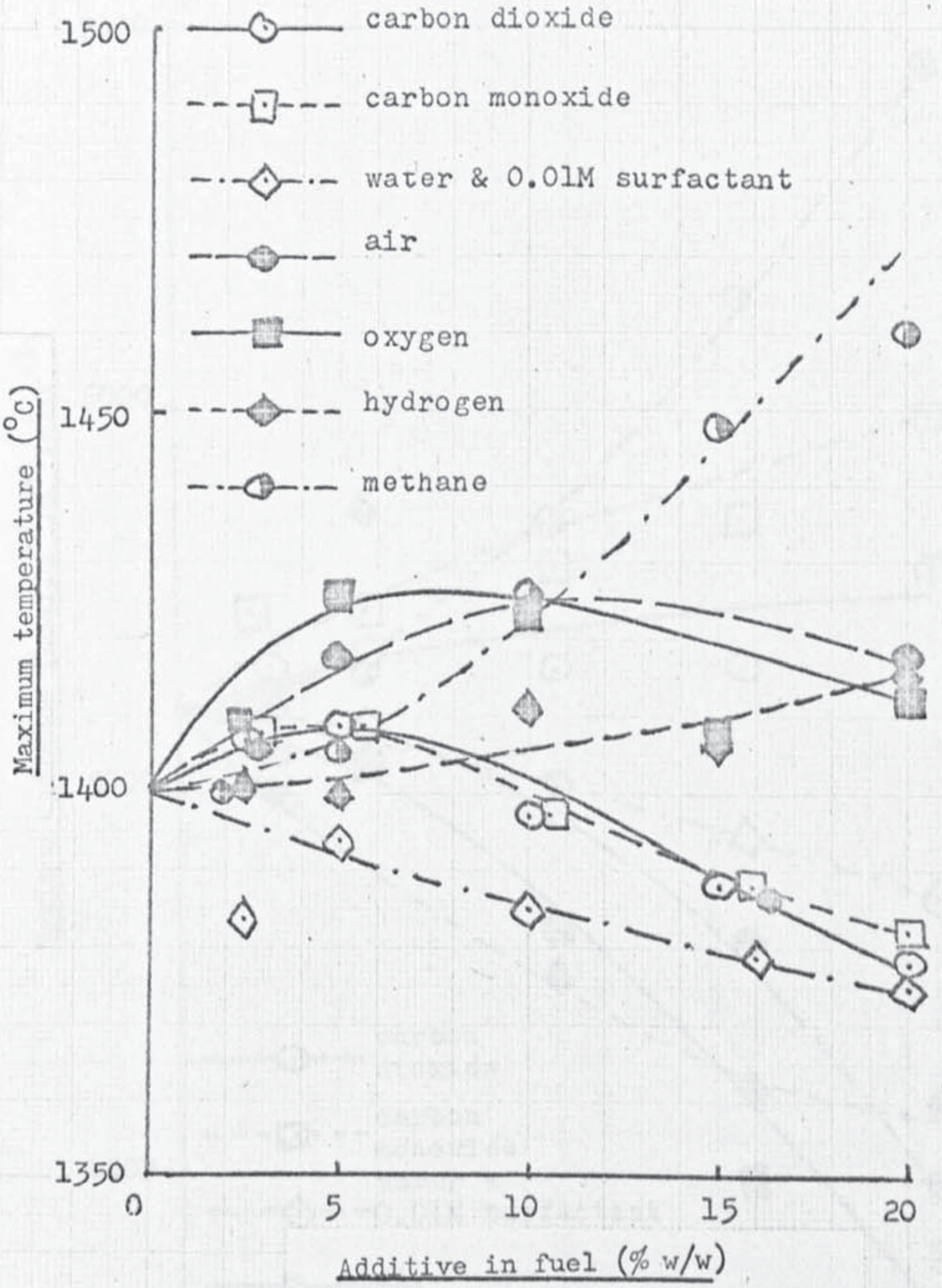


Figure 68.

Maximum radiances with reactants and products of combustion as additives.

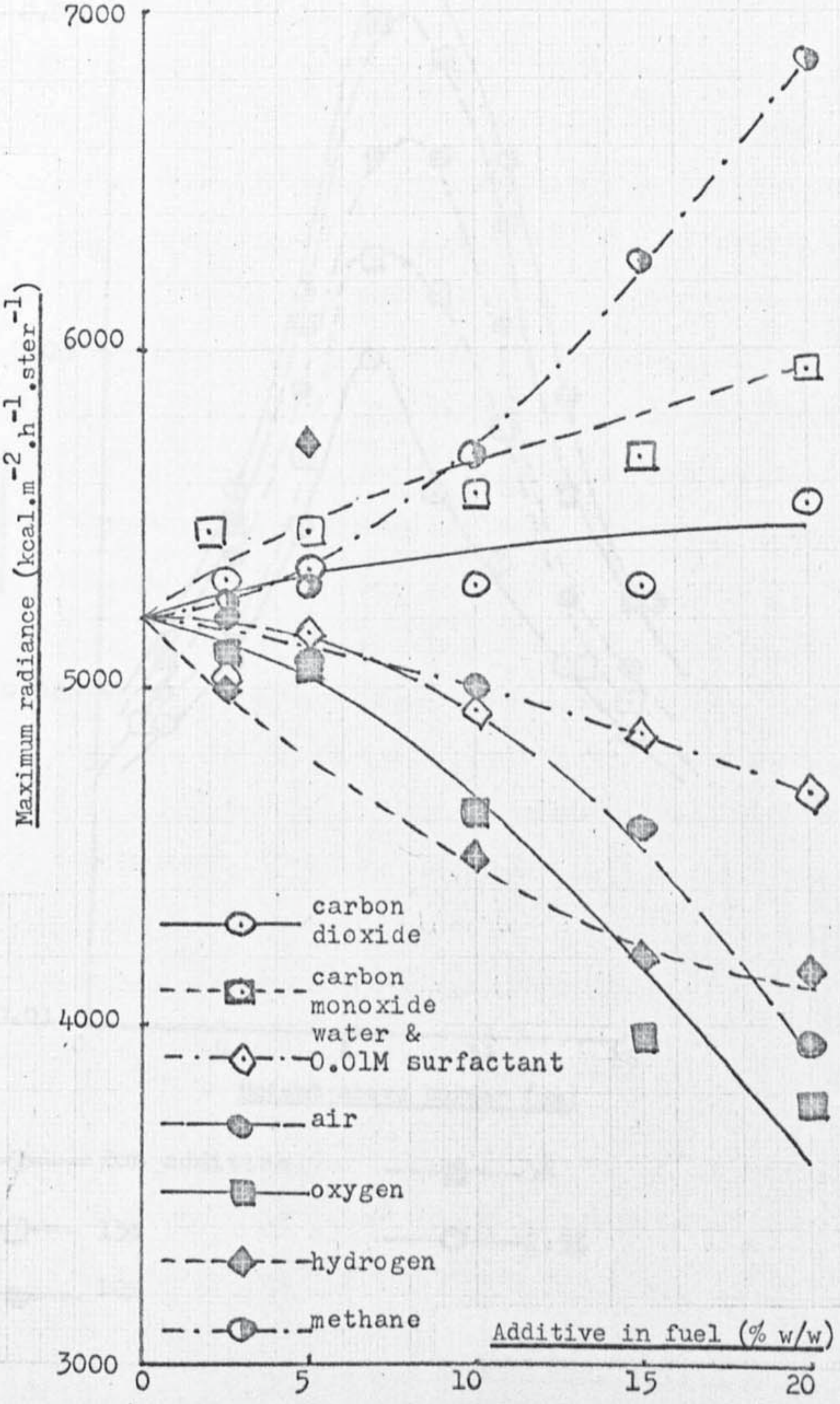
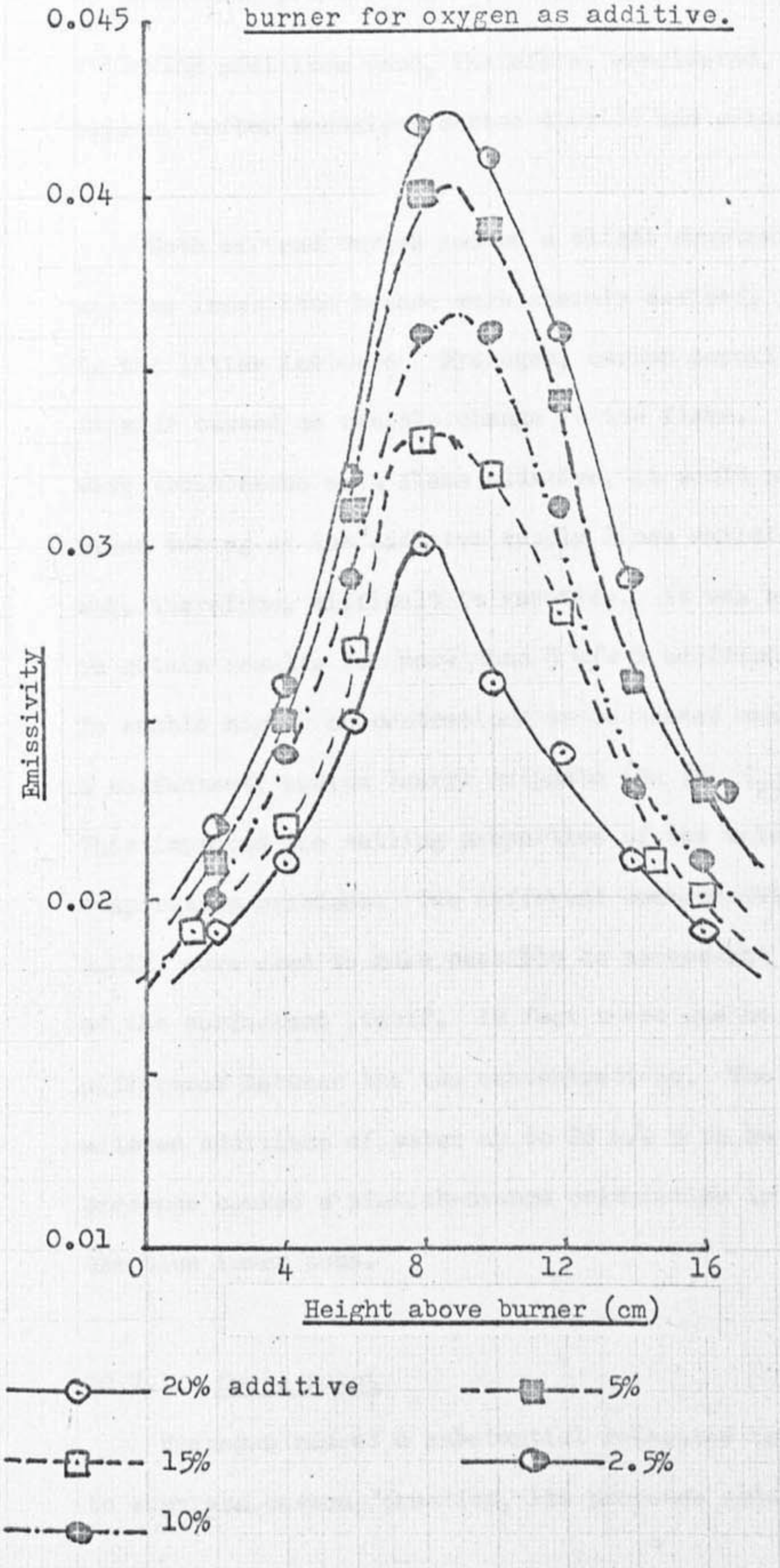


Figure 69.

Variation of emissivity with height above burner for oxygen as additive.



10.7 Flame reactants and products of combustion

Some industrial applications have made use of recirculation of combustion products in order to improve efficiency. The following additives were, therefore, considered, hydrogen, air, oxygen, carbon monoxide, carbon dioxide and water.

Both air and oxygen caused a slight shortening of the flame and the inner cone became more sharply defined, particularly in the latter instance. Hydrogen, carbon monoxide and carbon dioxide caused no visible change in the flame. Water proved very troublesome as a flame additive, it would not wet the glass tubing of the additive supply lines satisfactorily and was, therefore, difficult to vaporise. It was not possible to obtain results for more than 5 w/w % addition of distilled water. To enable higher concentrations to be tested small quantities of a surfactant, sodium lauryl sulphate ($Na\ (C_{12}H_{25})\ SO_4$), were added. This improved the wetting properties of the water and eased the evaporation problems. Two different concentrations, 0.005M and 0.01M, were used to make possible an assessment of the influence of the surfactant itself. In fact there was no significant difference between the two concentrations. The surfactant allowed additions of water up to 20 w/w % to be achieved, its presence caused a pinkish-orange colouration in the flame around the blue inner cone.

10.7.1. Smoke point

Hydrogen caused a substantial reduction in the air required to suppress carbon formation, its presence reducing the tendency for dehydrogenation of the methane to radicals to occur (fig. 65). Oxygen was even more effective, a 20% addition reduced the air required by more than 50%, the increased oxidation rate allowing little soot formation. Water and carbon dioxide had only slight effects on the smoke point but carbon monoxide behaved similarly to methane, promoting soot formation. It is probable that the carbon monoxide is to some extent preferentially oxidised to carbon dioxide causing a larger proportion of the methane to form soot than would otherwise be the case. It is unlikely that the carbon monoxide is a part of the soot forming mechanism since its own flame does not form soot (85).

10.7.2. Emissivity, temperature and radiance

Air, oxygen and hydrogen all caused reductions in the maximum emissivities of the flames. The reductions were almost linear with concentration (fig. 66). Oxygen was the most effective but not much more so than the others. This was because the contribution to the total emissivity by the soot emissivity was relatively low and so the maximum possible reduction was quite small; at the higher concentrations the total emissivity was approaching that of the gaseous products of combustion alone. In a flame, such as that of a higher paraffin, with a greater tendency to form soot the differences between the air, oxygen and hydrogen would have been more marked.

Water caused a very slight decrease in the maximum emissivity whereas carbon dioxide yielded a small increase. Carbon monoxide was again very similar to methane and the only one of these additives to achieve a significant increase.

None of these additives influenced the maximum flame temperature to a great extent (fig. 67). Water and the oxides of carbon reduced the maximum temperature a little at high concentrations whereas oxygen, air and hydrogen had the opposite effect. 5% oxygen caused the largest increase but this was not maintained at high addition rates.

The maximum radiances of the flames were not improved by any of these additives as much as by methane. The lower emissivities caused by the air, oxygen and hydrogen flames more than outweighed the slight increases in temperatures and resulted in reduced radiances (fig. 68).

These results indicate that the recirculation of combustion products is unlikely to yield large increases in the flame emissivity by virtue of their chemical composition, any improvement being brought about by carbon monoxide which would only be present in flue gases in significant quantities in a rather inefficient furnace. It is quite possible, however, that the high temperature of recirculated combustion products could have a greater influence by cracking of the methane.

Figure 70.

Smoke points with miscellaneous additives.

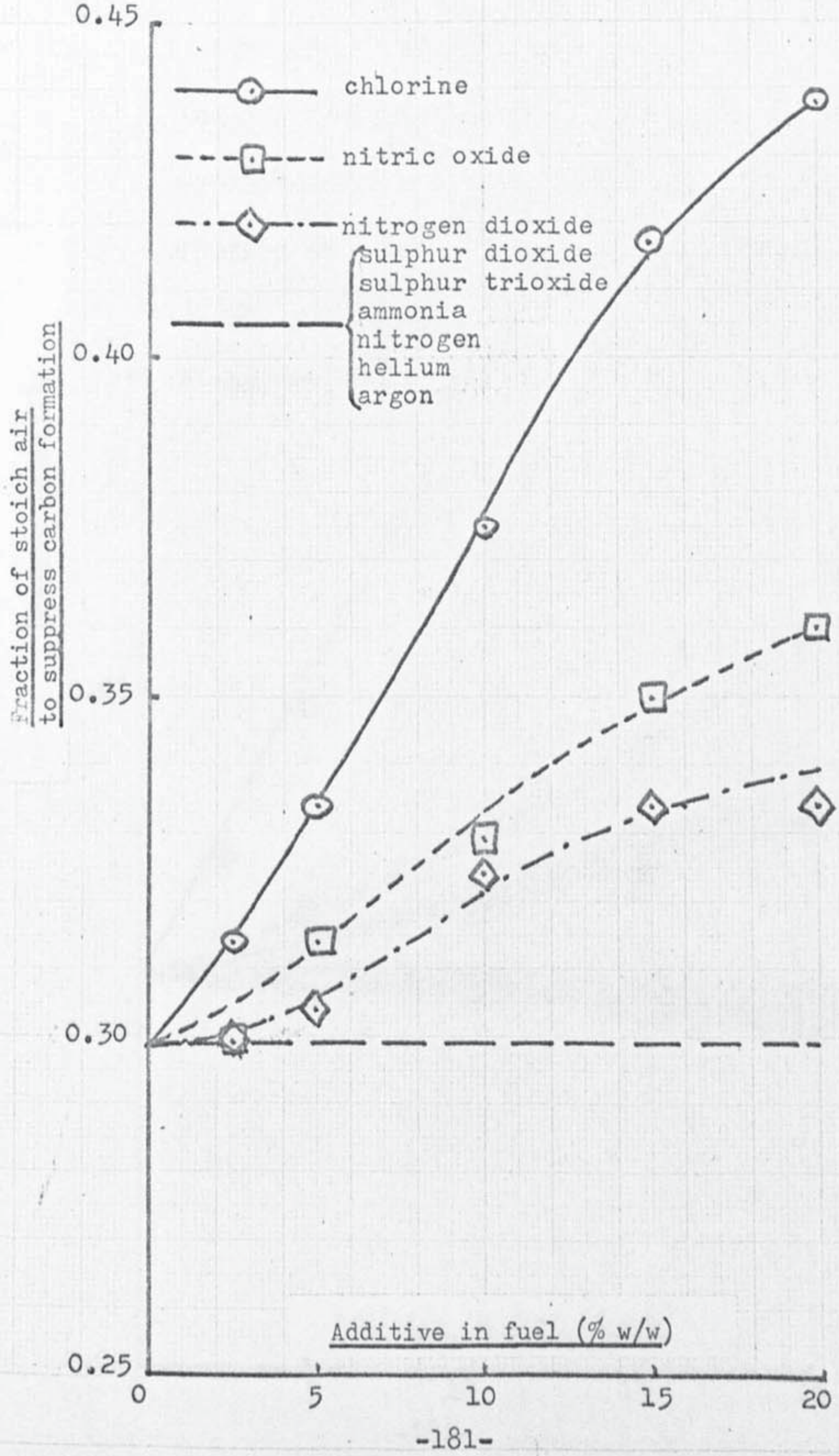


Figure 71.

Maximum emissivities with miscellaneous additives.

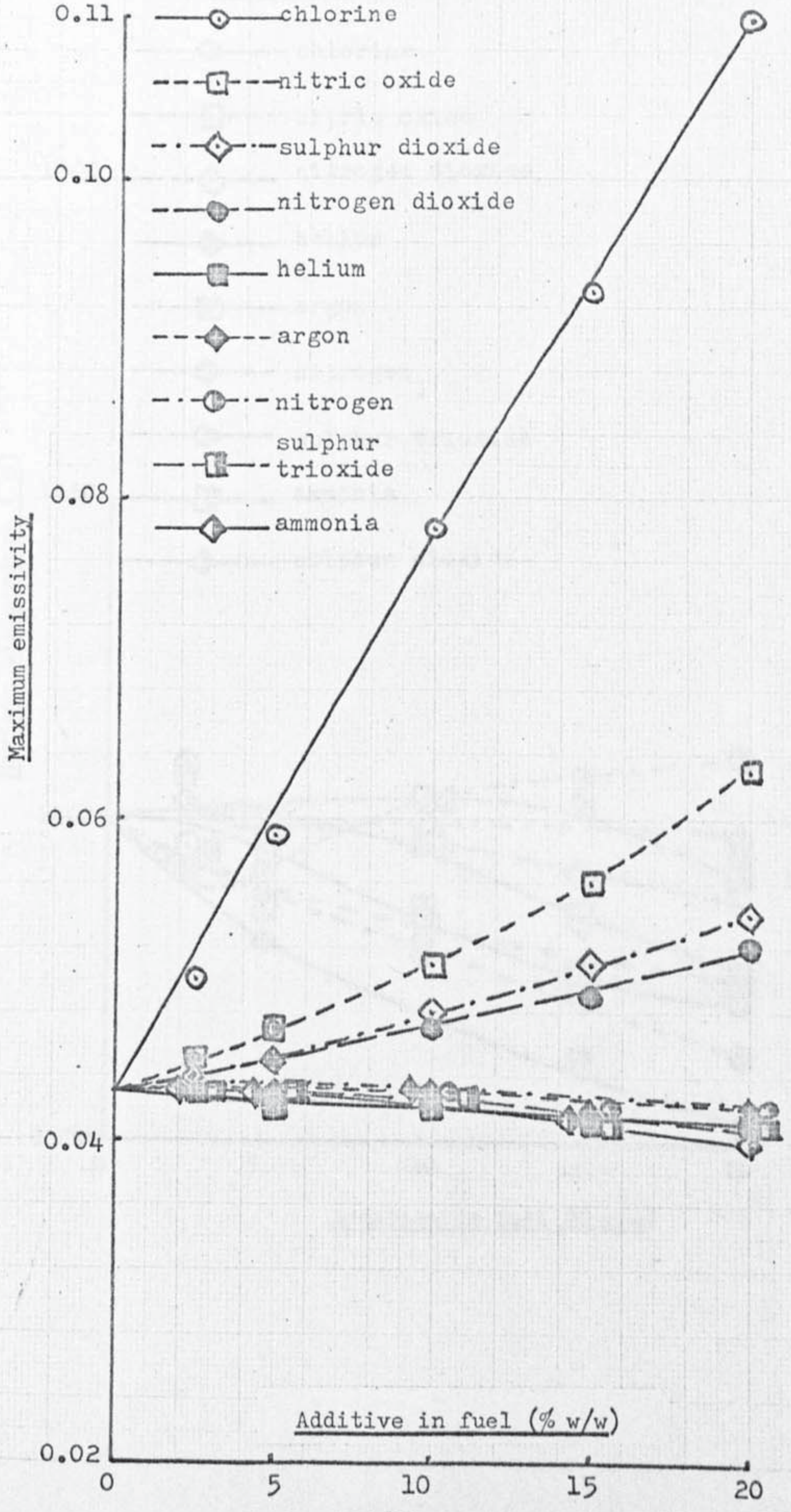


Figure 72.

Maximum temperatures with miscellaneous additives.

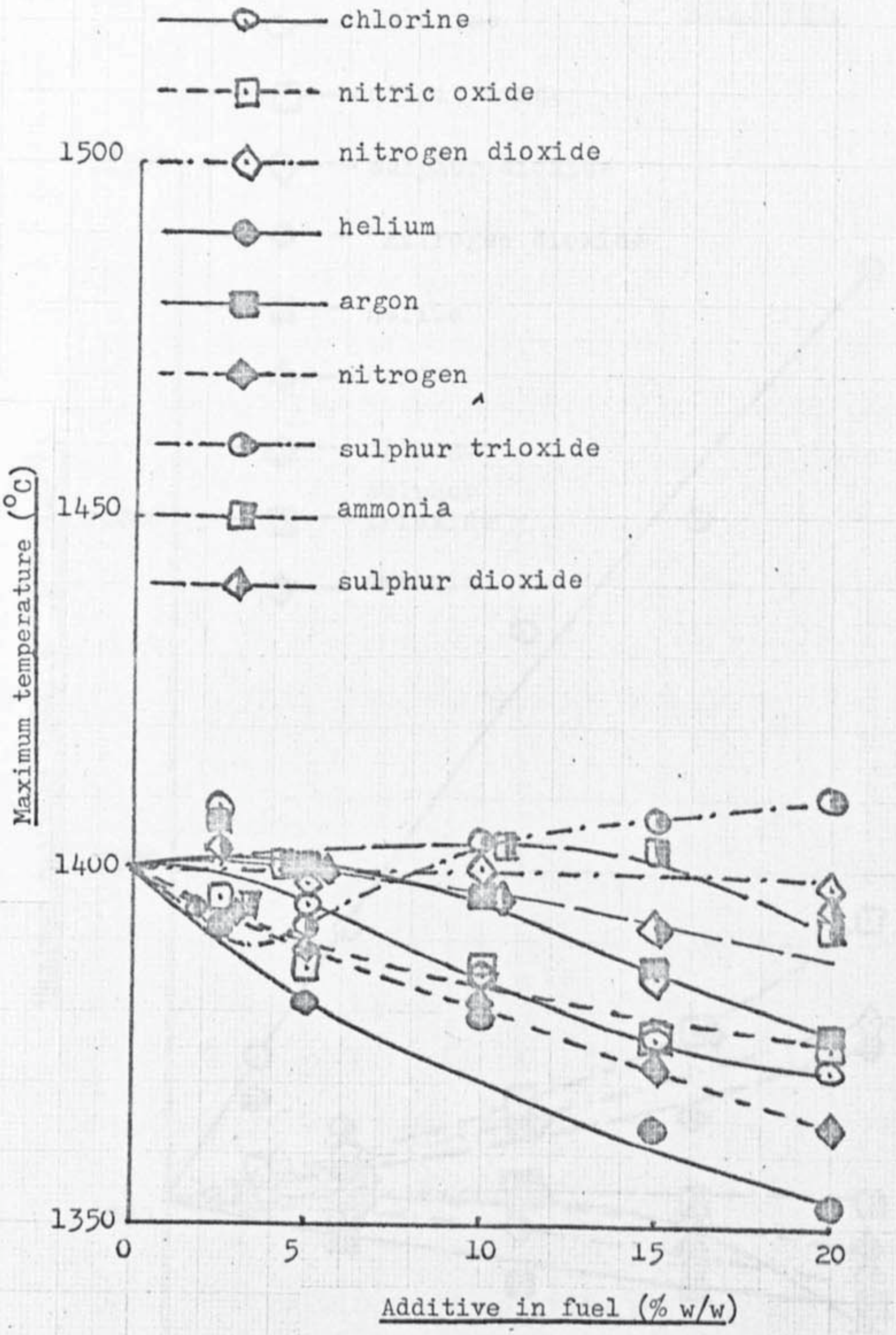
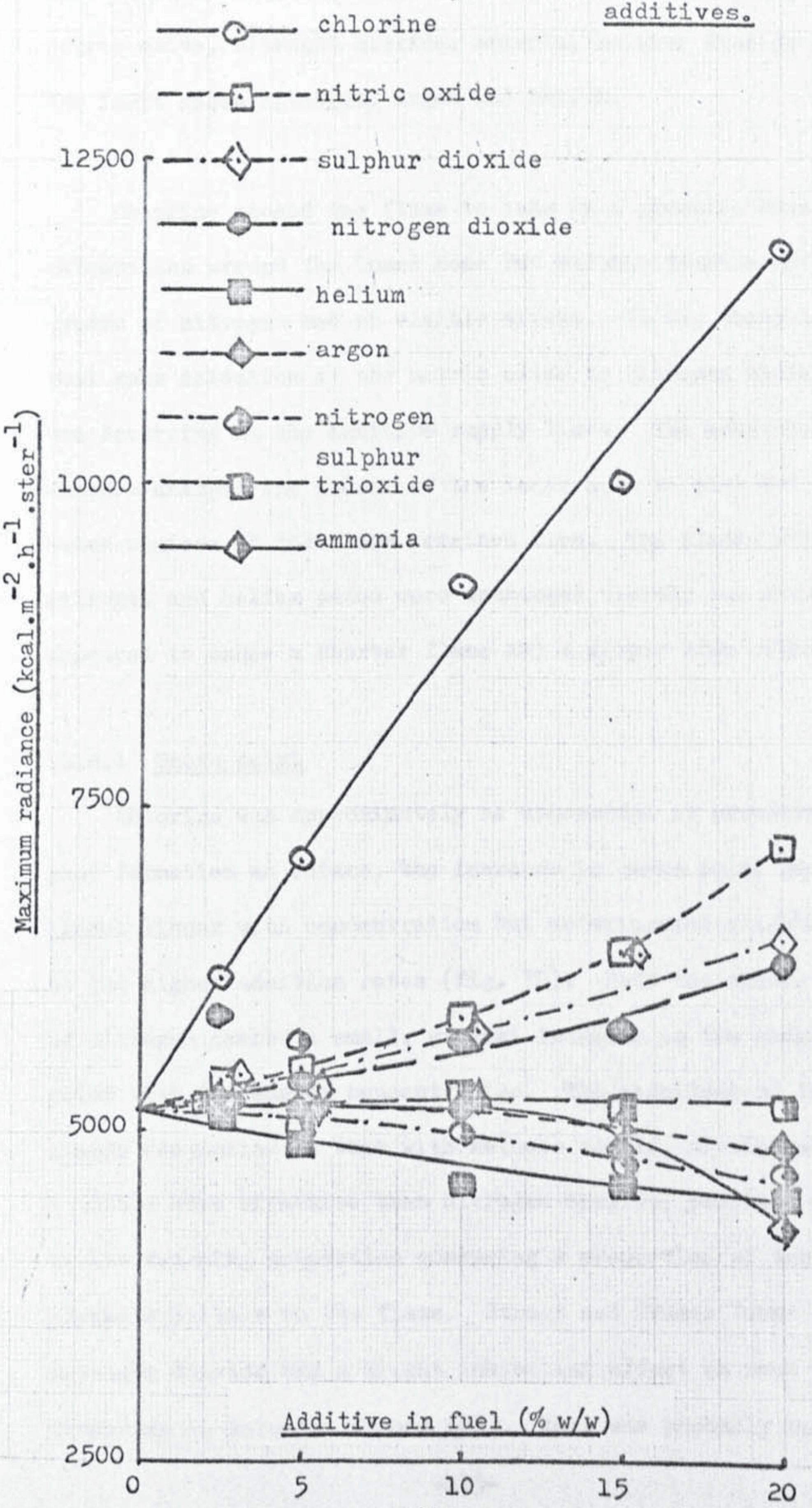


Figure 73.

Maximum radiances with miscellaneous additives.



10.8 Miscellaneous additives

Several other additives were evaluated but could not be classified under the previous headings. They were chlorine, nitric oxide, nitrogen dioxide, ammonia, sulphur dioxide and the inert gases nitrogen, argon and helium.

Chlorine caused the flame to take on a greenish blue colouration around the inner cone but sulphur dioxide and the oxides of nitrogen had no visible effect. It was observed that some oxidation of the nitric oxide to nitrogen dioxide was occurring in the additive supply lines. The addition of ammonia changed the colour of the inner cone to pink but the outer regions of the flame remained blue. The flames with nitrogen and helium added were unchanged visibly but argon appeared to cause a shorter flame and a deeper blue colour.

10.8.1 Smoke point

Chlorine was approximately as successful at promoting soot formation as butane, the increase in smoke point was almost linear with concentration but deteriorated slightly at the higher addition rates (fig. 70). Both the oxides of nitrogen caused a small, gradual increase in the smoke point with increasing concentration. The magnitude of the change was similar to that with methane itself, nitric oxide was a little more effective than nitrogen dioxide, possibly due to its reducing properties consuming a proportion of the oxygen available in the flame. Street and Thomas found that nitrogen dioxide had a slight inhibiting effect on soot formation in kerosene flames (85). This was probably due to the dissociation of the nitrogen dioxide to nitric oxide and oxygen,

$$2NO_2 \rightleftharpoons 2NO + O_2$$

the oxygen could then have its normal inhibiting effect. The lower temperatures of the small methane flame would have reduced the degree of dissociation.

The inert gases and sulphur dioxide had no significant effect on the smoke point. Street and Thomas found that nitrogen had a promoting influence on soot formation but they used much larger quantities, effectly reducing the oxygen content of the 'air' to as low as 13 v/v %. A nitrogen addition of 20 w/w % as defined earlier corresponds approximately to a reduction of the oxygen in the premixed air from 21 v/v % to 20.5 v/v %. The sulphur dioxide result agreed with that of Street and Thomas in contradiction to the work of Gaydon and Whittingham (74) who found that there was a suppression of the smoke point. The claim of the former that the quantity of soot formed was reduced was not confirmed, as will be seen the results for emissivity suggest that this was not the case.

10.8.2 Emissivity, temperature and radiance

Chlorine had a considerable effect on the maximum emissivity of the flame causing a linear increase with concentration reaching an emissivity of 0.11 at 20 w/w %

addition (fig. 71). As with the smoke point the behaviour was very similar to butane although the lower addition rates had slightly more effect than with the paraffin. The addition of the chlorine moved the point of maximum emissivity away from the burner but as with the other soot promoting additives the high values were achieved over short lengths of flame only.

Nitric oxide, nitrogen dioxide and sulphur dioxide all caused small increases in the maximum emissivity whereas the inerts and ammonia brought about very slight decreases. There was no significant variation among the inert gases.

Changes in the maximum flame temperature arising from the use of these additives were generally small and they all had a cooling effect (fig. 72). The degree of cooling by the inerts was inversely proportional to their molecular weights, helium having a greater influence than nitrogen which was in turn more effective than argon. This may have been due, in part, to the higher velocities of the combustion mixtures with the lighter gases creating turbulence and a more homogeneous flame without regions of extreme temperature. The Reynold's Number is not changed by the use of the different inerts, of course, and further work will be necessary to fully explain this phenomonon. The high emissivity of the chlorine flame in the absence of any additional input to compensate resulted in lower temperatures than for butane and the other paraffins.

The lower temperatures meant that the chlorine flames actually had lower maximum radiances than the ethane flames even though their emissivities were similar to those of flames with butane (fig. 73). This would not necessarily occur to the same extent with larger industrial scale flames. Sulphur dioxide and the oxides of nitrogen all achieved small increases in the maximum radiance. Ammonia lowered the radiance slightly, this was most marked at 15 w/w % and 20 w/w % concentrations. The inerts had little significant influence.

10.9 Sulphur trioxide

Following the work of Whittingham, Gaydon and Dooley (74, 75, 76) on sulphur trioxide with methane, ethane and coal gas and the work of Street and Thomas (85) on sulphur trioxide with benzene and kerosene flames it was anticipated that this additive would greatly enhance soot formation in the flame.

The sulphur trioxide was added to the flame by passing a suitable fraction of the air supply through a flask of oleum at the appropriate concentration and temperature for each addition rate to be achieved. The method was similar to that used by Gaydon and Whittingham.

It was found that the addition of sulphur trioxide in quantities up to 20 w/w % of the methane had no significant effect on the visual appearance of the flame nor on the measured quantities. This result was unexpected and so even larger addition rates, up to 40 w/w %, were tested but again with no increase in soot formation.

At this stage it was decided to determine the effect of sulphur trioxide on a flame which was already on the point of forming soot. A richer flame than normal was established (air flow 0.088 $l.s^{-1}$, methane flow 0.0238 $l.s^{-1}$) and sulphur trioxide was added, again with no improvement in the radiating properties. The sulphur trioxide was added to the methane instead of the air but this was also unsuccessful. The qualitative effects of these and other experiments involving sulphur trioxide are summarised in Appendix 6.

In order to ensure that the sulphur trioxide was being added satisfactorily and also to check some of the earlier work a town gas supply was run to the test rig, the gas was temporarily injected directly into the burner mixing chamber. A non-luminous town gas flame was set up and sulphur trioxide was added to the air supply. Soot formation was observed immediately. The appearance of the flame was quite different to that of the other luminous flames observed in that the yellow colouration due to the soot was present right from the base of the flame at the rim of the burner. At this time no measurements were made on the flame. It was thought that the sulphur trioxide was causing one of the hydrocarbons, other than methane, present in the town gas to form soot, ethane and propane were the only hydrocarbons which could be detected. It was decided, therefore, to contaminate the normal methane supply with these gases in turn to confirm or deny this theory. The sulphur trioxide was found to have no effect on these mixtures of methane and ethane or methane and propane. The problem of which component of the town gas was taking part in the soot formation remained. A simulated town gas was made up from pure components in an attempt to establish whether one of the major components was responsible or not. The composition was:

CO_2	12.4 v/v %
CO	1.5
H_2	53.6
N_2	0.5
CH_4	31.2
C_2H_6	0.7
C_3H_8	0.1
	100.0 v/v %

This gas was fed to the rig at the normal methane inlet point and therefore passed through the carbon dioxide and moisture absorber. The addition of sulphur trioxide caused no change in the visual appearanceof the flame, indicating that the soot formed in the genuine town gas flame was caused by a trace component.

It was considered necessary to make some measurements of this descrepancy so the town gas was reconnected but this time at the methane inlet, prior to the absorber, and not directly at the burner. On this occasion not even the genuine town gas was affected by the addition of the sulphur trioxide. Rechecking, the town gas was injected at the burner and the yellow colouration was observed again throughout the flame. Admitting the simulated town gas at this point yielded no increased soot formation. It was clear that the trace component of the town gas which caused soot formation with sulphur trioxide was absorbed by either silica gel or carbosorb. The town gas flow was 0.0326 $l.s^{-1}$, the air flow was 0.0351 $l.s^{-1}$.

The carbosorb was removed from the absorber and town gas was passed through again, there was noyellow colouration when sulphur trioxide was added. The silica gel was replaced by carbosorb and the yellow colouration returned. The important trace component was, therefore, absorbed by silica gel and so could have been water. Town gas was passed through silica gel and then bubbled through water while sulphur trioxide was added to the air, there was no soot formation indicating that water was not the trace component.

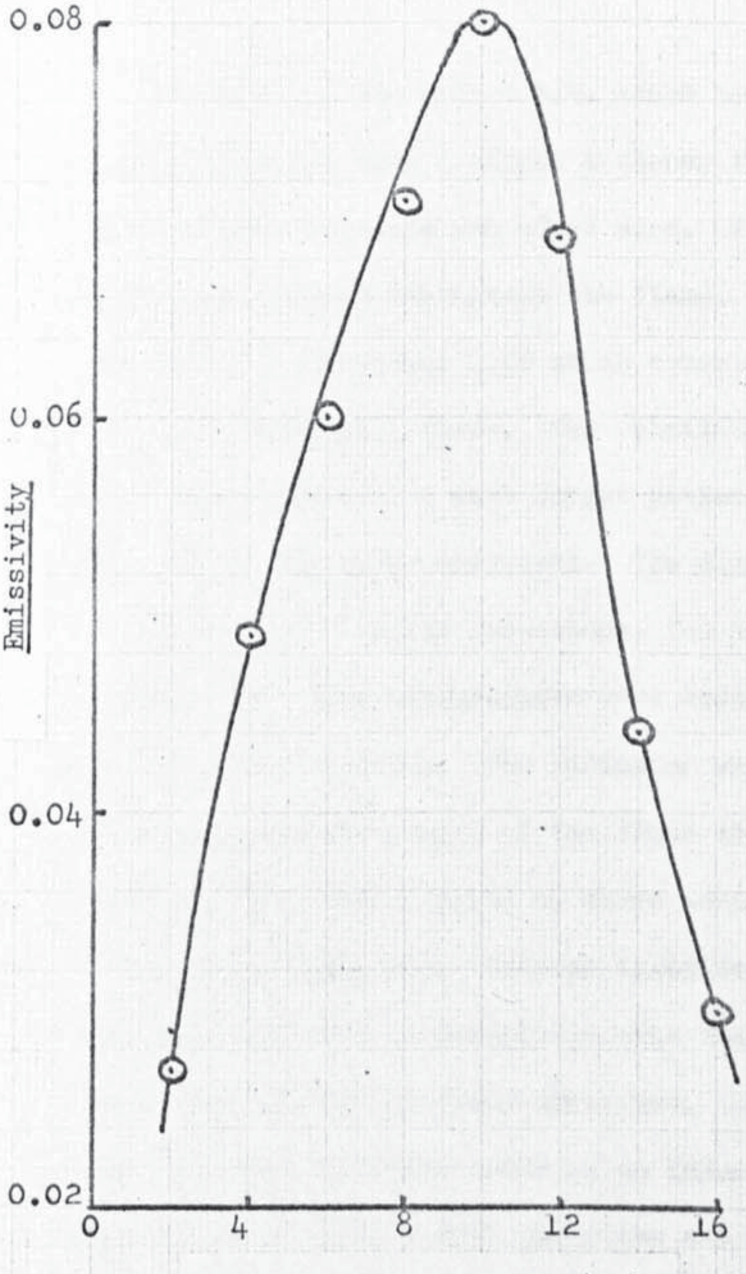
Three other possibilities were considered at this stage. The town gas supply to the laboratory originated at a gas works using I.C.I. steam-naphtha reformers and Gas Council recycle hydrogenators. The rich gas produced by these hydrogenators is passed through a benzene wash to remove aromatics such as naphthalene, the town gas could, therefore, have contained a trace of benzene and it was known that sulphur trioxide caused copious quantities of soot in benzene flames (85). The final stage of the gas-making process is a drying plant utilising triethylene glycol as an absorbant. The town gas could have been contaiminated by small quantities of triethylene glycol. Before the town gas is distributed a small proportion of odorant is added since it has no inherent smell. Usually about 1 $lb/10^6 sft^3$ of tetra-hydrothiophene (t.h.t.) is used and some of this was present in the town gas used in the tests.

The town gas was again passed through the silica gel to remove the important component and then through benzene, triethylene glycol and t.h.t. in three different experiments. All three gave slight yellow colourations at the flame tip, even without sulphur trioxide. When sulphur trioxide was added to the air supply there was no significant change in the flames with benzene or triethylene glycol but with t.h.t. there was a strong yellow colouration throughout the flame just as with the untreated town gas.

This evidence suggests that the soot formation caused by the addition of sulphur trioxide to coal gas, previously observed by others, was due to the presence of a compound or compounds

Figure 74.

Variation of emissivity with height above burner for sulphur trioxide (20% w/w) and tetrahydrothiophene (trace) as additives.



similar to t.h.t.. At the time of the previous work, 1945 - 1947, there was no oil reformed gas and no added odorant but the coal gas would have included sulphur containing compounds similar to t.h.t., e.g. thiophene, dihydrothiophene, produced during the carbonisation of the coal.

Tests were made with t.h.t. added to the usual methane flame, there was only a slight tendency for the flame to soot until sulphur trioxide was added also. This resulted in a yellow colouration throughout the flame. The maximum emissivity recorded was 0.08 which corresponds to approximately 0.8 in an industrial flame. The relatively high emissivities were maintained over a much larger proportion of the flame than with any of the other additives. The absolute values, however, were not as high as for iso-octane, for example, over this length. The flame temperatures were reduced by the use of the two additives together. The radiation was increased almost uniformly over the length of the flame though the highest increases were not as great as those achieved by the addition of paraffins (fig. 74). Sulphur trioxide and t.h.t. achieved a greater increase in emissivity over the early part of the flame than any of the other additives. Sulphur trioxide, however, would be undesirable as an industrial additive due to handling difficulties with the oleum and pollution problems with the flue gases.

Figure 75.

Plot of maximum emissivity against smoke point for methane, ethane, propane, commercial propane and butane at all concentrations.

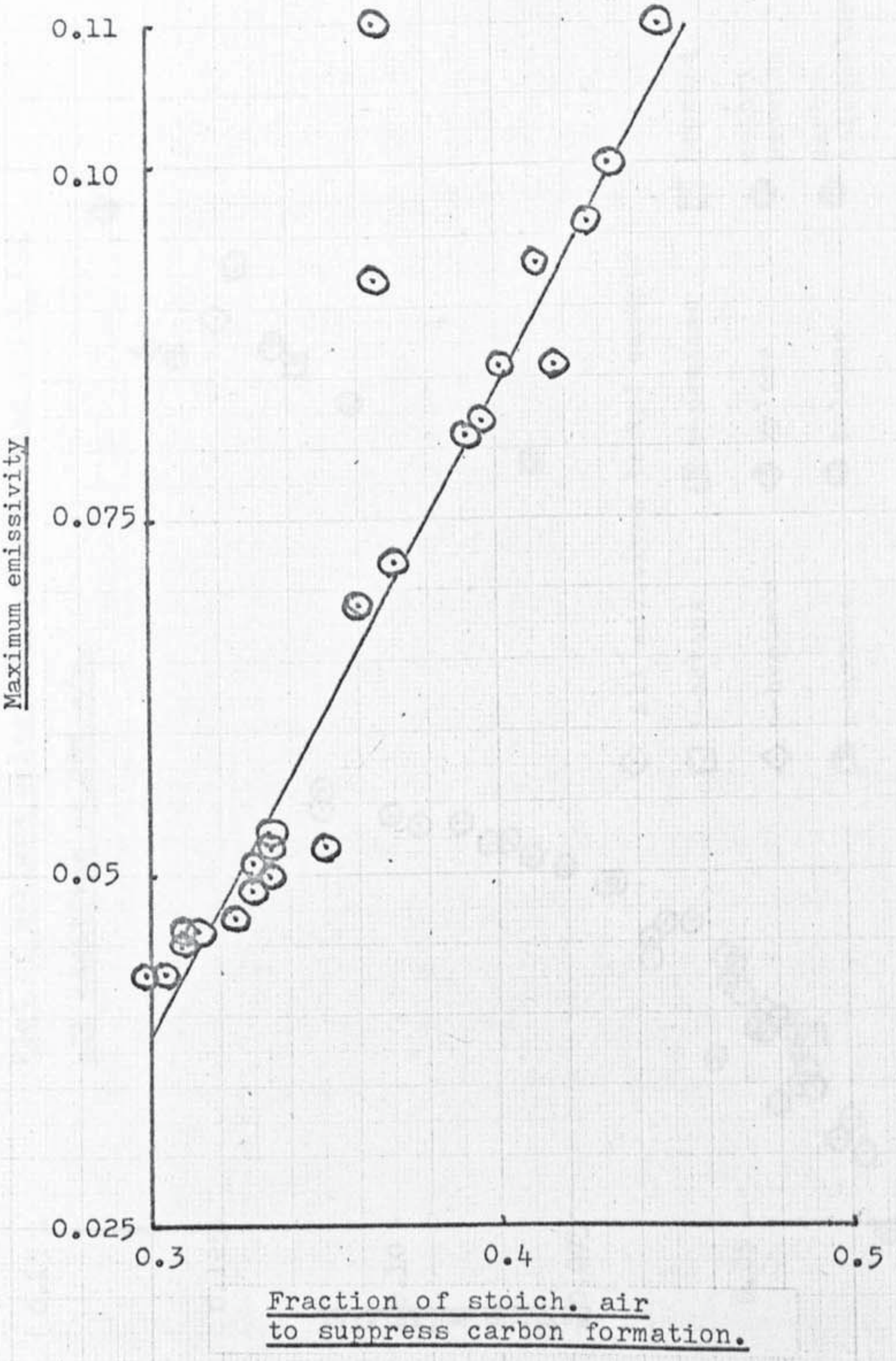
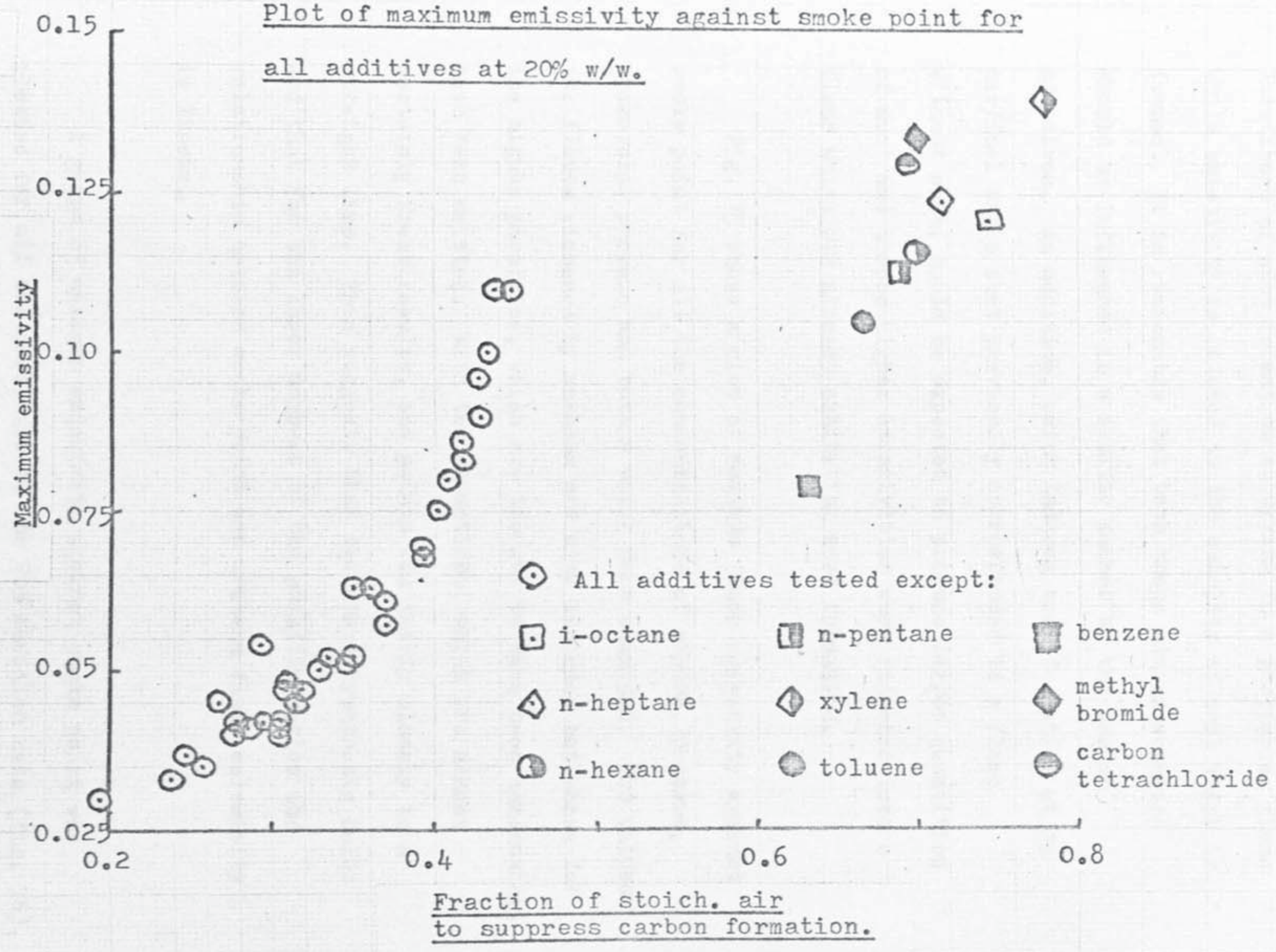


Figure 76



Plot of maximum emissivity against smoke point for all additives at 20% w/w.

10.10 The relationship between smoke point and emissivity

The smoke point can be considered as a measure of the likelihood of soot formation occurring in a particular flame while emissivity is related to the quantity of soot which is formed. It is reasonable that both these characteristics should be influenced in a similar manner by the use of additives. An additive, which induces soot formation at an air/fuel ratio that previously corresponded to a flame without soot, could be expected to produce larger quantities of soot and thence higher emissivities when injected into a flame which was already exhibiting soot formation.

Fig. 75 shows a plot of maximum flame emissivity against smoke point for all the concentrations of ethane, propane, commercial propane and butane which were examined. The values for flames richened by methane are also included but those for the higher paraffins, which are thought to have been condensing, have been omitted. With two exceptions, which are almost certainly freak results, the points lie fairly closely to a straight line. This suggests that the above hypothesis holds and that for the lower members of the paraffin series the relationship between smoke point and maximum flame emissivity is linear.

A graph of maximum emissivity against smoke point was plotted for all the additives at the 20% addition rate (fig. 76). The higher paraffins and the aromatic additives, which may also have condensed to some extent, together with methyl bromide

Figure 77.

Plot of maximum emissivity at 20% w/w addition against number of C atoms per molecule of additive.

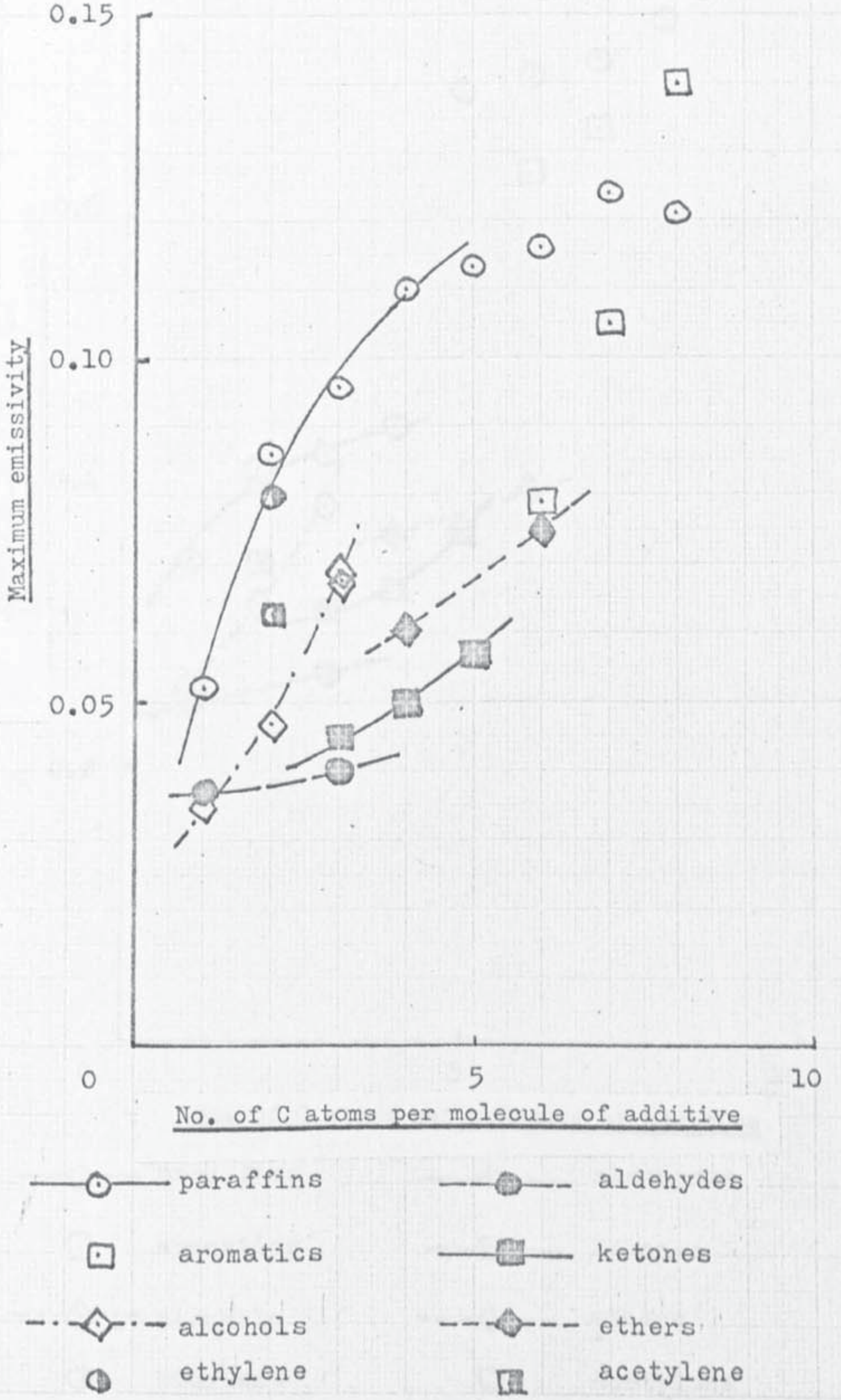
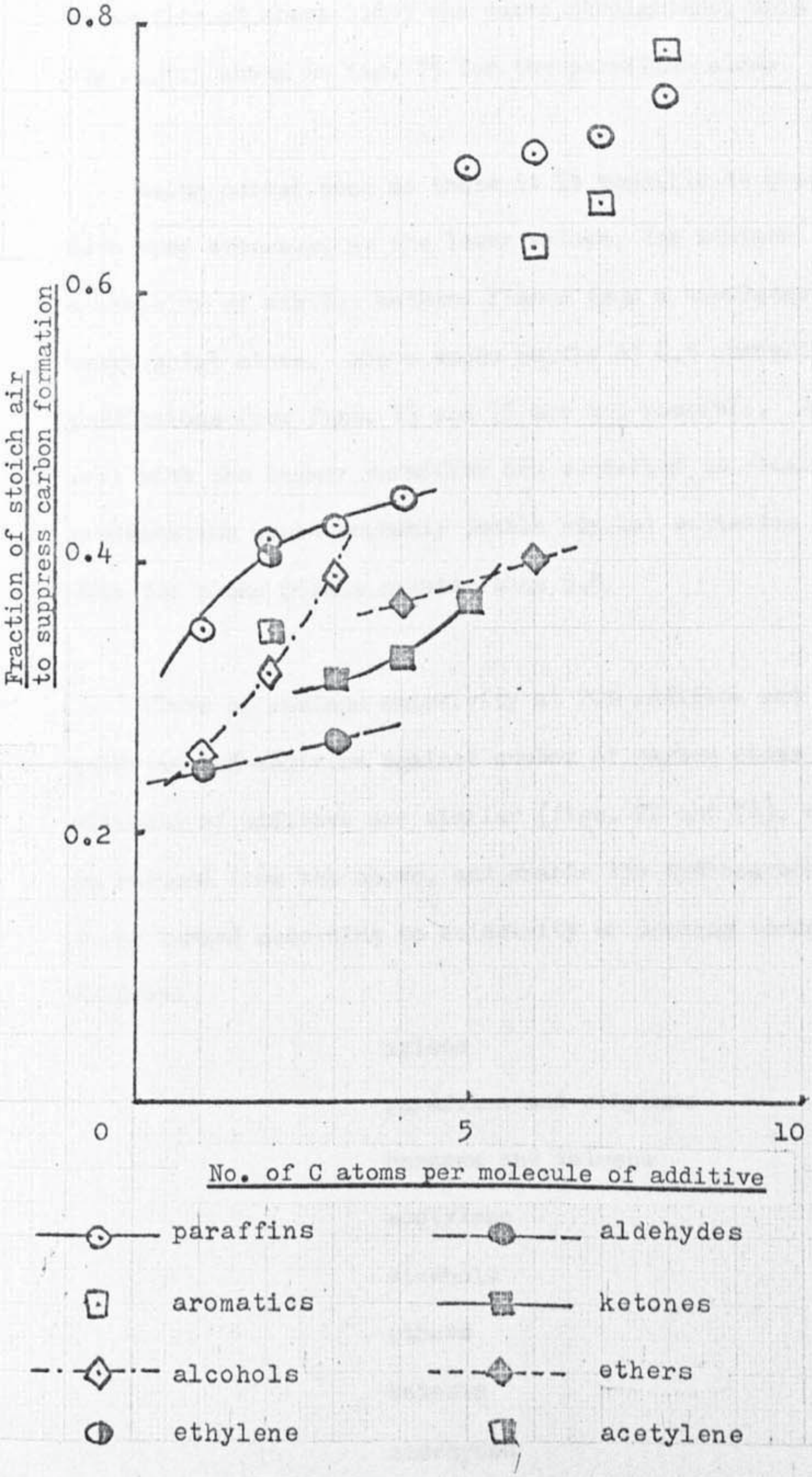


Figure 78.

Plot of smoke point at 20% w/w addition against number of C atoms per molecule of additive.



and carbon tetrachloride do not show the same behaviour as the rest of the additives which lie approximately on a smooth curve. The corresponding points for the other concentrations also lie close to this curve. Above an emissivity of about 0.055 the curve straightens, this being the region shown in fig. 75 for the paraffins alone.

Using curves such as these it is possible to predict with some accuracy, at the lower values, the maximum emissivity of similar methane flames from a knowledge of the smoke point alone. Above smoke points of 0.5 quantitative predictions from figs. 75 and 76 are not possible. Further work with the higher paraffins and aromatics to eliminate condensation would probably enable similar estimates to be made for smoke points greater than 0.5.

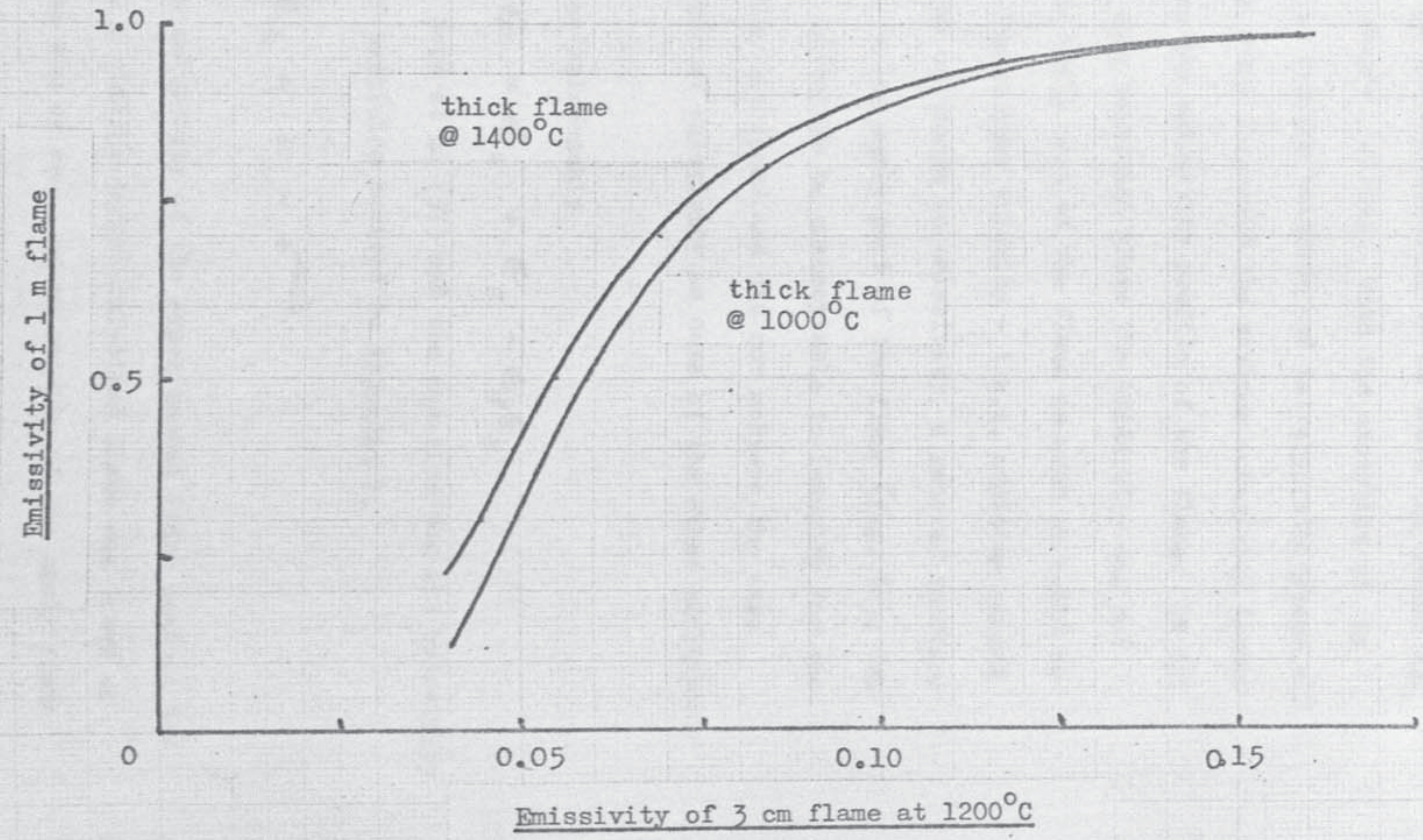
Plots of maximum emissivity at 20% addition and smoke point at 20% addition against number of carbon atoms per molecule of additive are similar (figs. 77 and 78), as can be deduced from the above, and enable the hydrocarbon additives to be ranked according to emissivity or sooting tendency as follows:

xylene
paraffins and ethylene
benzene and toluene
acetylene
alcohols
ethers
ketones
aldehydes

Of the hydrocarbons tested only methanol, formaldehyde and propionaldehyde caused a decrease in maximum emissivity and a lowering of the smoke point.

For estimating the influence of additives on the emissivity of a flame, the feasibility of measuring the smoke point as a first approximation of the relative effects, instead of measuring the emissivity itself, will be of considerable benefit.

Figure 79 Comparison of emissivities of similar thick and thin flames (section 10.11)



10.11 Scale-up

The emissivity of the methane flame without an additive rose to a peak at approximately 10 cm above the burner and declined at greater heights. With the exception of the combination of sulphur trioxide and tetrahydrothiophene all the additives which increased the maximum emissivity tended to exaggerate the emissivity profile of the flame. In all but the one case mentioned above the emissivity was not raised in the early part of the flame as much as would be desirable. The sulphur trioxide - t.h.t. addition caused the right kind of change in emissivity, a general increase particularly in the early part of the flame (fig. 74), but would almost certainly be unacceptable to industry for the reasons already mentioned and did not achieve the same absolute values of emissivity as some of the other additives.

Using the relationship

$$\epsilon = \epsilon_s + \epsilon_g - \epsilon_s \cdot \epsilon_g$$

developed by Sato et al (37) and the equation for the emissivity of a cloud of particles derived in Appendix 1,

$$\epsilon_s = 1 - e^{-k.L}$$

a plot of the emissivity of the experimental flame against the emissivity of a similar industrial-sized flame was drawn up (fig. 79). As can be seen, an emissivity of the small flame of about 0.1 would be necessary to achieve an emissivity of 0.9 in the larger flame, 1 m thick. At the addition rates used, such an emissivity was attained by butane, n-pentane, n-hexane, n-heptane, i-octane, toluene, xylene, methyl bromide, carbon tetrachloride and chlorine. The flame was considered to be a maximum of 16 cm long though this varied with the additive being used. Xylene and methyl bromide gave the greatest length of flame above an emissivity of 0.1, approximately 7 cm in both cases, slightly less than half the total and falling short of the 75 - 100% of the flame length which was considered desirable.

The higher paraffins and the aromatic hydrocarbons caused lower maximum flame temperatures than the lower paraffins. This was partly due to the relatively high emissivities leading to increased radiation from the flame and consequent cooling. In addition the efficiency of combustion of the flame was reduced by the formation of the soot and some of the heating potential of the flame was not realised, again resulting in lower temperatures. The latter effect was exaggerated by the condensation of some of the additives, the thermal cracking of the droplets probably resulted in larger soot particles than those formed according to a synthesis mechanism and the ultimate combustion of these particles would have been less likely with a resultant loss in the heat released in the flame. This cooling would occur in similar industrial-sized flames but it can be seen that for all these additives the simultaneous increase in emissivity was sufficient to yield a net increase in radiance compared with the pure methane flame.

11. Conclusions

1. The following additives were found to increase the maximum emissivity of the methane flame: ethane; propane; butane; n-pentane; n-hexane; n-heptane; i-octane; benzene; toluene; xylene; acetylene; ethylene; cyclohexane; chloroform; carbon tetrachloride; methyl bromide; ethanol; n-propanol; i-propanol; methyl ethyl ketone; methyl i-propyl ketone; di-ethyl ether; di-i-propyl ether; carbon monoxide; carbon dioxide; nitrogen dioxide; sulphur dioxide; nitric oxide; chlorine and a combination of sulphur trioxide with tetrahydrothiophene.

2. The following additives caused an increase in the air required to prevent soot formation in the flame: ethane; propane; butane; n-pentane; n-hexane; n-heptane; i-octane; benzene; toluene; xylene; acetylene; ethylene; cyclohexane; chloroform; carbon tetrachloride; methyl bromide; ethanol; n-propanol; i-propanol; methyl ethyl ketone; methyl i-propyl ketone; di-ethyl ether; di-i-propyl ether; carbon monoxide; carbon dioxide; nitrogen dioxide; nitric oxide and chlorine.

3. The following additives decreased the maximum emissivity of the methane flame: methanol; formaldehyde; propionaldehyde; oxygen and hydrogen.

4. The following additives caused a reduction in the air necessary to prevent soot formation: methanol; formaldehyde; propionaldehyde; water; oxygen and hydrogen.

5. The following additives had no significant influence on the maximum emissivity of the methane flame: hydrogen chloride; trichloro-trifluoroethane; acetone; water; helium; nitrogen; argon; ammonia and sulphur trioxide.

6. The following additives caused no significant change in the air necessary to prevent soot formation: hydrogen chloride; trichloro-trifluoroethane; acetone; helium; nitrogen; argon; ammonia; sulphur dioxide and sulphur trioxide.

7. The magnitudes of changes in emissivity and air required to suppress soot formation are dependant not only upon the quantity of additive used but also on the molecular structure of the addtive. The organic compounds tested may be ranked in order of decreasing effectiveness as follows:

xylene
paraffins and ethylene
benzene and toluene
acetylene
alcohols
ethers
ketones
aldehydes

8. The highest members of the homologous series produced the largest increases in emissivity and critical air concentration when used as additives, though not necessarily the largest increases in radiance.

9. In the paraffin series the difference in effectiveness between adjacent homologues is more marked at the lower end than at the high end.

10. The addition of ethane or higher paraffins has a much greater influence than supplying extra methane to the flame.

11. The increases in emissivity and critical air concentration caused by the addition of alkyl halides are greater for higher degrees of halation of the additive.

12. Brominated hydrocarbons have a greater influence than chlorinated hydrocarbons.

13. The greatly increased soot formation in coal gas and town gas flames after the addition of sulphur trioxide is due to reaction between the latter and traces of organic compounds containing sulphur which are present in these fuels.

14. Those additives which cause the greatest increases in emissivity also reduce the temperatures of the flames but there are, nevertheless, net gains in radiance.

15. None of the additives tested produced a flame which would be entirely suitable for industrial use. Satisfactory peak emissivities of 0.1 were obtained by the use of butane, n-pentane, n-hexane, n-heptane, i-octane, toluene, xylene, methyl bromide, carbon tetrachloride and chlorine but such high levels were not maintained over a large fraction of the flame. The mixture of sulphur trioxide and tetrahydrothiophene was the only additive to give relatively large increases in the emissivity in the early part of the flame, the absolute values were not sufficiently high, however.

16. The use of additives affects the maximum emissivity and the air concentration necessary for suppression of soot formation in similar ways. The relationship between the two effects is linear for the lower paraffins.

17. This makes it possible for experimentally determined values of the critical air concentration to be used for predicting the relative effects of additives on the emissivity.

12. Recommendations for future work

Since the commencement of this work, considerable effort has been applied to the design and development of the two-stage precracking burners referred to in section 2.3.2.. These have proved successful and are being adopted for a wide range of applications so that the need for additives to raise the emissivities of flames has been reduced. The following work would be of interest however:

1. Evaluation of the effects of higher aromatic compounds such as derivatives of naphthalene, e.g. tetralin, decalin, 1-methyl naphthalene.

2. Checks on the accuracy of the predictions of the scale-up of emissivity, preferably using a small furnace with a flame thickness of at least 0.5 m.

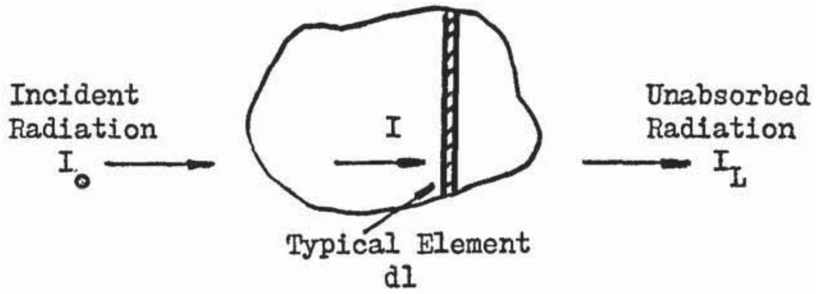
3. Experiments on the effects of the paraffins on a larger flame to establish if the gains in radiance are less with the higher members of the series, as occurred in the small flame.

4. Further experimentation with the liquid paraffins, taking further precautions to eliminate condensation in the burners, to find if the limits of the smoke point - emissivity relationship can be extended beyond butane.

5. Further experimentation on the effects of the addition of inert gases on the aerodynamic properties of flames with particular emphasis on their stability.

13. Appendices

Appendix 1 The emissivity of a cloud of particles



$$\frac{dI}{I} = -A_p . \frac{\text{Area of particles @ } 90^\circ \text{ to radiation}}{\text{Area of element @ } 90^\circ \text{ to radiation}}$$

$$= -A_p . \frac{\frac{\pi . d_p^2}{4} . (N_p/\text{volume of element})}{\text{Area of element}}$$

but $\frac{\text{volume element}}{\text{area of element}}$ = thickness of element, dl

$$\frac{dI}{I} = \frac{-A_p . \pi . d_p^2 .}{4} \quad N_p . dl$$

$$N_p = \frac{\text{Mass concentration of particles}}{\text{Mass of one particle}}$$

$$= \frac{6. c}{\rho . \pi d_p^3}$$

$$\frac{dI}{I} = \frac{-A_p . \pi . d_p^2 .}{4} \; dl. \; \frac{6.c}{\rho . \pi . d_p^3}$$

For a finite thickness L,

$$\int_0^L \frac{dI}{I} = - \int_0^L \frac{3}{2} . \frac{A_p . c.}{\rho . d_p} \; dl$$

$$\ln I - \ln I_o = - \left[\frac{3}{2} . \frac{A_p . c.}{\rho . d_p} \, l \right]_0^L$$

$$\ln \frac{I}{I_o} = -\frac{3}{2} \cdot A_p \frac{c}{\rho} \cdot \frac{L}{d_p}$$

For particles much smaller than the wavelengths being considered, it has been shown that scattering of the radiation may be disregarded (39, 40, 41, 42, 49). The average diameter of soot particles has been shown to be about 0.04μ(38) compared to the significant region of the infra red from approximately 1.0 to 15μ when considering heat transfer. Ignoring the effects of scattering will not in this case incur serious error. Furthermore, it has been shown that the possibility of reflection by soot particles may also be disregarded (43, 44, 45, 46, 47). Hence for soot particles,

$$A_p = E_p = 1$$

and for the cloud as a whole

$$\epsilon_s = \qquad = 1 - \frac{I}{I_o}$$

$$\underline{\epsilon_s = 1 - \exp(-\frac{3}{2} \cdot \frac{c}{\rho} \cdot \frac{L}{d_p})}$$

Appendix 2

The following computer program was used for curve fitting.

```
      DIMENSION X(200), Y(200), R(200), W(200),
               A(21), P(510)
      INTEGER WTS, STORE (21)
      READ (1,100) M,NMAX,WTS
  100 FORMAT (3IO)
C
C     TEST FOR NUMBER OF DATA POINTS>200
C
      IF (M-200) 4, 4, 5
  5   WRITE (2,200)
  200 FORMAT (/49 H ARRAYSIZE OF X, V, R AND W
     1ONLY DIMENSIONED TO 200, /60H THE FIRST
     2200 POINTS HAVE THEREFORE BEEN TAKEN AND
     3ANALYSED, /)
      M=200
C
C     TEST FOR DEGREE 20
C
  4   IF (NMAX -20) 1, 1, 2
C
C     INCREASE NMAX BY 1 TO FORM NEW NMAX
C
  1   NMAX = NMAX + 1
      GO TO 3
C
C     NMAX>OR EQUAL TO 20, NEW NMAX SET TO 21
C     OR M WHICHEVER IS THE SMALLER
C
  2   NMAX = 21
      NMAX = MINO (NMAX,M)
  3   MM = 5* NMAX + 2*M + 3
C
C     TEST FOR FORMAT 1 OR 2
C
      IF (WTS -2) 10, 11, 10
  11  DO 6 I = 1,M
C
C     READ IN DATA POINTS + FREQUENCY
C
      READ (1,101) X (I), Y(I), W(I)
  101 FORMAT (3FO.O)
  6   CONTINUE
      GO TO 140
  10  DO 12 I=1,M
C
C     READ IN DATA POINTS
C
  12  READ (1,101)X(I),Y(I)
  140 P(3)  = 0.0
      P (4) = 1.0
      P (5) = WTS-1
      P (1) = -1.0
```

```
      SUMX2 = 0
      SUMY  = 0
      SUMX  = 0
      DO 17 I=1,21
 17   STORE (I) = I-1
      DO 15 I=1,M
C
C     SUMMATION OF X AND Y POINTS
C
      SUMX = SUMX + X(I)
      SUMY = SUMY + Y(I)
 15   CONTINUE
C
C     CALCULATION OF MEAN X AND MEAN Y
C
      SUMX = SUMX/M
      SUMY = SUMY/M
      WRITE (2,206) SUMX, SUMY, M
 206  FORMAT (1H1,/////,8H MEANX = ,E21.12,
     14X,7H MEANY = ,E21.12, //, I4, 23H
     2PAIRS OF X AND Y INPUT)
      IDEG = NMAX -1
      WRITE (2,201) IDEG
 201  FORMAT (41H0 COEFFS FOUND FOR A
     1POLYNOMIAL OF DEGREE ,I3,//)
C
C     CHECK FOR OVERFLOW
C
      CALL OVERFL(I)
      IF (I-1) 155, 155, 156
 155  WRITE (2,225)
 255  FORMAT (//,19H** OVERFLOW SET ***,//)
 156  DO 7 I=1,NMAX
C
C     SCIENTIFIC SUBROUTINE CALLED IN A LOOP
C     FROM 1 to NEW NMAX
      CALL F40FORPL (M,NMAX,MM,X,Y,
     1R,W,A,P)
C
C     DEGREE 0 INFORMATION NOT CALCULATED
C
      IF (I-1) 7,7,16
 16   SUMSQ = 0.0
      DO 13 N=1,M
      YIJ = A(1)
      DO 14 II = 2,I
      IF (X(N)-0.0)8,14,8
 8    YIJ = TIJ + A(II) *X(N)**(II-1)
C
C     CALCULATION OF Y FROM CURRENT EQUATION
C     USING EACH X(INPUT)
 14   CONTINUE
C
C     SUMMATION OF Y(INPUT) - Y(CALCUIATED) **2
C
      SUMSQ = SUMSQ+(Y(N)-YIJ)*(Y(N)-YIJ)
 13   CONTINUE
      J=I-1
```

```
    WRITE (2,207)J,SUMSQ
207 FORMAT (//,8H DEGREE,I3,/,11H -----
   1------,/,27H SUM OF SQUARED
   2DEVIATIONS = ,E21,12,/)
    WRITE (2,203)((STORE (K),A(K)),K=1,I)
203 FORMAT (1X,I3,2X,E21.12)
7   CONTINUE
9   WRITE (2,204)
204 FORMAT (///,15H END OF PROGRAM)
    STOP
    END
```

Appendix 3 Calibration data.

Figure 80.

Calibration curves for scalamp.

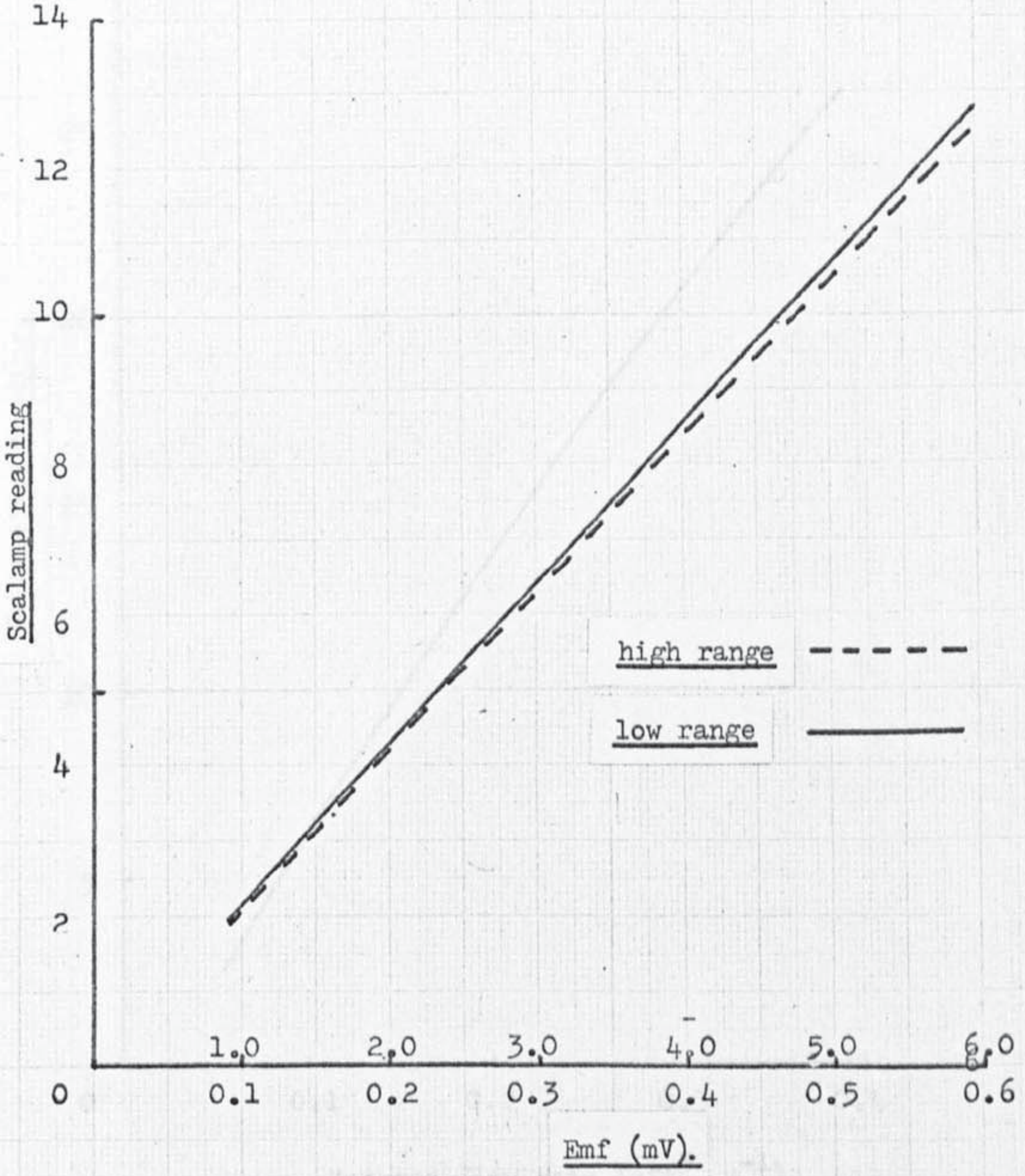


Figure 81.

Calibration curve for methane rotameter.

Metric 7X-dural.

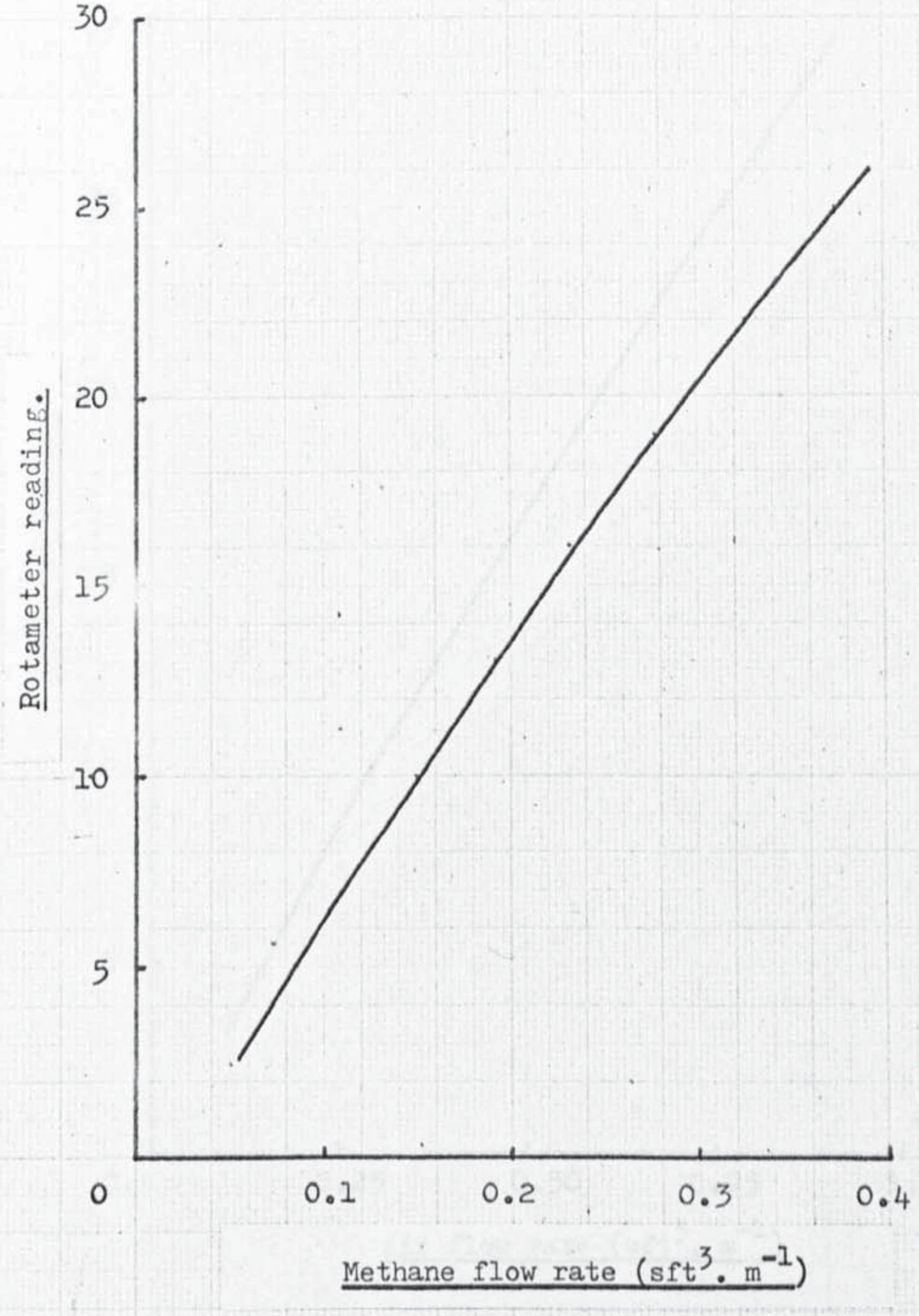


Figure 82.

Calibration curve for air rotameter.

Metric 10P-dural.

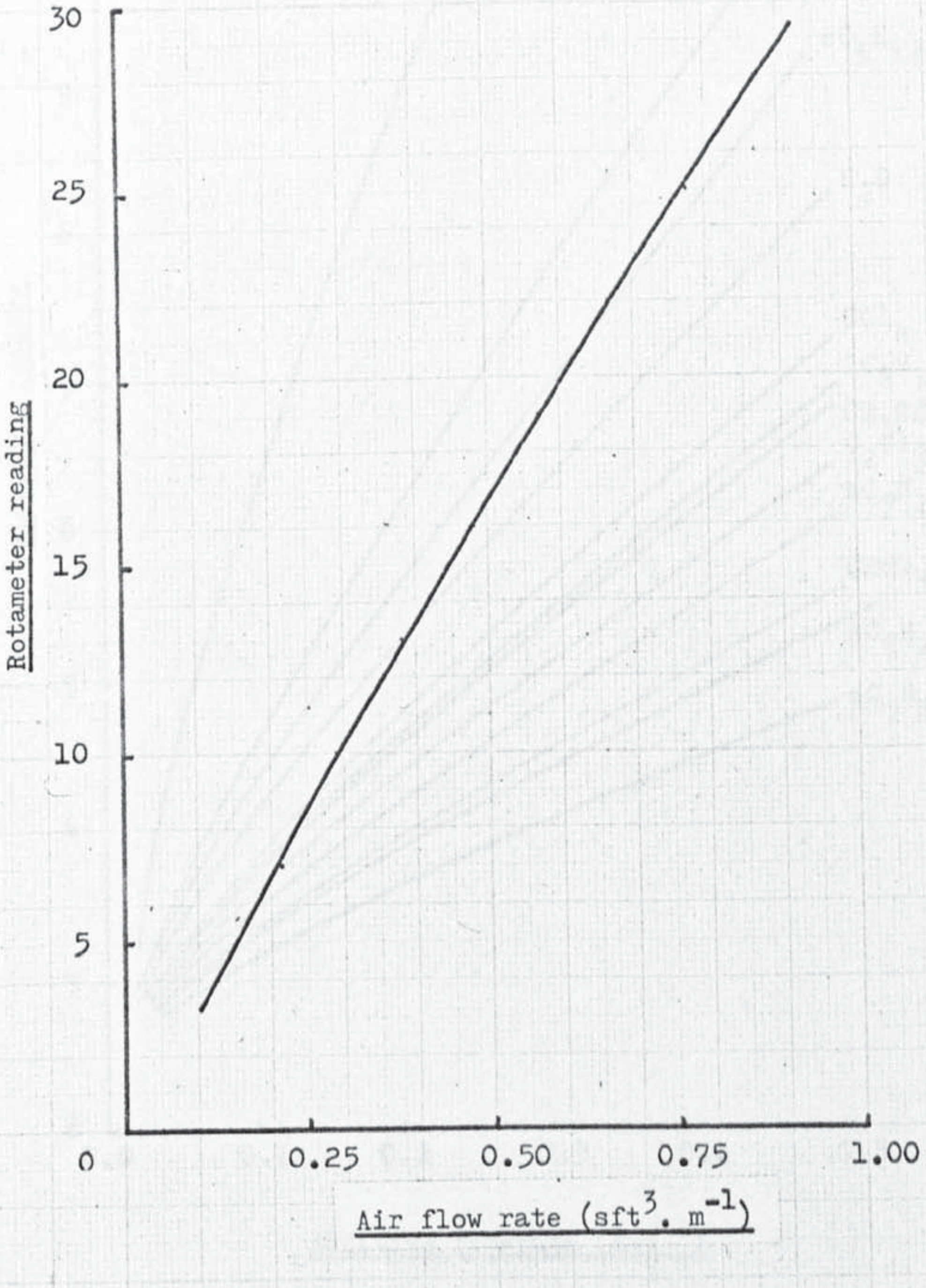


Figure 83.

Calibration curves for liquid additives.

FP1/16-10-G-5/36-SA

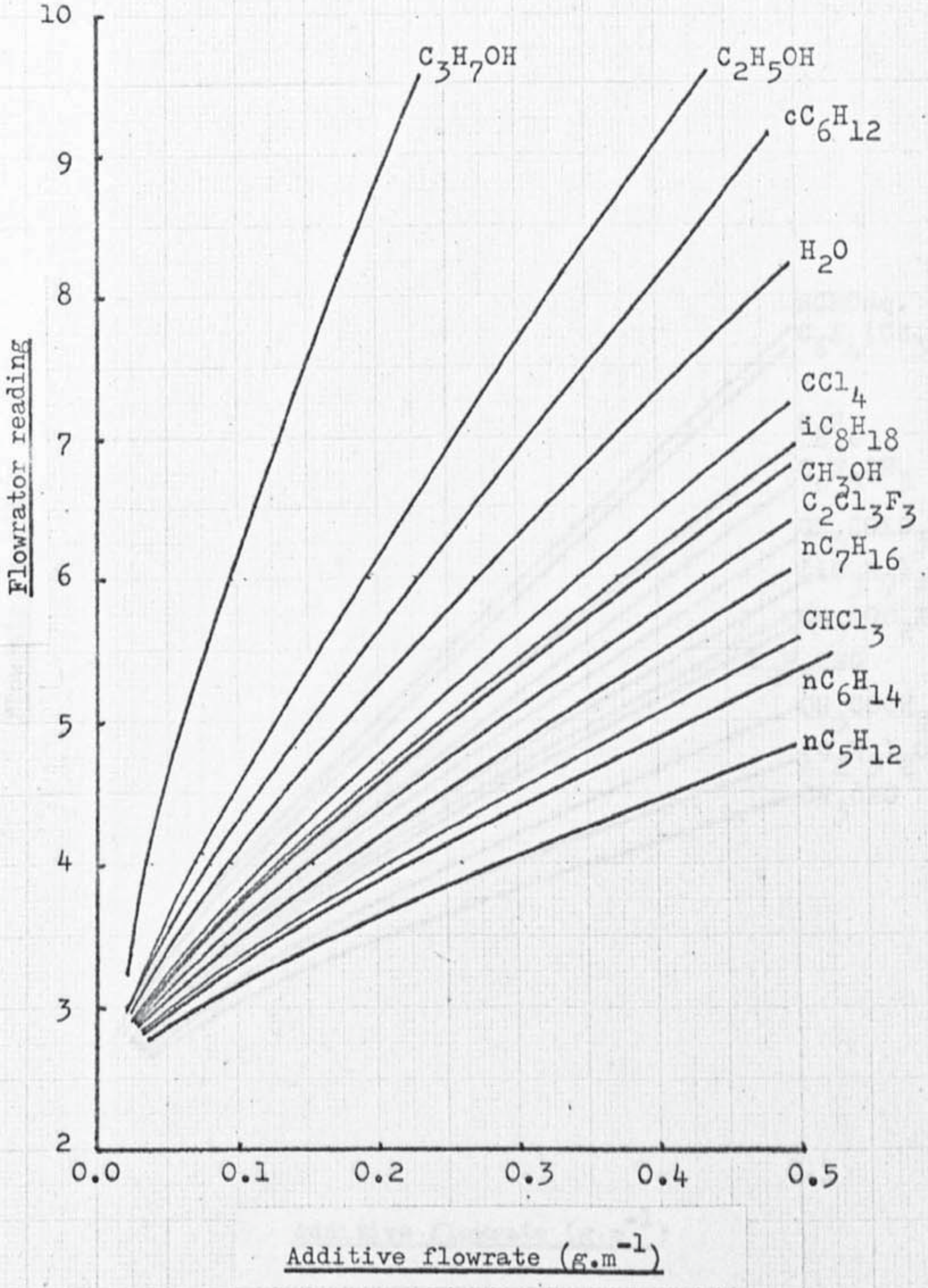


Figure 84.

Calibration curves for liquid additives.

FP-1/16-10-G-5/36-SA

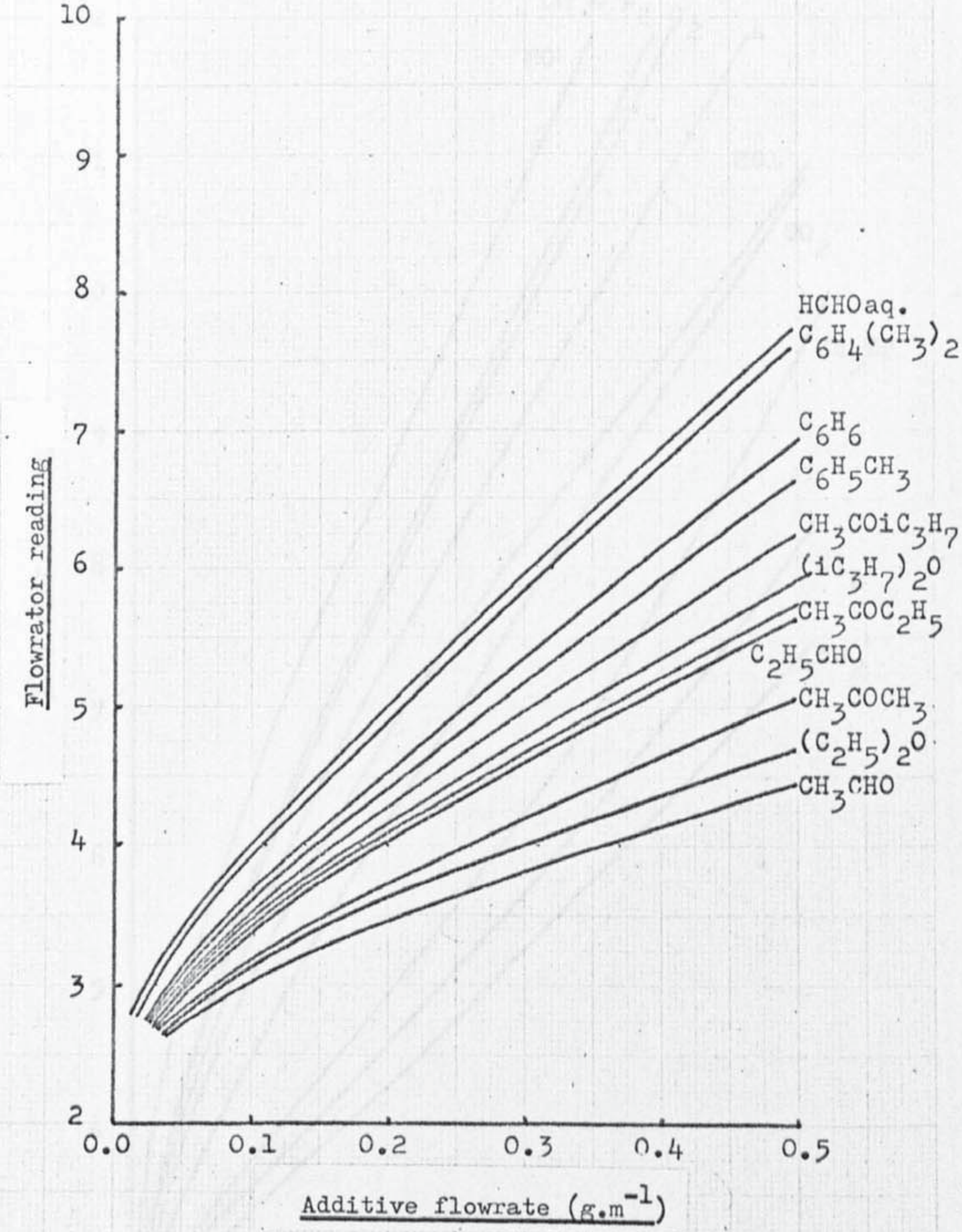


Figure 85.

Calibration curves for gaseous additives.

FP-1/16-16-G-5/36-TA

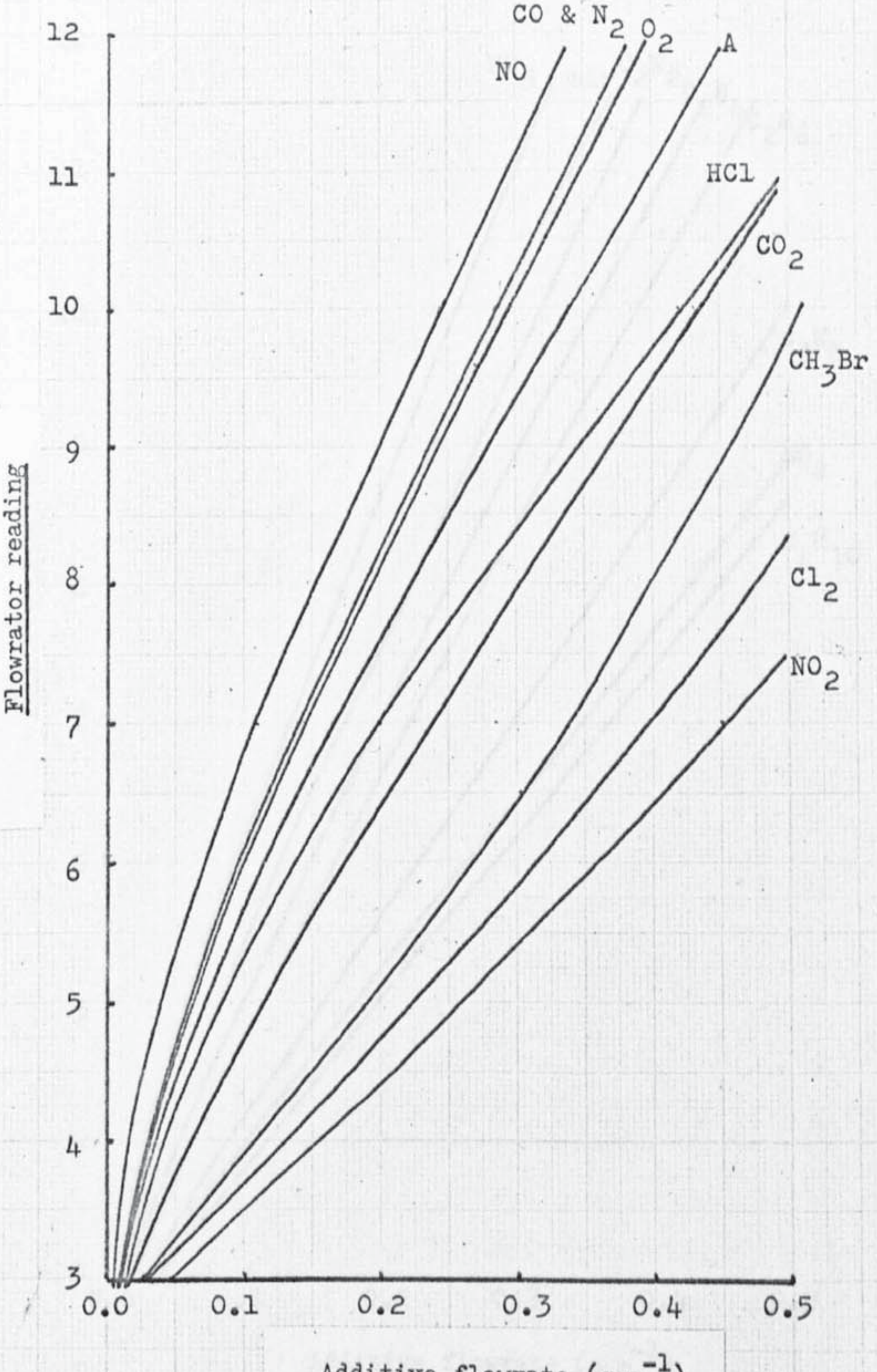


Figure 86.

Calibration curves for gaseous additives.

FP-1/16-16-G5/36-TA

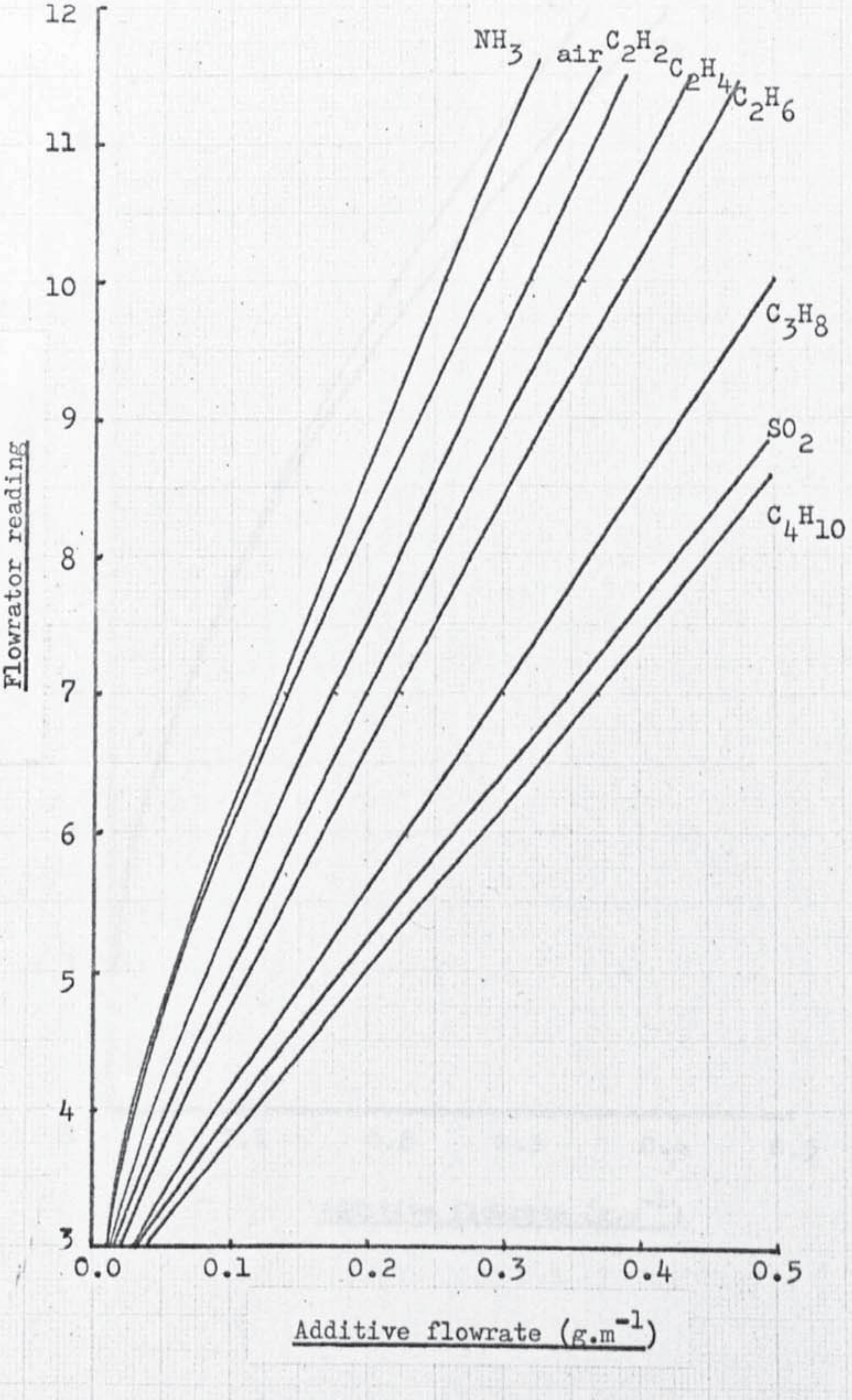


Figure 87.

Calibration curves for gaseous additives.

FP-1/8-10-G-5/36-TA

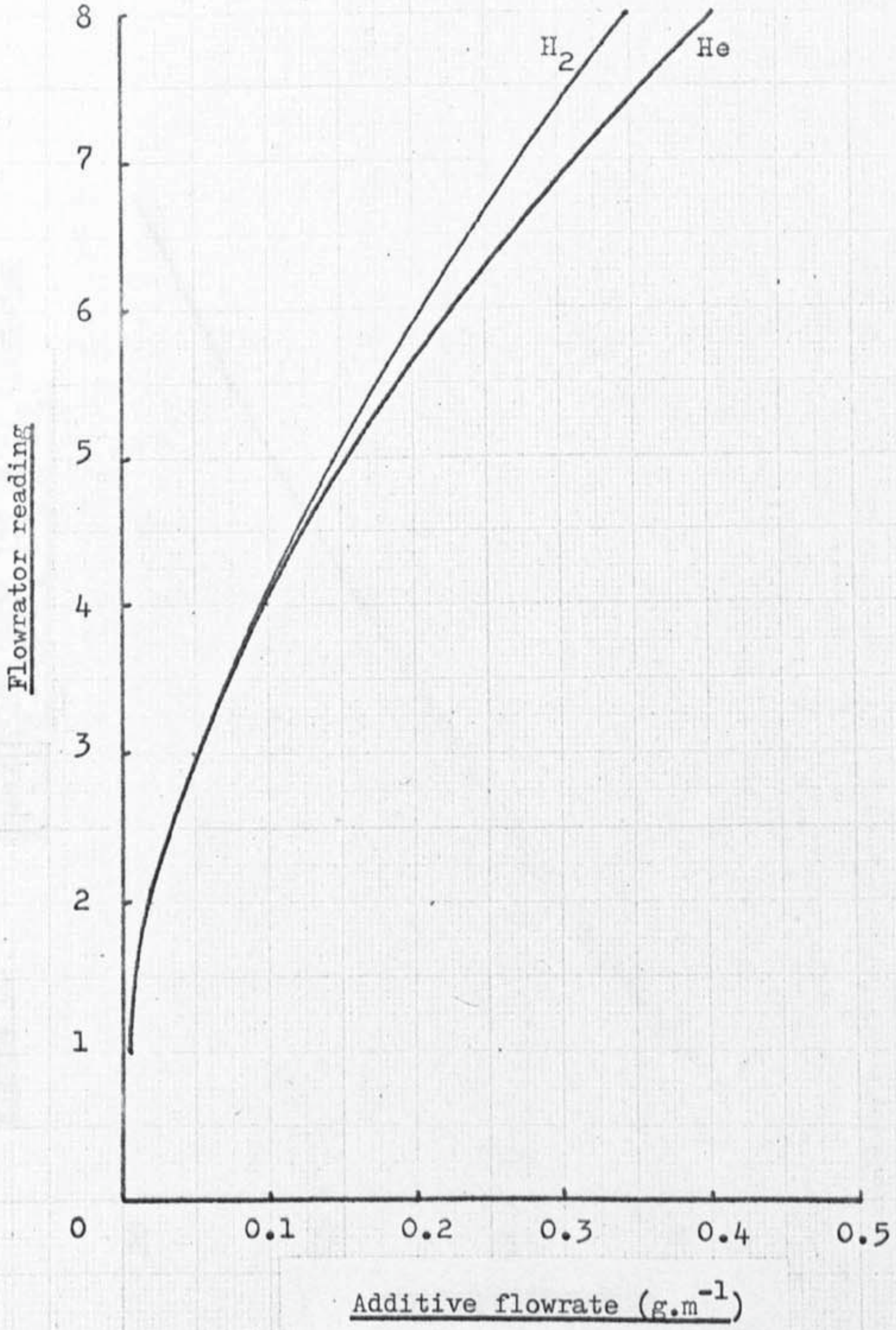
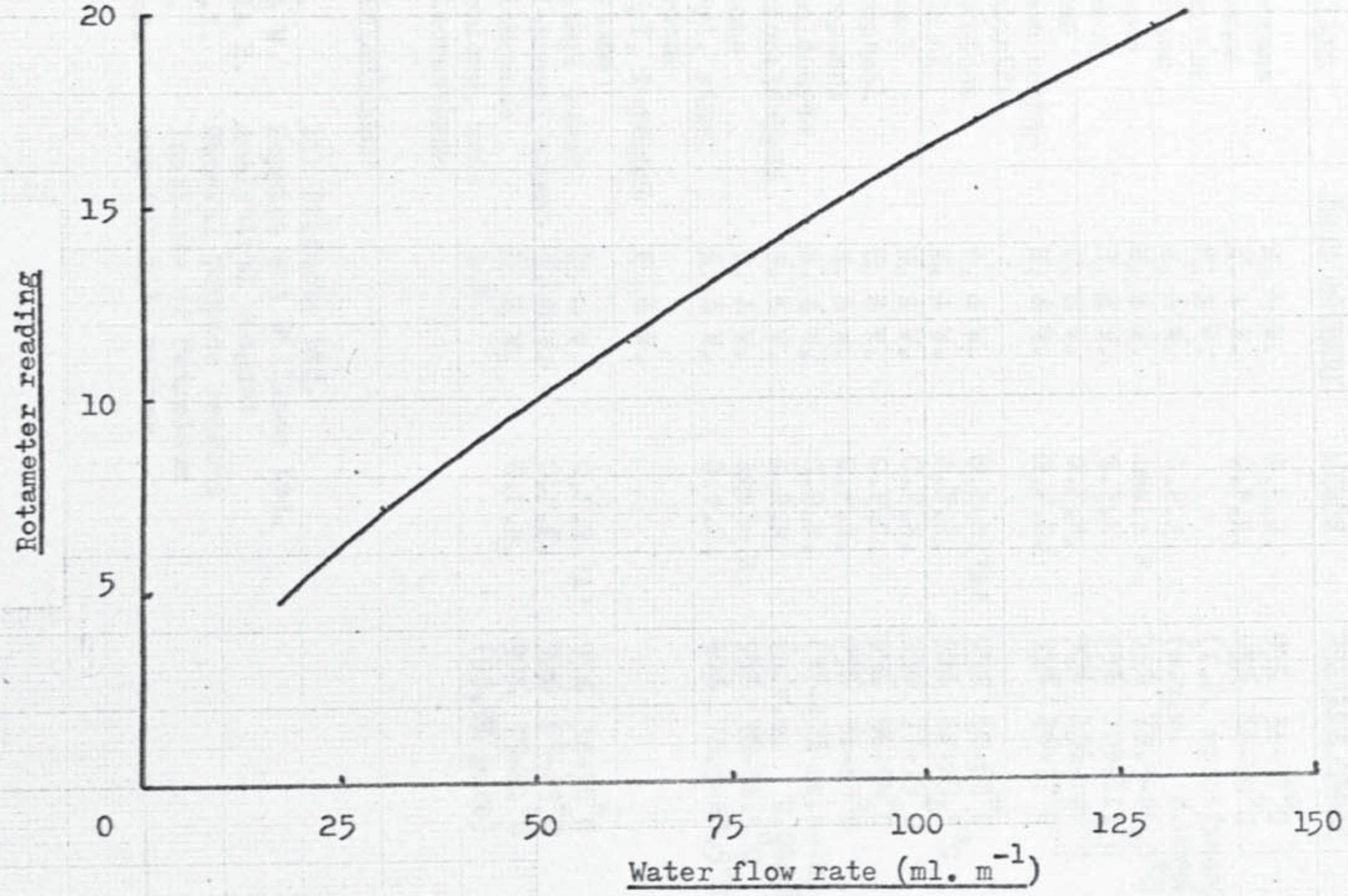


Figure 88 Calibration curve for water flowrator FP - 1/8 - 20 - G - 5/36 - SS



Appendix 4

Specifications of additives used.

Liquids

Additive	Manufacturer	Grade	Boiling Range
n-pentane	H. & W.	G.P.R.	95% 34-37°C
n-hexane	H. & W.	G.P.R.	95% 68-70°C
n-heptane	H. & W.		(I.P. specification)
i-octane	H. & W.	G.P.R.	(n.v.m. 0.005%)
benzene	H. & W.	Anala R.	95% 79.5-80.5°C
toluene	H. & W.	G.P.R.	95% 109-111°C
xylene	H. & W.	G.P.R.	90% 136-140°C
carbon tetrachloride	H. & W.	G.P.R.	95% 76-77°C
chloroform	H. & W.	G.P.R.'A'	95% 60-62°C
methanol	H. & W.	G.P.R.	90% 64-65.5°C
ethanol	H. & W.	G.P.R.	95% 77-79°C
n-propanol	H. & W.	G.P.R.	95% 96-98°C
i-propanol	H. & W.	G.P.R.	95% 81-83°C
formaldehyde	H. & W.	G.P.R.	(37-41% aq.soln.)
propionaldehyde	H. & W.	G.P.R.	(n.v.m. 0.004%)
acetone	H. & W.	Anala R.	95% 56-56.5°C
methyl, ethyl ketone	H. & W.	G.P.R.	90% 78.5-80.5°C
methyl, i-propyl ketone	H. & W.		
di-ethyl ether	H. & W.	G.P.R.'A'	95% 34-35°C
di-i-propyl ether	H. & W.	G.P.R.	90% 67-69°C
cyclohexane	H. & W.	G.P.R.	90% 79-81°C
trichloro, trifluoroethane	A.P.		(99.9% pure)

Abbreviations:

A.P.	Air Products Ltd.
H. & W.	Hopkins and Williams Ltd.
Anala R.	Analytical reagent
G.P.R.	General purpose reagent
I.P.	Institute of Petroleum
n.v.m.	non-volatile matter

Specification of additives used (continued)

Gases

Additive	Manufacturer	Grade	Purity (%)
ethane	B.O.C.	C.P.	99.0
propane	B.O.C.	Inst.	99.5
commercial propane	Bottogas		
butane	B.O.C.	Inst.	99.5
ethylene	A.P.	C.P.	99
acetylene	B.O.C.		99.5-99.8
methyl bromide	A.P.	C.P.	99.5
hydrogen chloride	B.O.C.	Tech.	99
carbon dioxide	A.P.	H.P.	99.995
carbon monoxide	A.P.	C.P.	99.5
oxygen	B.O.C.	C.P.	99.5
hydrogen	B.O.C.	C.P.	99.9
chlorine	A.P.	H.P.	99.5
nitric oxide	A.P.	C.P.	99
sulphur dioxide	A.P.	C.P.	99.9
nitrogen dioxide	A.P.	C.P.	99.5
helium	A.P.	H.P.	99.995
argon	A.P.	H.P.	99.998
nitrogen	B.O.C.	C.P.	99.5
ammonia	A.P.	Tech.	99.99

Abbreviations:

A.P.	Air Products Ltd.
B.O.C.	British Oxygen Company Ltd.
C.P.	Commercial purity
H.P.	High purity
Inst.	Instrument grade
Tech.	Technical grade

Appendix 5. Results of preliminary experiments.

Table 5. Observed results for identical methane-air flames (section 8.2).

Height above burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
	1 flame	2 flames			
2	3.21	6.20	0.022	1003	906
4	4.86	8.89	0.026	1067	1302
6	8.06	21.44	0.033	1160	2161
8	21.51	22.81	0.040	1323	4030
10	22.03	23.48	0.044	1388	5200
12	21.72	23.08	0.036	1401	4389
14	13.06	22.27	0.032	1313	3144
16	28.02	21.44	0.026	1235	2088
2	3.34	6.41	0.021	1026	929
4	5.15	9.43	0.026	1085	1373
6	8.07	21.44	0.031	1180	2145
8	21.56	22.87	0.042	1316	4157
10	22.19	23.67	0.043	1424	5537
12	21.74	23.10	0.038	1385	4458
14	12.09	22.17	0.030	1318	2985
16	7.61	21.34	0.025	1229	1976
2	3.50	6.65	0.023	1012	974
4	5.70	10.55	0.028	1095	1523
6	7.81	21.38	0.032	1159	2089
8	21.37	22.63	0.041	1287	3770
10	21.93	23.35	0.040	1404	4912
12	21.82	23.19	0.042	1364	4683
14	13.78	22.33	0.033	1312	3234
16	9.61	21.78	0.029	1261	2493
2	3.44	6.55	0.022	1020	955
4	4.82	8.82	0.025	1076	1286
6	7.05	21.19	0.029	1155	1872
8	21.56	22.87	0.043	1308	4171
10	21.90	23.30	0.041	1388	4845
12	21.62	22.95	0.038	1362	4216
14	21.28	22.51	0.033	1343	3494
16	8.61	21.57	0.025	1273	2217

Table 5 (continued)

Height above burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. m^{-2}h.$^{-1}$ ster.$^{-1}$)
	1 flame	2 flames			
2	3.63	6.86	0.022	1034	997
4	4.28	7.90	0.022	1079	1141
6	7.43	21.29	0.029	1173	1969
8	21.46	22.75	0.042	1297	3962
10	22.09	23.55	0.045	1390	5344
12	21.53	22.84	0.036	1364	4014
14	11.05	22.03	0.029	1305	2792
16	8.03	21.44	0.023	1276	2056
2	3.10	6.04	0.021	1008	878
4	5.32	9.76	0.027	1084	1422
6	7.56	21.32	0.031	1158	2018
8	21.43	22.70	0.042	1290	3892
10	22.00	23.43	0.044	1381	5113
12	21.75	23.12	0.038	1388	4491
14	21.15	22.36	0.031	1339	3250
16	8.21	21.48	0.024	1270	2112
2	3.09	6.02	0.022	994	880
4	5.10	9.34	0.026	1082	1361
6	7.17	21.22	0.030	1150	1910
8	21.36	22.62	0.040	1294	3745
10	22.10	23.57	0.042	1418	5332
12	21.70	23.05	0.040	1360	4416
14	21.14	22.34	0.029	1360	3202
16	9.39	21.73	0.028	1265	2433
2	3.79	7.09	0.024	1020	1042
4	4.56	8.37	0.025	1060	1226
6	8.00	21.43	0.031	1177	2128
8	21.48	22.76	0.039	1325	3949
10	22.05	23.49	0.044	1390	5225
12	21.77	23.14	0.041	1364	4571
14	12.09	22.17	0.028	1342	2957
16	8.67	21.58	0.029	1226	2273

Table 5 (continued)

Height above burner (cm)	Pyrometer Output 1 flame	 2 flames	Emiss.	Flame Temp. (°C)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
2	3.23	6.24	0.021	1018	906
4	4.84	8.85	0.027	1055	1304
6	7.87	21.40	0.030	1182	2088
8	21.55	22.85	0.041	1321	4110
10	22.14	23.62	0.043	1416	5433
12	21.75	23.12	0.041	1361	4538
14	21.21	22.44	0.032	1341	3372
16	7.96	21.42	0.026	1232	2071
2	3.33	6.39	0.022	1012	931
4	4.63	8.48	0.025	1064	1240
6	7.59	21.33	0.029	1180	2007
8	21.62	22.94	0.043	1318	4278
10	22.21	23.71	0.045	1412	5632
12	21.65	22.99	0.035	1398	4237
14	21.22	22.45	0.033	1332	3400
16	7.85	21.40	0.025	1240	2034
2	3.29	6.32	0.024	985	933
4	5.27	9.65	0.029	1060	1422
6	8.76	21.60	0.033	1188	2335
8	21.46	22.75	0.042	1297	3962
10	21.98	23.40	0.041	1403	5023
12	21.73	23.09	0.037	1394	4436
14	11.64	22.11	0.030	1308	2910
16	8.32	21.51	0.025	1261	2149
2	2.95	5.83	0.021	997	848
4	4.74	8.68	0.026	1060	1275
6	7.17	21.22	0.030	1150	1910
8	21.37	22.63	0.041	1287	3770
10	22.00	23.43	0.044	1381	5113
12	21.72	23.07	0.038	1381	4416
14	11.01	22.02	0.028	1316	2772
16	8.23	21.49	0.026	1244	2138

Table 6. Mean emissivities and 95% confidence limits of emissivities of themethane-air flame.

Height above burner (cm)	$\Sigma\epsilon$	$\Sigma\epsilon^2$	Mean emissivity
2	0.265	0.005865	0.0221
4	0.314	0.008238	0.0262
6	0.368	0.011308	0.0307
8	0.496	0.020518	0.0413
10	0.516	0.022218	0.0430
12	0.460	0.017688	0.0383
14	0.368	0.011326	0.0307
16	0.311	0.008099	0.0259

Height above burner (cm)	Standard deviation	Standard error	95% confidence limits	
			Lower	Upper
2	0.0011	0.0007	0.0214	0.0228
4	0.0014	0.0009	0.0253	0.0271
6	0.0014	0.0009	0.0298	0.0316
8	0.0012	0.0008	0.0405	0.0421
10	0.0017	0.0011	0.0419	0.0441
12	0.0022	0.0014	0.0369	0.0397
14	0.0019	0.0012	0.0295	0.0319
16	0.0019	0.0012	0.0247	0.0271

Table 7. Mean temperatures and 95% confidence limits of temperatures of the methane-air flame.

Height above burner (cm)	ΣT	ΣT^2	Mean temperature
2	12129	12261587	1011
4	12867	13798457	1072
6	14012	16363396	1168
8	15663	20446531	1305
10	16795	23508535	1400
12	16522	22750824	1377
14	15929	21147821	1327
16	15012	18783774	1251

Height above burner (cm)	Standard deviation	Standard error of mean	95% confidence limits	
			Lower	Upper
2	14	9	1002	1020
4	13	8	1064	1080
6	14	9	1159	1177
8	15	9	1296	1314
10	15	10	1390	1410
12	16	10	1367	1387
14	18	11	1316	1338
16	18	12	1239	1263

Table 8. Mean radiances and 95% confidence limits of radiances of the methane-air flame.

Height above burner (cm)	ΣW	ΣW^2	Mean radiance
2	11179	10446825	932
4	15875	21118745	1323
6	24632	50753138	2053
8	47796	190700152	3983
10	62719	328451063	5227
12	52865	233243369	4405
14	37512	117898638	3126
16	26040	56783598	2170

Height above burner (cm)	Standard deviation	Standard error of mean	95% confidence limits	
			Lower	Upper
2	54	35	897	967
4	103	66	1257	1989
6	132	84	1969	2137
8	173	109	3874	4092
10	242	154	5073	5381
12	179	113	4292	4518
14	240	153	2973	3279
16	159	101	2069	2271

Table 9. 95% significance levels for emissivity radiance and temperature.

Emissivity

	Standard error of difference	95% significance levels	
		Lower	Upper
2	0.0015	0.0206	0.0236
4	0.0020	0.0242	0.0282
6	0.0020	0.0287	0.0327
8	0.0017	0.0396	0.0430
10	0.0024	0.0406	0.0454
12	0.0031	0.0352	0.0414
14	0.0026	0.0281	0.0333
16	0.0026	0.0233	0.0285

Temperature

	Standard error of difference	95% significance levels	
		Upper	Lower
2	20	991	1031
4	18	1054	1090
6	20	1148	1188
8	21	1284	1326
10	21	1379	1421
12	22	1355	1399
14	25	1302	1352
16	25	1226	1276

Radiance

	Standard error of difference	95% significance levels	
		Upper	Lower
2	75	857	1007
4	143	1180	1466
6	184	1869	2237
8	241	3742	4224
10	338	4889	5565
12	250	4155	4655
14	334	2792	3460
16	222	1948	2392

Table 10. Observed results for identical methane-air flames with additive and mixing chamber heating (section 8.3)

Height above burner (cm)	Pyrometer Output		Emiss	Flame Temp. (°C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
	1 flame	2 flames			
2	3.09	6.02	0.021	1007	875
4	4.91	8.97	0.026	1070	1313
6	7.28	21.25	0.030	1155	1937
8	21.44	22.72	0.040	1309	3890
10	22.06	23.50	0.044	1392	5250
12	21.73	23.09	0.038	1384	4448
14	21.18	22.39	0.032	1334	3313
16	7.66	21.35	0.024	1245	1979
2	3.47	6.60	0.022	1022	961
4	4.52	8.29	0.025	1057	1215
6	7.16	21.22	0.029	1160	1899
8	21.41	22.68	0.042	1287	3862
10	22.16	23.63	0.044	1410	5481
12	21.66	23.00	0.036	1389	4265
14	21.32	22.57	0.034	1341	3582
16	9.31	21.71	0.030	1239	2435
2	3.07	6.00	0.021	1006	873
4	4.87	8.91	0.026	1068	1306
6	7.38	21.28	0.030	1160	1964
8	21.41	22.68	0.041	1295	3848
10	22.08	23.53	0.043	1404	5280
12	21.88	23.28	0.041	1385	4810
14	11.36	22.07	0.029	1313	2849
16	9.03	21.66	0.027	1264	2340
2	3.31	6.35	0.023	998	932
4	5.36	9.83	0.027	1086	1430
6	7.83	21.39	0.032	1160	2095
8	21.48	22.76	0.043	1291	3995
10	21.98	23.40	0.043	1386	5057
12	21.70	23.05	0.040	1360	4416
14	13.80	22.33	0.031	1334	3210
16	8.84	21.62	0.026	1269	2282

Table 10 (continued)

Height above burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
	1 flame	2 flames			
2	3.21	6.20	0.022	1003	906
4	5.10	9.32	0.028	1060	1373
6	8.34	21.50	0.032	1181	2221
8	21.46	22.74	0.040	1312	3920
10	21.93	23.34	0.041	1394	4916
12	21.56	22.87	0.037	1360	4085
14	12.62	22.23	0.029	1340	3048
16	7.89	21.41	0.025	1242	2045
2	3.41	6.51	0.022	1018	949
4	4.93	9.02	0.025	1083	1312
6	8.53	21.55	0.033	1179	2278
8	21.56	22.87	0.042	1316	4157
10	22.09	23.55	0.042	1415	5294
12	21.71	23.06	0.037	1389	4383
14	11.95	22.15	0.030	1315	2962
16	8.71	21.59	0.026	1264	2253

Table 11. Derived results to show effect of heating additive supply and mixing chamber on emissivity.

Height above burner (cm)	$\Sigma\epsilon$	$\Sigma\epsilon^2$	Mean emissivity
2	0.131	0.002863	0.0218
4	0.157	0.004115	0.0262
6	0.186	0.005778	0.0310
8	0.248	0.010258	0.0413
10	0.257	0.011015	0.0428
12	0.229	0.008759	0.0382
14	0.185	0.005723	0.0308
16	0.158	0.004182	0.0263

Height above burner (cm)	Standard deviation	Combined standard deviation	t
2	0.0008	0.0010	-0.30
4	0.0012	0.0014	0.00
6	0.0015	0.0015	0.20
8	0.0012	0.0013	0.00
10	0.0000	0.0015	-0.13
12	0.0019	0.0022	-0.05
14	0.0019	0.0020	0.05
16	0.0021	0.0020	0.20

Table 12. Derived results to show effect of heating additive supply and mixing chamber on temperatures.

Height above burner (cm)	ΣT	ΣT^2	Mean temperatures
2	6054	6108906	1009
4	6424	6878658	1071
6	6995	8155627	1166
8	7810	10166756	1302
10	8401	11763437	1400
12	8267	11391523	1378
14	7977	10606187	1330
16	7523	943463	1254

Height above burner (cm)	Standard deviation	Combined standard deviation	t
2	9	13	-0.15
4	12	13	-0.08
6	11	13	-0.15
8	12	14	-0.21
10	11	14	0.0
12	14	15	0.07
14	12	16	0.19
16	13	17	0.18

Table 13. Derived results to show effect of heating additive supply and mixing chamber on radiance.

Height above burner (cm)	W	W^2	Mean radiance
2	5496	5041336	916
4	7949	10557203	1324
6	12394	25726616	2066
8	23672	93461322	3945
10	31278	163249002	5213
12	26407	116509999	4401
14	18964	60291342	3160
16	13334	29786824	2222

Height above burner (cm)	Standard deviation	Combined standard deviation	t
2	37	50	-0.32
4	72	95	0.01
6	158	141	0.092
8	116	157	-3.8
10	198	230	-0.06
12	240	200	-0.02
14	266	249	0.14
16	176	164	0.32

Table 14. Observed results for single flame with 20% acetone to evaluate efficiency of mixing chamber (section 8.4)

First flame

Height above burner (cm)	Pyro. output	Pyro. output	Pyro. output	Pyro. output
2	3.30	3.24	3.35	3.16
4	4.89	5.00	5.16	4.81
6	7.70	7.96	8.02	7.91
8	1.46	1.51	1.54	1.69
10	2.10	2.18	2.20	2.00
12	1.85	1.77	1.75	1.81
14	1.17	1.20	1.12	1.06
16	8.39	7.94	8.39	8.44

Height above burner (cm)	Pyro. output	Pyro. output	Pyro. output	Pyro. output
2	3.04	3.11	3.02	3.40
4	4.92	4.77	4.72	4.99
6	7.70	7.53	7.61	7.76
8	1.53	1.55	1.49	1.58
10	2.06	2.04	2.06	2.18
12	1.64	1.79	1.79	1.69
14	1.16	1.29	1.31	1.20
16	8.62	8.71	8.17	8.54

Height above burner (cm)	Pyro. output	Pyro. output	Pyro. output	Pyro. output
2	3.33	3.11	3.26	3.27
4	5.00	5.16	5.03	4.80
6	7.85	7.67	7.95	7.83
8	1.47	1.45	1.63	1.55
10	2.22	2.20	2.07	2.20
12	1.63	1.85	1.88	1.70
14	1.14	1.09	1.09	1.12
16	8.62	8.25	8.19	8.44

Table 14 (continued)

Second flame

Height above burner (cm)	Pyro. output	Pyro. output	Pyro. output	Pyro. output
2	3.25	3.36	3.20	3.11
4	5.06	4.96	4.88	4.81
6	7.90	7.88	7.70	7.54
8	1.50	1.46	1.52	1.60
10	2.06	2.10	2.15	2.17
12	1.80	1.71	1.60	1.75
14	1.25	1.10	1.08	1.07
16	7.88	8.39	8.46	8.55

Height above burner (cm)	Pyro. output	Pyro. output	Pyro. output	Pyro. output
2	3.08	3.17	3.29	3.38
4	4.83	4.77	4.90	5.06
6	7.60	7.60	7.65	7.60
8	1.65	1.63	1.55	1.53
10	2.13	2.18	2.26	2.23
12	1.84	1.82	1.77	1.87
14	1.10	1.29	1.25	1.18
16	8.30	8.75	8.33	8.05

Height above burner (cm)	Pyro. output	Pyro. output	Pyro. output	Pyro. output
2	3.40	3.20	3.10	3.08
4	5.05	5.21	4.90	4.90
6	7.66	7.88	7.99	7.92
8	1.56	1.44	1.40	1.57
10	2.18	2.07	2.07	2.18
12	1.91	1.86	1.71	1.77
14	1.09	1.14	1.05	1.23
16	8.55	8.64	8.69	8.34

Table 15. Derived results to evaluate efficiency of mixing chamber (section 8.4).

Height above burner (cm)	Standard deviation	Difference of means	*t*
2	0.1214	-0.00250	-0.0504
4	0.1367	-0.00666	-0.1196
6	0.1577	0.04750	0.7380
8	0.07328	0.00334	0.1118
10	0.07141	-0.02250	-0.7710
12	0.08390	-0.02166	-0.6590
14	0.08062	0.01166	0.3540
16	0.2402	-0.01917	-0.1951

Appendix 6

Results - observed and calculated

The results are tabulated in order of Run No. and have been divided into two parts. The smoke point and calorimeter results are presented before the pyrometer results.

Run No. L1 Additive n-pentane

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	12.4	9.4	6.9	5.9	5.5
Air Flow (l.s^{-1})	0.173	0.132	0.098	0.085	0.079
Fraction of stoich.flow	0.692	0.521	0.391	0.343	0.314
Calorimeter					
1 flame					
Inlet Temp. (°C)	24	24	24	24	24
Outlet Temp. (°C)	53	51	50	48	47
Heat Transfer (cal.s^{-1})	55.6	51.7	49.8	46.0	44.1
2 flames					
Inlet Temp. (°C)	24	24	24	24	24
Outlet Temp. (°C)	68	65	63	61	59
Heat Transfer (cal.s^{-1})	84.3	78.6	74.7	70.9	67.1

Run No. L2 Additive n-hexane

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	12.6	9.6	7.0	6.1	5.5
Air Flow (l.s^{-1})	0.176	0.134	0.100	0.088	0.080
Fraction of stoich.flow	0.701	0.531	0.400	0.354	0.319
Calorimeter					
1 flame					
Inlet Temp. (°C)	22	22	22	22	22
Outlet Temp. (°C)	54	54	52	49	48
Heat Transfer (cal.s^{-1})	61.3	61.3	57.5	51.7	49.8
2 flames					
Inlet Temp. (°C)	22	22	22	22	22
Outlet Temp. (°C)	72	70	66	62	59
Heat Transfer (cal. s^{-1})	95.8	92.0	84.3	76.6	70.9

Run No. L3 Additive cyclohexane

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	7.6	7.2	6.5	5.8	5.4
Air Flow (l.s^{-1})	0.108	0.102	0.093	0.584	0.079
Fraction of stoich.flow	0.428	0.407	0.370	0.334	0.314
Calorimeter					
1 flame					
Inlet Temp. ($^{\circ}$C)	23	23	23	23	23
Outlet Temp.($^{\circ}$C)	55	54	53	51	49
Heat Transfer (cal. s^{-1})	61.3	59.4	57.5	53.6	49.8
2 flames					
Inlet Temp. ($^{\circ}$C)	23	23	23	23	23
Outlet Temp.($^{\circ}$C)	66	66	63	59	59
Heat Transfer (cal. s^{-1})	82.4	82.4	76.6	69.0	69.0

Run No. L4 Additive chloroform

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	7.4	7.1	6.7	5.8	5.4
Air Flow (l.s^{-1})	0.105	0.101	0.096	0.084	0.079
Fraction of stoich.flow	0.417	0.401	0.381	0.334	0.314
Calorimeter					
1 flame					
Inlet Temp. ($^{\circ}$C)	21	21	21	21	21
Outlet Temp.($^{\circ}$C)	48	49	47	47	46
Heat Transfer (cal. s^{-1})	51.7	53.6	49.8	49.8	47.9
2 flames					
Inlet Temp. ($^{\circ}$C)	21	21	21	21	21
Outlet Temp.($^{\circ}$C)	64	64	64	62	61
Heat Transfer (cal. s^{-1})	82.4	82.4	82.4	78.6	76.6

Run No. L5 Additive acetone

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	5.4	5.3	5.2	5.1	5.1
Air Flow (1.s^{-1})	0.079	0.078	0.078	0.075	0.075
Fraction of stoich.flow	0.314	0.309	0.304	0.299	0.299
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	21	21	21	21	21
Outlet Temp.(^{o}C)	47	48	47	47	45
Heat Transfer (cal.s^{-1})	49.8	51.7	49.8	49.8	46.0
2 flames					
Inlet Temp. (^{o}C)	21	21	21	21	21
Outlet Temp.(^{o}C)	60	60	59	57	57
Heat Transfer (cal.s^{-1})	74.7	74.7	72.8	69.0	69.0

Run No. L6 Additive methanol

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	4.3	4.5	4.5	4.7	4.8
Air Flow (1.s^{-1})	0.065	0.068	0.070	0.070	0.071
Fraction of stoich.flow	0.258	0.268	0.268	0.278	0.284
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp.(^{o}C)	48	48	48	46	46
Heat Transfer (cal.s^{-1})	49.8	49.8	49.8	46.0	46.0
2 flames					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp.(^{o}C)	62	62	62	60	59
Heat Transfer (cal.s^{-1})	76.6	76.6	76.6	72.8	70.9

Run No. L7 — Additive methyl ethyl ketone

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	5.7	5.6	5.4	5.2	5.2
Air Flow (l.s^{-1})	0.083	0.082	0.079	0.076	0.076
Fraction of stoich.flow	0.329	0.324	0.314	0.304	0.304
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp.(^{o}C)	49	49	48	48	47
Heat Transfer (cal.s^{-1})	49.8	49.8	47.9	47.9	46.0
2 flames					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp.(^{o}C)	59	60	60	60	58
Heat Transfer (cal.s^{-1})	69.0	70.9	70.9	70.9	67.1

Run No. L8 — Additive benzene

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	11.4	9.9	8.0	6.6	5.5
Air Flow (l.s^{-1})	0.159	0.138	0.113	0.094	0.080
Fraction of stoich.flow	0.632	0.550	0.448	0.375	0.319
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp.(^{o}C)	51	51	50	48	46
Heat Transfer (cal.s^{-1})	55.6	55.6	53.6	49.8	46.0
2 flames					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp.(^{o}C)	68	67	66	63	60
Heat Transfer (cal.s^{-1})	88.1	86.2	84.3	78.6	72.8

Run No. L9 Additive carbon tetrachloride

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	12.5	10.1	8.2	6.7	5.3
Air Flow ($l.s^{-1}$)	0.175	0.141	0.116	0.096	0.078
Fraction of stoich.flow	0.694	0.561	0.459	0.381	0.309
Calorimeter					
1 flame					
Inlet Temp. (°C)	22	22	22	22	22
Outlet Temp. (°C)	50	49	48	48	48
Heat Transfer ($cal.s^{-1}$)	53.6	51.7	49.8	49.8	49.8
2 flames					
Inlet Temp. (°C)	22	22	22	22	22
Outlet Temp. (°C)	64	64	62	62	62
Heat Transfer ($cal.s^{-1}$)	80.5	80.5	76.6	76.6	76.6

Run No. L10 Additive i-propanol

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	6.9	6.5	6.0	5.7	5.3
Air Flow ($l.s^{-1}$)	0.098	0.093	0.087	0.083	0.078
Fraction of stoich.flow	0.391	0.370	0.344	0.329	0.309
Calorimeter					
1 flame					
Inlet Temp. (°C)	21	21	21	21	21
Outlet Temp. (°C)	50	50	49	48	48
Heat Transfer ($cal.s^{-1}$)	55.6	55.6	53.6	51.7	51.7
2 flames					
Inlet Temp. (°C)	21	21	21	21	21
Outlet Temp. (°C)	65	68	66	66	64
Heat Transfer ($cal.s^{-1}$)	84.3	90.1	86.2	86.2	82.4

Run No. L11 **Additive** n-propanol

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	6.9	6.6	6.0	5.8	5.3
Air Flow (l.s^{-1})	0.098	0.094	0.087	0.084	0.078
Fraction of stoich.flow	0.391	0.375	0.344	0.334	0.309
Calorimeter					
1 flame					
Inlet Temp. (°C)	22	22	22	22	22
Outlet Temp.(°C)	49	49	47	47	46
Heat Transfer (cal.s^{-1})	51.7	51.7	47.9	47.9	46.0
2 flames					
Inlet Temp. (°C)	22	22	22	22	22
Outlet Temp.(°C)	67	65	63	63	61
Heat Transfer (cal.s^{-1})	86.2	82.4	78.6	78.6	74.7

Run No. L12 **Additive** di-ethyl ether

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	6.5	6.5	6.2	5.7	5.2
Air Flow (l.s^{-1})	0.093	0.093	0.089	0.083	0.076
Fraction of stoich.flow	0.370	0.370	0.355	0.329	0.304
Calorimeter					
1 flame					
Inlet Temp. (°C)	22	22	22	22	22
Outlet Temp.(°C)	51	49	49	48	47
Heat Transfer (cal.s^{-1})	55.6	51.7	51.7	49.8	47.9
2 flames					
Inlet Temp. (°C)	22	22	22	22	22
Outlet Temp.(°C)	63	62	62	60	58
Heat Transfer (cal.s^{-1})	78.6	76.6	76.6	72.8	69.0

Run No. L13 Additive toluene

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	12.0	10.1	8.3	6.9	5.6
Air Flow (l.s^{-1})	0.167	0.141	0.117	0.098	0.082
Fraction of stoich.flow	0.666	0.561	0.464	0.391	0.324
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp.(^{o}C)	50	50	50	49	47
Heat Transfer (cal.s^{-1})	53.6	53.6	53.6	51.7	47.9
2 flames					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp.(^{o}C)	65	63	63	61	58
Heat Transfer (cal.s^{-1})	82.4	78.6	78.6	74.7	69.0

Run No. L14 Additive i-octane

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	13.4	10.2	7.3	6.4	5.5
Air Flow (l.s^{-1})	0.187	0.143	0.104	0.092	0.080
Fraction of stoich.flow	0.744	0.566	0.412	0.365	0.319
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp.(^{o}C)	49	51	50	48	48
Heat Transfer (cal.s^{-1})	49.8	53.6	51.7	47.9	47.9
2 flames					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp.(^{o}C)	66	65	62	60	57
Heat Transfer (cal.s^{-1})	82.4	80.5	74.7	70.9	65.1

Run No. L15 **Additive** methyl i-propyl ketone

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	6.5	6.4	6.0	5.6	5.3
Air Flow (l.s^{-1})	0.093	0.092	0.087	0.082	0.078
Fraction of stoich.flow	0.370	0.365	0.344	0.324	0.309
Calorimeter					
1 flame					
Inlet Temp. (°C)	22	22	22	22	22
Outlet Temp. (°C)	48	48	48	47	45
Heat Transfer (cal.s^{-1})	49.8	49.8	49.8	47.9	44.1
2 flames					
Inlet Temp. (°C)	22	22	22	22	22
Outlet Temp. (°C)	60	60	59	57	56
Heat Transfer (cal.s^{-1})	72.8	72.8	70.9	67.1	65.1

Run No. L16 **Additive** water

Add. Conc.	20%	15%	10%	5%	2.5%
Air Rotameter	incomplete vaporisation			4.8	4.9
Air Flow (l.s^{-1})				0.071	0.073
Fraction of stoich.flow				0.284	0.289
Calorimeter					
1 flame					
Inlet Temp. (°C)				22	22
Outlet Temp. (°C)				42	42
Heat Transfer (cal.s^{-1})				38.3	38.3
2 flames					
Inlet Temp. (°C)				22	22
Outlet Temp. (°C)				56	56
Heat Transfer (cal.s^{-1})				65.1	65.1

Run No. L17 Additive n-heptane

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	12.9	10.0	7.8	6.3	5.2
Air Flow (l.s^{-1})	0.180	0.140	0.110	0.091	0.076
Fraction of stoich.flow	0.716	0.556	0.438	0.365	0.319
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp. (^{o}C)	52	50	49	49	47
Heat Transfer (cal.s^{-1})	57.5	53.6	51.7	51.7	47.9
2 flames					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp. (^{o}C)	70	67	64	61	58
Heat Transfer (cal.s^{-1})	92.0	86.2	80.5	74.7	69.0

Run No. L18 Additive water + 0.005M surfactant

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	4.7	4.8	4.9	4.9	5.0
Air Flow (l.s^{-1})	0.070	0.071	0.073	0.073	0.074
Fraction of stoich.flow	0.278	0.284	0.289	0.289	0.294
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp. (^{o}C)	44	44	43	42	42
Heat Transfer (cal.s^{-1})	40.2	40.2	38.3	36.4	36.4
2 flames					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp. (^{o}C)	60	58	58	56	54
Heat Transfer (cal.s^{-1})	70.9	67.1	67.1	63.2	59.4

Run No. L19 Additive water + 0.01M surfactant

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	4.8	4.8	4.8	4.9	5.0
Air Flow (l.s^{-1})	0.071	0.071	0.071	0.073	0.074
Fraction of stoich.flow	0.284	0.284	0.284	0.289	0.294
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp.(^{o}C)	45	45	43	42	42
Heat Transfer (cal. s^{-1})	44.1	44.1	40.2	38.3	38.3
2 flames					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp.(^{o}C)	59	58	55	55	54
Heat Transfer (cal. s^{-1})	70.9	69.0	63.2	63.2	61.3

Run No. L20 Additive xylene

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	14.0	10.9	7.8	6.6	5.6
Air Flow (l.s^{-1})	0.196	0.152	0.110	0.094	0.082
Fraction of stoich.flow	0.779	0.605	0.438	0.375	0.325
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	21	21	21	21	21
Outlet Temp.(^{o}C)	52	50	49	47	45
Heat Transfer (cal.s^{-1})	59.4	55.6	53.6	49.8	46.0
2 flames					
Inlet Temp. (^{o}C)	21	21	21	21	21
Outlet Temp.(^{o}C)	68	65	62	59	56
Heat Transfer (cal.s^{-1})	90.1	84.3	78.6	72.8	67.1

Run No. L21 Additive di-i-propyl ether

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	7.1	6.9	6.4	5.7	5.3
Air Flow (l.s^{-1})	0.101	0.098	0.092	0.083	0.078
Fraction of stoich.flow	0.401	0.391	0.365	0.329	0.309
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	21	21	21	21	21
Outlet Temp.(^{o}C)	46	44	43	43	42
Heat Transfer (cal.s^{-1})	47.9	44.1	42.2	42.2	40.2
2 flames					
Inlet Temp. (^{o}C)	21	21	21	21	21
Outlet Temp.(^{o}C)	60	59	57	56	56
Heat Transfer (calss^{-1})	74.7	72.8	69.0	67.1	67.1

Run No. L22 Additive propionaldelyde

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	4.5	4.6	4.6	4.8	4.9
Air Flow (l.s^{-1})	0.068	0.069	0.069	0.071	0.073
Fraction of stoich.flow	0.268	0.273	0.273	0.284	0.289
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	21	21	21	21	21
Outlet Temp.(^{o}C)	47	46	46	45	45
Heat Transfer (cal.s^{-1})	49.8	47.9	47.9	46.0	46.0
2 flames					
Inlet Temp. (^{o}C)	21	21	21	21	21
Outlet Temp.(^{o}C)	61	61	58	57	57
Heat Transfer (cal.s^{-1})	76.6	76.6	70.9	69.0	69.0

Run No. L23 Additive ethanol

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	5.5	5.4	5.3	5.1	5.0
Air Flow (l.s^{-1})	0.080	0.079	0.078	0.075	0.074
Fraction of stoich.flow	0.319	0.314	0.309	0.299	0.294
Calorimeter					
1 flame					
Inlet Temp. (°C)	21	21	21	21	21
Outlet Temp.(°C)	48	48	47	46	44
Heat Transfer (cal.s^{-1})	51.7	51.7	49.8	47.9	44.1
2 flames					
Inlet Temp. (°C)	21	21	21	21	21
Outlet Temp.(°C)	61	62	60	58	58
Heat Transfer (cal.s^{-1})	76.6	78.6	74.7	70.9	70.9

Run No. L24 Additive formaldelyde

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	4.1	4.2	4.4	4.6	4.8
Air Flow (l.s^{-1})	0.063	0.064	0.066	0.069	0.071
Fraction of stoich.flow	0.248	0.253	0.263	0.273	0.284
Calorimeter					
1 flame					
Inlet Temp. (°C)	22	22	22	22	22
Outlet Temp.(°C)	45	43	43	43	43
Heat Transfer (cal.s^{-1})	44.1	40.2	40.2	40.2	40.2
2 flames					
Inlet Temp. (°C)	22	22	22	22	22
Outlet Temp.(°C)	61	59	58	58	58
Heat Transfer (cal.s^{-1})	74.7	70.9	69.0	69.0	69.0

Run No. L25 Additive trichloro-trifluoroethane

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	4.7	4.7	4.8	4.9	5.1
Air Flow (l.s^{-1})	0.070	0.070	0.071	0.073	0.075
Fraction of stoich.flow	0.278	0.278	0.284	0.289	0.291
Calorimeter					
1 flame					
Inlet Temp. (°C)	21	21	21	21	21
Outlet Temp. (°C)	47	47	46	45	43
Heat Transfer (cal.s^{-1})	49.8	49.8	47.9	46.0	42.2
2 flames					
Inlet Temp. (°C)	21	21	21	21	21
Outlet Temp. (°C)	61	60	58	58	56
Heat Transfer (cal.s^{-1})	76.6	74.7	70.9	70.9	67.1

Run No. G1 Additive nitrogen

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	5.0	5.0	5.1	5.1	4.9
Air Flow (l.s^{-1})	0.074	0.074	0.075	0.075	0.073
Fraction of stoich.flow	0.294	0.294	0.299	0.299	0.289
Calorimeter					
1 flame					
Inlet Temp. (°C)	22	22	22	22	22
Outlet Temp. (°C)	41	41	43	43	44
Heat Transfer (cal.s^{-1})	36.4	36.4	40.2	40.2	42.2
2 flames					
Inlet Temp. (°C)	22	22	22	22	22
Outlet Temp. (°C)	56	57	58	58	60
Heat Transfer (cal.s^{-1})	65.1	67.1	69.0	69.0	72.8

Run No. G2 Additive argon

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	5.2	5.1	5.3	5.1	5.1
Air Flow (l.s^{-1})	0.076	0.075	0.077	0.075	0.075
Fraction of stoich.flow	0.384	0.299	0.309	0.299	0.299
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp.(^{o}C)	40	40	42	42	44
Heat Transfer (cal.s^{-1})	32.6	32.6	36.4	36.4	40.2
2 flames					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp.(^{o}C)	54	56	57	58	60
Heat Transfer (cal.s^{-1})	59.4	63.2	65.1	67.1	70.9

Run No. G3 Additive carbon dioxide

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	5.3	5.2	5.2	5.2	5.1
Air Flow (l.s^{-1})	0.077	0.076	0.076	0.076	0.075
Fraction of stoich.flow	0.309	0.304	0.304	0.304	0.299
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	24	24	24	24	24
Outlet Temp.(^{o}C)	47	47	46	46	45
Heat Transfer (cal.s $^{-1}$)	44.1	44.1	69.0	65.1	65.1
2 flames					
Inlet Temp. (^{o}C)	24	24	24	24	24
Outlet Temp.(^{o}C)	61	61	60	58	58
Heat Transfer (cal.s^{-1})	70.9	70.9	69.0	65.1	65.1

Run No. G4 Additive commercial propane

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	7.7	7.1	6.4	5.8	5.4
Air Flow ($l.s^{-1}$)	0.109	0.101	0.092	0.084	0.079
Fraction of stoich.flow	0.433	0.401	0.365	0.334	0.314
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp. (^{o}C)	49	50	50	50	49
Heat Transfer ($cal.s^{-1}$)	51.7	53.6	53.6	53.6	51.7
2 flames					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp. (^{o}C)	65	64	62	60	58
Heat Transfer ($cal.s^{-1}$)	82.4	80.5	76.6	72.8	69.0

Run No. G5 Additive carbon monoxide

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	6.0	5.9	5.6	5.3	5.0
Air Flow ($l.s^{-1}$)	0.087	0.086	0.082	0.077	0.074
Fraction of stoich.flow	0.344	0.339	0.324	0.309	0.294
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	24	24	24	24	24
Outlet Temp. (^{o}C)	43	44	44	45	45
Heat Transfer ($cal.s^{-1}$)	36.4	38.3	38.3	40.2	40.2
2 flames					
Inlet Temp. (^{o}C)	24	24	24	24	24
Outlet Temp. (^{o}C)	59	59	59	60	61
Heat Transfer ($cal.s^{-1}$)	67.1	67.1	67.1	69.0	70.9

Run No. G6 Additive oxygen

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	3.0	3.3	3.8	4.2	4.5
Air Flow (l.s^{-1})	0.049	0.053	0.059	0.064	0.068
Fraction of stoich.flow	0.194	0.209	0.234	0.253	0.268
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	24	24	24	24	24
Outlet Temp.(^{o}C)	47	48	47	47	46
Heat Transfer (cal.s^{-1})	44.1	46.0	44.1	44.1	42.2
2 flames					
Inlet Temp. (^{o}C)	24	24	24	24	24
Outlet Temp.(^{o}C)	61	61	60	59	58
Heat Transfer (cal.s^{-1})	70.9	70.9	69.0	67.1	65.1

Run No. G7 Additive acetylene

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	6.1	6.0	5.8	5.4	5.1
Air Flow (l.s^{-1})	0.088	0.087	0.084	0.079	0.075
Fraction of stoich.flow	0.350	0.344	0.334	0.314	0.299
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp.(^{o}C)	50	51	49	47	44
Heat Transfer (cal.s^{-1})	53.6	55.6	51.7	47.9	42.2
2 flames					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp.(^{o}C)	67	66	63	60	57
Heat Transfer (cal.s^{-1})	86.2	84.3	78.6	72.8	67.1

Run No. G8 Additive methane

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	6.1	5.8	5.6	5.2	5.1
Air Flow ($l.s^{-1}$)	0.088	0.084	0.082	0.076	0.075
Fraction of stoich.flow	0.350	0.334	0.324	0.304	0.299
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp. (^{o}C)	52	50	49	47	45
Heat Transfer ($cal.s^{-1}$)	57.5	53.6	51.7	47.9	44.1
2 flames					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp. (^{o}C)	67	66	63	61	58
Heat Transfer ($cal.s^{-1}$)	86.2	84.3	78.6	74.7	69.0

Run No. G9 Additive air

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	-	-	-	-	-
Air Flow ($l.s^{-1}$)	-	-	-	-	-
Fraction of stoich.flow	-	-	-	-	-
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp. (^{o}C)	40	42	42	41	42
Heat Transfer ($cal.s^{-1}$)	34.5	30.3	38.3	36.4	38.3
2 flames					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp. (^{o}C)	57	57	57	55	55
Heat Transfer ($cal.s^{-1}$)	67.1	67.1	67.1	63.2	63.2

Run No. G10 Additive hydrogen

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	3.9	4.0	4.2	4.5	4.7
Air Flow ($l.s^{-1}$)	0.060	0.061	0.064	0.068	0.070
Fraction of stoich.flow	0.239	0.243	0.253	0.268	0.278
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp. (^{o}C)	43	43	44	44	43
Heat Transfer ($cal.s^{-1}$)	38.3	38.3	40.2	40.2	38.3
2 flames					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp. (^{o}C)	55	56	57	57	57
Heat Transfer ($cal.s^{-1}$)	61.3	63.2	65.1	65.1	65.1

Run No. G11 Additive helium

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	5.2	5.2	5.1	5.2	5.2
Air Flow ($l.s^{-1}$)	0.076	0.076	0.075	0.076	0.076
Fraction of stoich.flow	0.304	0.304	0.299	0.304	0.304
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp. (^{o}C)	44	44	42	42	44
Heat Transfer ($cal.s^{-1}$)	40.2	40.2	36.4	36.4	40.2
2 flames					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp. (^{o}C)	59	58	58	58	59
Heat Transfer ($cals.^{-1}$)	69.0	67.1	67.1	67.1	69.0

Run No. G12 Additive methyl bromide

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	12.6	11.0	9.0	7.3	5.7
Air Flow ($l.s^{-1}$)	0.176	0.154	0.126	0.104	0.083
Fraction of stoich.flow	0.699	0.610	0.502	0.412	0.329
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	21	21	21	21	21
Outlet Temp. (^{o}C)	50	49	49	49	46
Heat Transfer ($cal.s^{-1}$)	55.6	53.6	53.6	53.6	47.9
2 flames					
Inlet Temp. (^{o}C)	21	21	21	21	21
Outlet Temp. (^{o}C)	63	63	61	59	57
Heat Transfer ($cal.s^{-1}$)	80.5	80.5	76.6	72.8	69.0

Run No. G13 Additive ethane

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	7.4	6.9	6.3	5.7	5.3
Air Flow ($l.s^{-1}$)	0.105	0.098	0.091	0.083	0.078
Fraction of stoich.flow	00.417	0.391	0.360	0.329	0.309
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp. (^{o}C)	52	50	48	48	46
Heat Transfer ($cal.s^{-1}$)	57.5	53.6	49.8	49.8	46.0
2 flames					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp. (^{o}C)	69	69	65	61	59
Heat Transfer ($cal.s^{-1}$)	90.1	90.1	82.4	74.7	70.9

Run No. G14 Additive propane

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	7.6	7.0	6.4	5.7	5.3
Air Flow (l.s^{-1})	0.108	0.100	0.092	0.083	0.078
Fraction of stoich.flow	0.427	0.396	0.365	0.329	0.309
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	24	24	24	24	24
Outlet Temp. (^{o}C)	52	52	51	50	48
Heat Transfer (cal.s^{-1})	53.6	53.6	51.7	49.8	46.0
2 flames					
Inlet Temp. (^{o}C)	24	24	24	24	24
Outlet Temp. (^{o}C)	67	66	63	60	59
Heat Transfer (cal.s^{-1})	82.4	80.5	74.7	69.0	67.1

Run No. G15 Additive butane

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	8.0	7.3	6.5	5.8	5.4
Air Flow (l.s^{-1})	0.113	0.104	0.093	0.084	0.079
Fraction of stoich.flow	0.448	0.412	0.370	0.334	0.314
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp. (^{o}C)	51	49	48	45	44
Heat Transfer (cal.s^{-1})	53.6	49.8	47.9	42.2	40.2
2 flames					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp. (^{o}C)	69	65	62	58	55
Heat Transfer (cal.s^{-1})	88.1	80.5	74.7	67.1	61.3

Run No. G16 Additive ethylene

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	7.2	6.8	6.3	5.8	5.4
Air Flow ($1.s^{-1}$)	0.102	0.097	0.091	0.084	0.079
Fraction of stoich.flow	0.407	0.386	0.360	0.334	0.314
Calorimeter					
1 flame					
Inlet Temp.(^{o}C)	22	22	22	22	22
Outlet Temp.(^{o}C)	49	49	48	48	46
Heat Transfer ($cal.s^{-1}$)	51.7	51.7	49.8	49.8	46.0
2 flames					
Inlet Temp. (^{o}C)	22	22	22	22	22
Outlet Temp.(^{o}C)	64	63	61	60	58
Heat Transfer ($cal.s^{-1}$)	80.5	78.6	74.7	72.8	69.0

Run No. G17 Additive nitrogen dioxide

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	5.8	5.8	5.6	5.2	5.1
Air Flow ($1.s^{-1}$)	0.084	0.084	0.082	0.076	0.075
Fraction of stoich.flow	0.334	0.334	0.324	0.304	0.299
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp.(^{o}C)	46	46	44	46	46
Heat Transfer ($cal.s^{-1}$)	44.1	44.1	40.2	44.1	44.1
2 flames					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp.(^{o}C)	62	60	59	61	61
Heat Transfer ($cal.s^{-1}$)	74.7	70.9	69.0	72.8	72.8

Run No. G18 Additive hydrogen chloride

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	5.3	5.2	5.2	5.1	5.1
Air Flow (l.s^{-1})	0.078	0.076	0.076	0.075	0.075
Fraction of stoich.flow	0.309	0.304	0.304	0.299	0.299
Calorimeter					
1 flame					
Inlet Temp. (°C)	21	21	21	21	21
Outlet Temp.(°C)	44	45	46	46	46
Heat Transfer (cal.s^{-1})	44.1	46.0	47.9	47.9	47.9
2 flames					
Inlet Temp. (°C)	21	21	21	21	21
Outlet Temp.(°C)	58	58	58	60	60
Heat Transfer (cal.s^{-1})	70.9	70.9	70.9	74.7	74.7

Run No. G19 Additive chlorine

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	7.8	7.4	6.6	5.8	5.4
Air Flow (l.s^{-1})	0.110	0.105	0.094	0.084	0.079
Heat Transfer (cal.s^{-1})	0.438	0.417	0.375	0.334	0.314
Calorimeter					
1 flame					
Inlet Temp. (°C)	23	23	23	23	23
Outlet Temp.(°C)	50	50	49	47	47
Heat Transfer (cal.s^{-1})	51.7	51.7	49.8	46.0	46.0
2 flames					
Inlet Temp. (°C)	23	23	23	23	23
Outlet Temp.(°C)	63	65	65	63	61
Heat Transfer (cal.s^{-1})	76.6	80.5	80.5	76.6	72.8

Run No. G20 Additive nitric oxide

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	6.3	6.1	5.7	5.4	5.1
Air Flow (l.s^{-1})	0.091	0.088	0.082	0.079	0.075
Fraction of stoich.flow	0.360	0.350	0.329	0.314	0.299
Calorimeter					
1 flame					
Inlet Temp. (°C)	23	23	23	23	23
Outlet Temp. (°C)	45	45	44	43	43
Heat Transfer (cal.s^{-1})	42.2	42.2	40.2	38.3	38.3
2 flames					
Inlet Temp. (°C)	23	23	23	23	23
Outlet Temp. (°C)	60	60	61	60	58
Heat Transfer (cal.s^{-1})	70.9	70.9	72.8	70.5	67.1

Run No. G21 Additive sulphur dioxide

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	5.0	5.0	5.0	5.1	5.1
Air Flow (l.s^{-1})	0.074	0.074	0.074	0.075	0.075
Fraction of stoich.flow	0.294	0.294	0.294	0.299	0.299
Calorimeter					
1 flame					
Inlet Temp. (°C)	24	24	24	24	24
Outlet Temp. (°C)	44	45	45	46	46
Heat Transfer (cal.s^{-1})	38.3	40.2	40.2	42.2	42.2
2 flames					
Inlet Temp. (°C)	24	24	24	24	24
Outlet Temp. (°C)	58	58	60	60	61
Heat Transfer (cal.s^{-1})	65.1	65.1	69.0	69.0	70.9

Run No. G22 **Additive** ammonia

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	5.2	5.2	5.2	5.1	5.1
Air Flow (l.s^{-1})	0.076	0.076	0.076	0.075	0.075
Fraction of stoich.flow	0.304	0.304	0.304	0.299	0.299
Calorimeter					
1 flame					
Inlet Temp (^{o}C)	22	22	22	22	22
Outlet Temp(^{o}C)	42	42	44	44	46
Heat Transfer (cal.s^{-1})	38.3	38.3	42.2	42.2	46.0
2 flames					
Inlet Temp (^{o}C)	22	22	22	22	22
Outlet Temp(^{o}C)	59	59	60	62	64
Heat Transfer (cal.s^{-1})	70.9	70.9	72.8	76.6	80.5

Run No. G23 **Additive** sulphur trioxide

Add. Conc.	20%	15%	10%	5%	2.5%
Smoke Point					
Air Rotameter	5.2	5.2	5.1	5.1	5.1
Air Flow (l.s^{-1})	0.076	0.076	0.075	0.075	0.075
Fraction of stoich.flow	0.304	0.304	0.299	0.299	0.299
Calorimeter					
1 flame					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp.(^{o}C)	45	45	46	48	48
Heat Transfer (cal.s^{-1})	42.2	42.2	44.1	47.9	47.9
2 flames					
Inlet Temp. (^{o}C)	23	23	23	23	23
Outlet Temp.(^{o}C)	51	51	51	53	53
Heat Transfer (cal.s^{-1})	53.6	53.6	53.6	57.5	57.5

Run No. L1 Additive n-pentane

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (°C)	Rad. (Kcal. $m^{-2}h.^{-1}ster.^{-1}$)
		1 flame	2 flames			
20	2	2.33	4.92	0.020	961	720
	4	4.82	8.82	0.027	1054	1300
	6	21.29	22.51	0.055	1176	3761
	8	22.80	24.42	0.082	1295	7692
	10	24.07	26.13	0.104	1388	12278
	12	24.71	27.05	0.113	1436	14952
	14	23.83	25.80	0.100	1371	11336
	16	22.80	24.42	0.082	1295	7692
15	2	2.61	5.33	0.021	971	780
	4	5.00	9.14	0.028	1054	1348
	6	21.24	22.45	0.055	1166	3662
	8	22.57	24.14	0.072	1305	6935
	10	23.78	25.75	0.090	1402	10999
	12	24.03	26.09	0.095	1416	11992
	14	22.73	24.37	0.059	1401	7197
	16	22.50	24.05	0.074	1285	6773
10	2	3.12	6.07	0.023	984	893
	4	5.54	10.18	0.030	1065	1494
	6	13.46	22.29	0.049	1177	3365
	8	22.31	23.81	0.062	1314	6106
	10	23.32	25.14	0.074	1409	9200
	12	23.13	24.89	0.070	1401	8539
	14	23.53	24.10	0.061	1356	6676
	16	21.77	23.14	0.052	1281	4711
5	2	3.52	6.67	0.024	1001	982
	4	5.58	10.27	0.030	1068	1505
	6	9.69	21.78	0.038	1176	2598
	8	21.89	23.29	0.050	1317	4964
	10	22.65	24.27	0.055	1413	6903
	12	22.26	23.77	0.048	1397	5799
	14	21.54	22.85	0.039	1338	4079
	16	10.58	21.95	0.031	1269	2723
2.5	2	3.76	7.04	0.024	1018	1035
	4	2.10	9.33	0.027	1071	1367
	6	8.34	21.51	0.033	1172	2232
	8	21.57	22.88	0.043	1310	4192
	10	22.22	23.71	0.046	1405	5665
	12	21.90	23.30	0.041	1388	4850
	14	21.19	22.41	0.033	1326	3349
	16	8.62	21.57	0.027	1248	2241

Run No. L.2 Additive n-hexane

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.36	4.96	0.020	964	726
	4	4.37	8.04	0.025	1048	1181
	6	21.17	22.36	0.055	1152	3525
	8	22.83	24.47	0.085	1288	7844
	10	24.08	26.14	0.108	1376	12386
	12	24.65	26.94	0.116	1418	14726
	14	23.80	25.75	0.103	1356	11250
	16	21.85	23.24	0.040	1388	4723
15	2	3.42	6.52	0.023	1006	956
	4	4.70	8.60	0.026	1057	1264
	6	21.19	22.38	0.054	1162	3555
	8	22.67	24.27	0.078	1293	7287
	10	23.79	25.75	0.095	1384	11109
	12	24.16	26.27	0.100	1413	12551
	14	23.42	25.26	0.090	1353	9772
	16	22.57	24.13	0.076	1286	6971
10	2	2.81	5.61	0.022	973	824
	4	5.25	9.61	0.029	1059	1417
	6	11.85	22.12	0.049	1152	3134
	8	22.32	23.83	0.065	1300	6185
	10	23.30	25.12	0.075	1402	9166
	12	23.22	25.01	0.072	1404	8850
	14	22.48	24.04	0.062	1343	8562
	16	21.81	23.18	0.054	1276	4832
5	2	3.70	6.96	0.025	1003	1028
	4	5.48	10.06	0.030	1062	1480
	6	9.40	21.73	0.039	1158	2539
	8	21.84	23.21	0.050	1307	4836
	10	23.17	24.94	0.075	1383	8753
	12	22.28	23.79	0.049	1393	5864
	14	21.53	22.83	0.040	1327	4068
	16	10.36	21.91	0.031	1263	2678
2.5	2	3.68	6.92	0.025	1001	1023
	4	5.13	9.39	0.028	1062	1381
	6	8.15	21.46	0.033	1164	2182
	8	21.54	22.84	0.043	1303	4117
	10	22.32	23.84	0.048	1407	5934
	12	21.87	23.26	0.042	1374	4798
	14	21.24	22.47	0.033	1336	3431
	16	8.06	21.44	0.026	1236	2095

Run No. L3 Additive cyclohexane

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
20	2	2.07	4.56	0.020	940	673
	4	4.12	8.36	0.026	1048	1321
	6	8.58	21.56	0.034	1172	2299
	8	22.79	24.42	0.075	1324	7582
	10	23.63	25.55	0.084	1407	10384
	12	24.12	26.23	0.090	1447	12224
	14	23.41	25.24	0.084	1376	9634
	16	22.49	24.04	0.070	1302	6688
15	2	2.36	4.96	0.021	951	731
	4	4.65	8.51	0.026	1054	1252
	6	21.23	22.44	0.054	1170	3635
	8	22.46	24.00	0.065	1322	6532
	10	23.48	25.35	0.077	1417	9757
	12	23.84	25.84	0.082	1444	11075
	14	22.89	24.57	0.070	1365	7828
	16	22.01	23.42	0.059	1280	5334
10	2	3.09	6.03	0.024	971	892
	4	5.12	9.36	0.028	1061	1378
	6	12.54	22.20	0.047	1177	3228
	8	22.16	23.62	0.057	1318	5671
	10	23.02	24.75	0.066	1406	8143
	12	22.89	24.58	0.062	1409	7708
	14	22.14	23.60	0.053	1340	5576
	16	21.38	22.64	0.044	1265	3825
5	2	3.44	6.55	0.025	984	970
	4	5.38	9.86	0.029	1066	1448
	6	9.36	21.72	0.037	1173	2513
	8	21.70	23.04	0.045	1317	4468
	10	22.40	23.94	0.050	1406	6169
	12	21.99	23.42	0.042	1396	5065
	14	21.40	22.67	0.036	1338	3765
	16	9.78	21.81	0.028	1279	2521
2.5	2	3.52	6.67	0.024	1001	982
	4	5.10	9.33	0.027	1071	1367
	6	8.32	21.50	0.033	1171	2227
	8	21.54	22.84	0.042	1312	4111
	10	22.20	23.69	0.046	1402	5622
	12	22.01	23.45	0.044	1384	5145
	14	21.54	22.84	0.043	1303	4117
	16	8.41	21.53	0.026	1252	2181

Run No. L4 Additive chloroform

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
20	2	3.07	5.99	0.023	980	882
	4	5.14	9.40	0.029	1052	1390
	6	21.20	22.39	0.056	1152	3589
	8	22.60	24.17	0.075	1295	7036
	10	23.21	24.98	0.083	1352	8977
	12	23.18	24.94	0.081	1356	8847
	14	22.83	24.49	0.072	1346	7680
	16	21.81	23.17	0.060	1241	4897
15	2	3.37	6.44	0.024	991	951
	4	5.65	10.41	0.031	1062	1529
	6	21.23	22.45	0.034	1323	3423
	8	22.42	23.95	0.069	1296	6486
	10	23.24	25.02	0.078	1378	8998
	12	23.11	24.86	0.073	1383	8520
	14	22.73	24.36	0.066	1360	7294
	16	21.77	23.12	0.055	1263	4751
10	2	3.70	6.96	0.025	1003	1028
	4	5.90	10.97	0.031	1076	1592
	6	11.06	22.01	0.046	1154	2962
	8	22.13	23.58	0.058	1307	5609
	10	23.16	24.93	0.071	1400	8644
	12	22.91	24.61	0.063	1406	7773
	14	22.08	23.53	0.052	1337	5427
	16	21.39	22.65	0.043	1275	3832
5	2	3.70	6.96	0.025	1003	1028
	4	5.39	9.88	0.029	1067	1451
	6	10.06	21.85	0.040	1171	2699
	8	21.86	23.24	0.049	1317	4865
	10	23.18	24.95	0.079	1365	8834
	12	22.51	24.10	0.050	1426	6468
	14	21.63	22.96	0.038	1364	4233
	16	10.58	21.95	0.031	1269	2723
2.5	2	3.76	7.04	0.024	1018	1035
	4	5.95	9.43	0.027	1074	1380
	6	9.32	21.71	0.036	1180	2494
	8	21.71	23.06	0.045	1320	4504
	10	22.59	24.20	0.053	1418	6728
	12	22.21	23.70	0.045	1411	5616
	14	21.39	22.66	0.035	1346	3734
	16	9.03	21.66	0.028	1252	2349

Run No. L5 Additive acetone

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	2 flames	Emiss.	Flame Temp. (°C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
20	2	2.59	5.30	0.021	969	776
	4	4.96	9.06	0.028	1052	1338
	6	5.57	10.24	0.032	1048	1515
	8	21.64	22.97	0.044	1315	4342
	10	22.12	23.59	0.045	1396	5416
	12	21.90	23.31	0.042	1380	4873
	14	21.51	22.81	0.038	1341	4006
	16	8.81	21.61	0.029	1232	2308
15	2	2.79	5.58	0.022	972	820
	4	4.92	8.99	0.027	1060	1322
	6	8.28	21.49	0.033	1169	2217
	8	21.54	22.84	0.043	1303	4117
	10	22.04	23.48	0.044	1388	5205
	12	21.88	23.28	0.041	1385	4813
	14	21.44	22.73	0.036	1347	3848
	16	8.87	21.62	0.030	1223	2332
10	2	2.98	5.86	0.023	974	864
	4	6.60	12.87	0.037	1060	1812
	6	7.68	21.35	0.032	1153	2856
	8	21.55	22.86	0.042	1314	4136
	10	22.08	23.53	0.044	1396	5296
	12	21.86	23.26	0.040	1391	4759
	14	21.44	22.73	0.035	1356	3830
	16	13.49	22.28	0.052	1159	3393
5	2	2.98	5.86	0.022	986	858
	4	4.81	8.81	0.026	1064	1292
	6	7.62	21.33	0.031	1160	2032
	8	21.57	22.88	0.042	1318	4178
	10	22.15	23.63	0.043	1418	5459
	12	21.87	23.26	0.039	1400	4748
	14	21.34	22.59	0.033	1356	3604
	16	8.58	21.56	0.027	1246	2232
2.5	2	3.22	6.21	0.022	1004	907
	4	4.94	9.05	0.026	1072	1323
	6	7.78	21.37	0.031	1168	2073
	8	21.53	22.84	0.041	1319	4088
	10	22.13	23.61	0.043	1415	5418
	12	21.75	23.11	0.038	1387	4478
	14	21.17	22.38	0.031	1343	3281
	16	8.39	21.52	0.026	1251	2177

Run No. L6 Additive methanol

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.64	5.37	0.021	973	787
	4	5.22	9.56	0.029	1057	1410
	6	8.96	21.64	0.034	1186	2392
	8	21.34	22.60	0.035	1336	3646
	10	21.73	23.10	0.034	1425	4390
	12	21.27	22.51	0.028	1400	3409
	14	8.92	21.64	0.021	1346	2240
	16	6.32	12.14	0.019	1252	1597
15	2	3.06	5.97	0.023	980	879
	4	5.17	9.45	0.029	1054	1396
	6	9.21	21.69	0.034	1195	2450
	8	21.42	22.69	0.037	1332	3808
	10	21.91	23.32	0.037	1428	4814
	12	21.36	22.63	0.030	1396	3611
	14	10.10	21.87	0.024	1343	2540
	16	6.71	13.49	0.021	1241	1714
10	2	3.06	5.97	0.023	980	879
	4	5.15	9.41	0.028	1063	1384
	6	8.53	21.55	0.033	1179	2276
	8	21.46	22.74	0.039	1321	3911
	10	21.92	23.33	0.039	1411	4867
	12	21.48	22.77	0.033	1384	3866
	14	10.65	21.96	0.026	1332	2676
	16	7.55	21.33	0.023	1254	1942
5	2	3.16	6.13	0.024	976	906
	4	5.11	9.36	0.027	1072	1370
	6	8.05	21.44	0.032	1169	2150
	8	21.47	22.75	0.040	1314	3939
	10	22.00	23.43	0.041	1407	5068
	12	21.64	22.98	0.036	1386	4234
	14	12.51	22.22	0.029	1338	3033
	16	7.52	21.32	0.023	1252	1934
2.5	2	3.20	6.20	0.022	1003	905
	4	5.04	9.22	0.026	1078	1345
	6	7.62	21.33	0.031	1160	2032
	8	21.32	22.54	0.060	1152	3846
	10	22.01	23.45	0.042	1401	5123
	12	21.56	22.87	0.037	1360	4081
	14	12.37	22.20	0.030	1324	3027
	16	7.82	21.39	0.025	1239	2028

Run No. L7 Additive methyl ethyl ketone

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
		1 flame	2 flames			
20	2	2.82	5.63	0.022	974	826
	4	5.22	9.56	0.029	1057	1410
	6	8.27	21.49	0.035	1150	2228
	8	21.70	23.05	0.047	1304	4509
	10	22.31	23.82	0.050	1390	5937
	12	22.15	23.62	0.047	1384	5506
	14	11.76	22.11	0.045	1176	3084
	16	10.56	21.94	0.035	1228	2761
15	2	2.74	5.50	0.022	968	809
	4	4.92	8.99	0.028	1049	1329
	6	7.90	21.40	0.033	1153	2120
	8	21.64	22.96	0.045	1306	4343
	10	22.28	23.80	0.048	1401	5855
	12	22.03	23.47	0.044	1388	5195
	14	21.55	22.85	0.039	1339	4087
	16	10.53	21.94	0.033	1247	2734
10	2	3.00	5.89	0.023	976	868
	4	4.93	9.01	0.027	1060	1325
	6	7.43	21.29	0.032	1142	1992
	8	21.51	22.80	0.043	1297	4058
	10	22.17	23.65	0.046	1396	5547
	12	21.97	23.39	0.042	1392	5016
	14	21.45	22.74	0.036	1348	3863
	16	10.75	21.98	0.031	1274	2757
5	2	3.09	6.02	0.022	994	880
	4	4.64	8.49	0.026	1053	1249
	6	7.48	21.30	0.031	1154	1996
	8	21.53	22.83	0.042	1309	4087
	10	22.15	23.62	0.044	1408	5460
	12	21.88	23.28	0.040	1394	4796
	14	21.38	22.64	0.034	1353	3692
	16	9.31	21.72	0.028	1262	2414
2.5	2	3.31	6.36	0.022	1011	928
	4	4.79	8.76	0.026	1063	1285
	6	7.78	21.37	0.031	1168	2073
	8	21.51	22.81	0.041	1315	4046
	10	22.15	23.63	0.043	1417	5449
	12	21.88	23.28	0.039	1403	4775
	14	21.24	22.47	0.032	1347	3420
	16	8.30	21.50	0.026	1247	2154

Run No. L8 Additive benzene

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.61	5.32	0.022	958	785
	4	5.05	9.22	0.029	1047	1366
	6	21.23	22.43	0.056	1158	3646
	8	22.20	23.66	0.068	1265	5911
	10	22.99	24.68	0.079	1336	8229
	12	22.68	24.28	0.070	1332	7205
	14	22.90	24.57	0.074	1346	7894
	16	21.90	23.28	0.057	1272	5048
15	2	3.09	6.03	0.024	971	892
	4	5.24	9.59	0.030	1048	1420
	6	12.96	22.24	0.051	1158	3321
	8	22.01	23.42	0.060	1275	5347
	10	23.08	24.81	0.076	1364	8465
	12	23.22	25.00	0.074	1394	8872
	14	22.55	24.13	0.063	1348	6760
	16	22.00	23.41	0.058	1284	5298
10	2	3.38	6.46	0.025	980	958
	4	5.35	9.81	0.030	1055	1448
	6	10.34	21.90	0.042	1164	2778
	8	21.74	23.09	0.051	1283	4639
	10	22.95	24.65	0.068	1384	7967
	12	22.77	24.42	0.060	1401	7319
	14	22.17	23.65	0.050	1367	5613
	16	21.37	22.63	0.042	1279	3782
5	2	3.38	6.46	0.024	992	953
	4	5.42	9.94	0.029	1068	1458
	6	9.18	21.68	0.037	1167	2469
	8	21.65	22.98	0.047	1294	4400
	10	22.73	24.37	0.059	1401	7197
	12	22.36	23.90	0.048	1415	6048
	14	21.69	23.04	0.040	1358	4395
	16	10.44	21.93	0.031	1265	2695
2.5	2	3.34	6.40	0.023	1000	939
	4	5.35	9.81	0.028	1075	1435
	6	8.54	21.55	0.034	1170	2289
	8	21.68	22.89	0.044	1303	4212
	10	22.60	24.20	0.054	1412	6752
	12	22.10	23.56	0.044	1400	5347
	14	21.39	22.65	0.035	1345	3726
	16	9.05	21.66	0.028	1252	2354

Run No. L9 Additive carbon tetrachloride

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	2 flames	Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
20	2	2.83	5.64	0.022	975	828
	4	5.52	10.14	0.031	1055	1496
	6	21.32	22.54	0.058	1164	3835
	8	22.68	24.27	0.086	1262	7413
	10	23.77	25.69	0.113	1320	11287
	12	24.32	26.43	0.130	1338	13595
	14	23.92	25.89	0.115	1332	11860
	16	22.63	24.18	0.095	1220	7337
15	2	3.07	5.99	0.023	980	882
	4	5.69	10.51	0.031	1064	1540
	6	11.76	22.11	0.045	1176	3084
	8	22.61	24.18	0.080	1276	7144
	10	23.79	25.74	0.106	1345	11285
	12	24.16	26.23	0.117	1356	12804
	14	23.45	25.29	0.096	1335	9960
	16	22.29	23.76	0.080	1225	6258
10	2	3.38	6.46	0.024	992	953
	4	6.12	11.51	0.033	1069	1663
	6	12.97	22.24	0.050	1164	3314
	8	22.60	24.17	0.076	1291	7057
	10	23.70	25.63	0.095	1372	10790
	12	23.62	25.52	0.093	1368	10481
	14	22.91	24.59	0.075	1344	7953
	16	21.83	23.19	0.061	1239	4948
5	2	3.69	6.94	0.025	1002	1026
	4	5.78	10.70	0.031	1069	1562
	6	11.15	22.03	0.044	1170	2962
	8	22.31	23.81	0.063	1308	6118
	10	23.21	25.00	0.071	1408	8811
	12	22.69	24.31	0.058	1400	7061
	14	22.13	23.59	0.050	1359	5504
	16	21.20	22.40	0.041	1252	3447
2.5	2	3.52	6.69	0.023	1013	977
	4	5.22	9.56	0.027	1078	1397
	6	10.19	21.87	0.039	1183	2720
	8	21.85	23.23	0.048	1324	4843
	10	22.86	24.55	0.059	1423	7575
	12	22.49	24.06	0.052	1407	6428
	14	21.68	23.02	0.041	1347	4382
	16	10.82	21.99	0.032	1265	2782

Run No. L10 Additive i-propanol

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
20	2	2.45	5.09	0.020	971	743
	4	5.06	9.25	0.029	1048	1370
	6	10.25	21.88	0.042	1161	2759
	8	22.08	23.51	0.058	1298	5485
	10	23.01	24.73	0.068	1393	8137
	12	22.78	24.73	0.065	1374	7426
	14	22.29	23.78	0.061	1316	6044
	16	21.42	22.68	0.052	1218	3990
15	2	2.85	5.67	0.022	976	832
	4	5.45	10.00	0.030	1060	1473
	6	9.55	21.75	0.039	1163	2574
	8	21.93	23.33	0.053	1303	5074
	10	23.31	25.13	0.072	1418	9140
	12	22.46	24.02	0.056	1376	6423
	14	21.94	23.34	0.051	1318	5074
	16	21.25	22.47	0.044	1240	3576
10	2	3.18	6.15	0.023	988	904
	4	5.22	9.56	0.029	1057	1410
	6	8.70	21.58	0.036	1158	2344
	8	21.79	23.16	0.048	1313	4718
	10	22.37	23.90	0.052	1387	6128
	12	22.13	23.60	0.047	1382	5475
	14	21.62	22.95	0.042	1328	4280
	16	11.77	22.12	0.036	1249	3576
5	2	3.22	6.22	0.023	992	913
	4	4.98	9.11	0.027	1064	1338
	6	8.36	21.51	0.033	1172	2236
	8	21.65	22.98	0.044	1316	4360
	10	22.24	23.74	0.047	1401	5733
	12	22.00	23.43	0.043	1389	5096
	14	21.35	22.61	0.035	1338	3660
	16	9.15	21.68	0.029	1244	2387
2.5	2	3.09	6.02	0.022	994	880
	4	4.93	9.02	0.026	1072	1320
	6	8.28	21.49	0.032	1179	2207
	8	21.59	22.90	0.042	1320	4204
	10	22.68	24.31	0.057	1406	7033
	12	21.87	23.27	0.040	1392	4768
	14	21.27	22.51	0.033	1343	3492
	16	11.76	22.11	0.045	1176	3084

Run No. L11 Additive n-propanol

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
		1 flame	2 flames			
20	2	2.50	5.16	0.020	975	753
	4	5.17	9.45	0.029	1054	1396
	6	10.14	21.86	0.042	1158	2735
	8	22.09	23.53	0.058	1300	5519
	10	22.97	24.68	0.069	1383	8053
	12	22.76	24.41	0.066	1366	7395
	14	22.28	23.77	0.061	1315	6020
	16	21.33	22.56	0.050	1212	3779
15	2	2.87	5.70	0.022	978	837
	4	5.41	9.92	0.030	1052	1462
	6	9.64	21.77	0.040	1158	2604
	8	21.95	23.36	0.053	1308	5136
	10	22.69	24.32	0.060	1389	7111
	12	22.43	23.97	0.057	1364	6349
	14	21.99	23.41	0.052	1321	5215
	16	21.16	22.36	0.043	1229	3400
10	2	3.15	6.12	0.023	987	900
	4	5.22	9.56	0.029	1057	1410
	6	9.11	21.67	0.037	1164	2452
	8	21.72	23.07	0.048	1300	4558
	10	22.35	23.88	0.052	1384	6080
	12	22.13	23.59	0.048	1373	5473
	14	21.56	22.87	0.042	1316	4153
	16	11.10	22.03	0.035	1243	2869
5	2	3.29	6.32	0.023	996	927
	4	4.94	9.04	0.027	1061	1329
	6	8.54	21.55	0.034	1170	2289
	8	21.55	22.85	0.044	1297	4153
	10	22.19	23.68	0.047	1392	5614
	12	22.47	24.02	0.056	1376	6435
	14	21.35	22.61	0.036	1328	3676
	16	10.18	21.88	0.031	1257	2639
2.5	2	3.15	6.12	0.022	999	894
	4	4.81	8.81	0.026	1064	1292
	6	7.96	21.42	0.032	1165	2126
	8	21.52	22.81	0.042	1307	4062
	10	22.17	23.65	0.045	1404	5531
	12	21.85	23.24	0.040	1388	4723
	14	12.55	22.22	0.033	1294	3089
	16	8.90	21.63	0.028	1247	2319

Run No. L12 Additive di-ethyl ether

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	2 flames	Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
20	2	2.60	5.31	0.020	983	772
	4	5.04	9.21	0.028	1056	1358
	6	8.98	21.64	0.038	1152	2430
	8	21.83	23.20	0.053	1286	4861
	10	22.62	24.22	0.061	1372	6928
	12	22.35	23.87	0.056	1357	6141
	14	21.90	23.30	0.050	1319	4984
	16	10.96	22.01	0.086	1230	2852
15	2	2.79	5.58	0.021	984	815
	4	5.31	9.72	0.030	1052	1438
	6	8.41	21.52	0.036	1147	2271
	8	21.73	23.08	0.050	1288	4605
	10	22.42	23.97	0.055	1376	6308
	12	22.08	23.53	0.048	1364	5357
	14	21.60	22.91	0.043	1314	4235
	16	10.41	21.91	0.036	1215	2739
10	2	3.26	6.28	0.023	995	923
	4	5.15	9.41	0.028	1063	1384
	6	7.88	21.40	0.033	1152	2115
	8	21.62	22.94	0.046	1296	4324
	10	22.27	23.78	0.050	1384	5858
	12	21.86	23.25	0.042	1372	4770
	14	21.32	22.56	0.036	1321	3610
	16	9.06	21.66	0.030	1230	2377
5	2	3.39	6.47	0.023	1004	949
	4	5.15	9.43	0.027	1074	1380
	6	8.07	21.44	0.033	1160	2163
	8	21.57	22.88	0.044	1302	4204
	10	22.16	23.64	0.046	1395	5526
	12	21.74	23.10	0.040	1368	4499
	14	21.27	22.50	0.034	1331	3493
	16	8.49	21.54	0.029	1219	2230
2.5	2	3.31	6.36	0.022	1011	928
	4	4.85	8.88	0.026	1067	1301
	6	8.05	21.44	0.032	1169	2150
	8	11.49	22.09	0.027	1341	2846
	10	22.13	23.60	0.044	1406	5429
	12	21.76	21.13	0.039	1380	4525
	14	21.25	22.48	0.033	1338	3451
	16	7.77	21.38	0.026	1224	2025

Run No. L13 Additive toluene

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.49	5.15	0.021	961	757
	4	4.75	8.68	0.028	1039	1288
	6	21.16	22.35	0.055	1152	3517
	8	22.34	23.83	0.075	1254	6331
	10	23.32	25.11	0.093	1327	9458
	12	24.02	26.05	0.105	1377	12089
	14	23.60	25.49	0.096	1355	10465
	16	22.66	24.24	0.081	1278	7278
15	2	2.75	5.52	0.022	968	811
	4	4.87	8.90	0.029	1036	1324
	6	11.73	22.10	0.050	1143	3119
	8	22.19	23.65	0.068	1264	5886
	10	23.26	25.05	0.085	1351	9175
	12	23.62	25.52	0.094	1364	10491
	14	21.18	24.95	0.083	1348	8889
	16	22.39	23.90	0.074	1267	6459
10	2	3.11	6.05	0.023	984	891
	4	5.32	9.75	0.030	1053	1441
	6	10.72	21.96	0.045	1152	2884
	8	22.05	23.47	0.061	1276	5447
	10	22.42	23.95	0.063	1327	6407
	12	23.29	25.10	0.077	1391	9161
	14	22.81	24.47	0.068	1363	7560
	16	22.04	23.46	0.061	1274	5425
5	2	3.53	6.69	0.024	1002	985
	4	5.17	9.46	0.028	1064	1391
	6	9.33	21.71	0.038	1164	2513
	8	21.76	23.12	0.051	1287	4687
	10	22.86	24.54	0.064	1392	7644
	12	22.69	24.31	0.058	1400	7061
	14	22.10	23.55	0.050	1354	5440
	16	21.27	22.50	0.042	1259	3590
2.5	2	3.45	6.52	0.023	1006	956
	4	5.05	9.23	0.027	1068	1354
	6	8.60	21.56	0.034	1172	2304
	8	21.59	22.90	0.045	1297	4247
	10	22.64	24.26	0.056	1406	6910
	12	22.29	23.80	0.049	1394	5875
	14	21.67	23.01	0.042	1337	4384
	16	9.61	21.77	0.031	1239	2514

Run No. L14 Additive i-octane

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. m^{-2}h.$^{-1}$ ster.$^{-1}$)
		1 flame	2 flames			
20	2	2.24	4.79	0.020	954	704
	4	4.48	8.23	0.025	1055	1207
	6	21.29	22.51	0.058	1159	3785
	8	22.74	24.35	0.085	1275	7574
	10	24.05	26.09	0.109	1368	12260
	12	24.62	26.89	0.121	1400	14703
	14	23.81	25.75	0.108	1340	11362
	16	22.75	24.36	0.088	1264	7633
15	2	2.56	5.25	0.021	967	770
	4	4.67	8.55	0.027	1044	1263
	6	21.37	22.55	0.060	1154	3863
	8	22.42	23.93	0.073	1276	6519
	10	23.87	25.86	0.100	1376	11491
	12	24.05	26.11	0.102	1392	12182
	14	23.38	25.20	0.090	1348	9639
	16	22.55	24.11	0.078	1275	6951
10	2	2.85	5.67	0.022	976	832
	4	5.01	9.16	0.028	1055	1351
	6	8.46	21.53	0.033	1176	2261
	8	22.25	23.73	0.066	1283	6004
	10	23.27	25.07	0.078	1383	9103
	12	23.17	24.94	0.075	1383	8753
	14	22.38	23.91	0.060	1338	6275
	16	21.51	22.80	0.049	1254	4136
5	2	3.84	7.17	0.026	1001	1064
	4	5.16	9.44	0.028	1064	1388
	6	9.87	21.82	0.040	1165	2657
	8	21.76	23.12	0.050	1293	4671
	10	22.67	24.29	0.059	1391	7020
	12	22.18	23.65	0.050	1368	5624
	14	21.46	22.74	0.038	1331	3904
	16	10.21	21.89	0.030	1269	2635
2.5	2	3.54	6.70	0.025	992	993
	4	5.25	9.62	0.028	1069	1411
	6	8.58	21.56	0.034	1172	2299
	8	21.60	22.92	0.044	1307	4255
	10	22.24	23.74	0.047	1400	5722
	12	21.81	23.20	0.040	1381	4650
	14	21.23	22.45	0.034	1323	3423
	16	8.29	21.50	0.027	1234	2162

Run No. L15 Additive methyl i-propyl ketone

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
20	2	2.41	5.03	0.020	968	736
	4	5.02	9.18	0.028	1056	1355
	6	9.31	21.71	0.039	1155	2517
	8	21.86	23.24	0.053	1292	4931
	10	22.51	24.09	0.057	1378	6575
	12	22.29	23.80	0.054	1360	5956
	14	21.85	23.23	0.050	1308	4855
	16	11.79	22.12	0.041	1207	3053
15	2	2.85	5.67	0.022	976	832
	4	5.09	9.30	0.029	1049	1376
	6	8.91	21.63	0.037	1157	2404
	8	21.62	22.93	0.048	1280	4840
	10	23.01	24.72	0.071	1377	8175
	12	22.17	23.64	0.049	1373	5587
	14	21.67	23.01	0.044	1320	4404
	16	10.90	22.00	0.036	1228	2840
10	2	3.14	6.10	0.023	986	897
	4	5.02	9.18	0.028	1056	1355
	6	8.23	21.48	0.035	1148	2218
	8	21.61	22.93	0.046	1294	4306
	10	22.34	23.87	0.050	1396	6029
	12	22.11	23.57	0.046	1386	5410
	14	21.59	22.91	0.040	1339	4192
	16	10.92	22.00	0.034	1248	2822
5	2	3.32	6.37	0.023	999	934
	4	5.01	9.16	0.027	1065	1345
	6	8.03	21.43	0.033	1159	2153
	8	21.58	22.89	0.043	1304	4221
	10	22.25	23.75	0.047	1402	5744
	12	22.05	23.49	0.043	1399	5215
	14	21.53	22.83	0.036	1364	1010
	16	9.43	21.74	0.029	1255	2453
2.5	2	3.18	6.16	0.022	1001	901
	4	4.94	9.05	0.026	1072	1323
	6	7.84	21.39	0.032	1160	2098
	8	21.63	22.96	0.043	1321	4312
	10	22.23	23.73	0.045	1415	5670
	12	21.91	23.33	0.040	1400	4870
	14	21.29	22.54	0.033	1347	3527
	16	7.23	21.24	0.023	1238	1862

Run No. L16 Additive water

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
.5	2	3.24	6.25	0.022	1005	912
	4	4.94	9.05	0.026	1072	1323
	6	7.85	21.39	0.031	1171	2092
	8	21.35	22.60	0.040	1291	3714
	10	22.05	23.50	0.044	1391	5235
	12	21.79	23.16	0.039	1385	4578
	14	11.62	22.11	0.030	1308	2907
	16	7.31	21.26	0.025	1215	1902
2.5	2	3.24	6.25	0.022	1005	912
	4	4.67	8.56	0.026	1056	1258
	6	8.00	21.43	0.031	1177	2129
	8	21.41	22.68	0.041	1295	3846
	10	22.05	23.50	0.043	1400	5225
	12	21.67	23.01	0.038	1372	4316
	14	12.43	22.21	0.031	1313	3047
	16	7.72	21.36	0.027	1209	2023

Run No. L.17 Additive n-heptane

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
		1 flame	2 flames			
20	2	2.30	4.87	0.020	959	715
	4	4.35	8.00	0.025	1046	1175
	6	21.27	22.48	0.058	1154	3734
	8	22.63	24.21	0.082	1270	7217
	10	23.93	25.92	0.112	1344	11877
	12	24.55	26.79	0.124	1383	14472
	14	23.92	25.90	0.112	1342	11830
	16	22.79	24.41	0.086	1278	7727
15	2	2.59	5.30	0.021	969	776
	4	4.56	8.36	0.026	1048	1231
	6	21.29	22.51	0.058	1159	3785
	8	22.34	23.84	0.073	1264	6319
	10	23.77	25.72	0.100	1363	11117
	12	24.03	26.08	0.102	1389	12089
	14	23.43	25.27	0.091	1351	9823
	16	22.59	24.15	0.077	1284	7033
10	2	2.89	5.73	0.022	980	841
	4	4.89	8.94	0.028	1048	1322
	6	21.23	22.43	0.054	1169	3627
	8	22.19	23.66	0.065	1279	5852
	10	23.26	25.06	0.079	1377	9096
	12	24.14	26.26	0.093	1438	12375
	14	22.58	24.17	0.065	1343	6879
	16	21.73	23.07	0.053	1268	4636
5	2	3.46	6.58	0.024	997	970
	4	5.45	10.00	0.030	1060	1473
	6	11.04	22.01	0.045	1160	2950
	8	13.06	22.25	0.047	1185	3300
	10	22.67	24.29	0.059	1391	7020
	12	22.23	23.73	0.048	1392	5722
	14	21.57	22.88	0.040	1334	4142
	16	10.42	21.92	0.032	1254	2701
2.5	2	3.72	6.97	0.025	1004	1031
	4	5.61	10.33	0.030	1069	1512
	6	9.40	21.73	0.038	1166	2530
	8	21.71	23.05	0.048	1297	4530
	10	22.37	23.91	0.050	1402	6111
	12	21.96	23.38	0.043	1383	5018
	14	21.32	22.57	0.035	1332	3610
	16	8.15	21.47	0.026	1240	2118

Run No. L18   Additive water + 0.005M surfactant

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $M^{-2}h.^{-1}$ $ster.^{-1}$)
20	2	2.46	5.10	0.020	972	745
	4	4.21	7.77	0.024	1048	1136
	6	6.90	21.15	0.029	1148	1834
	8	21.20	22.42	0.038	1280	3428
	10	21.86	23.25	0.042	1372	4770
	12	21.50	22.80	0.036	1359	3963
	14	11.43	22.08	0.029	1315	2862
	16	6.04	11.38	0.021	1204	1550
15	2	2.71	5.46	0.021	978	799
	4	4.51	8.27	0.025	1056	1212
	6	8.38	21.51	0.034	1164	2249
	8	21.26	22.49	0.039	1282	3540
	10	21.89	23.30	0.042	1379	4854
	12	21.56	22.87	0.037	1360	4081
	14	11.32	22.07	0.030	1300	2855
	16	6.46	12.55	0.023	1198	1672
10	2	2.83	5.64	0.021	988	824
	4	4.51	8.27	0.025	1056	1212
	6	6.89	21.15	0.030	1136	1838
	8	21.37	22.63	0.040	1296	3760
	10	21.96	23.38	0.042	1391	4997
	12	21.58	22.90	0.037	1364	4121
	14	11.94	22.15	0.030	1315	2960
	16	6.61	13.06	0.023	1206	1709
5	2	3.24	6.25	0.022	1005	912
	4	4.65	8.51	0.025	1065	1245
	6	7.31	21.26	0.030	1156	1945
	8	21.41	22.68	0.040	1304	3837
	10	22.43	23.99	0.052	1398	6294
	12	21.67	23.02	0.038	1372	4324
	14	13.60	22.31	0.031	1332	3191
	16	7.31	21.26	0.025	1215	1902
2.5	2	3.18	6.16	0.022	1001	901
	4	4.80	8.79	0.026	1064	1289
	6	7.43	21.79	0.030	1162	1975
	8	21.47	22.75	0.040	1314	3939
	10	22.09	23.55	0.043	1407	5316
	12	21.67	23.02	0.038	1372	4324
	14	21.15	22.36	0.031	1339	3248
	16	7.88	21.40	0.026	1228	2051

Run No. L19 Additive water + 0.01M surfactant

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.50	5.6	0.020	975	753
	4	4.42	8.13	0.025	1051	1192
	6	6.79	13.74	0.029	1142	1805
	8	21.24	22.46	0.038	1287	3492
	10	21.83	23.21	0.041	1375	4693
	12	21.49	22.79	0.036	1356	3940
	14	10.88	22.00	0.029	1300	2760
	16	5.69	10.57	0.020	1199	1457
15	2	2.70	5.45	0.021	977	797
	4	4.32	7.96	0.025	1044	1169
	6	7.12	21.22	0.030	1150	1910
	8	21.30	22.53	0.039	1259	3607
	10	21.89	23.30	0.042	1379	4854
	12	21.61	22.94	0.037	1370	4186
	14	11.52	22.09	0.030	1305	2890
	16	4.53	8.32	0.025	1058	1218
10	2	2.78	5.57	0.021	984	813
	4	4.46	8.19	0.025	1053	1201
	6	7.24	21.24	0.030	1153	1927
	8	21.33	22.57	0.039	1296	3666
	10	21.93	23.34	0.042	1385	4930
	12	21.59	22.92	0.037	1367	4154
	14	11.87	22.14	0.030	1313	2949
	16	6.07	11.45	0.021	1205	1557
5	2	3.12	6.07	0.022	996	887
	4	4.74	8.67	0.026	1060	1273
	6	7.46	21.30	0.030	1164	1984
	8	21.40	22.66	0.040	1300	3806
	10	22.02	23.46	0.043	1394	5156
	12	21.64	22.97	0.037	1376	4244
	14	12.74	22.24	0.031	1319	3090
	16	6.49	12.65	0.022	1214	1670
2.5	2	3.22	6.21	0.022	1004	907
	4	4.85	8.88	0.026	1067	1301
	6	7.89	21.40	0.031	1172	2101
	8	21.43	22.70	0.040	1307	3868
	10	21.97	23.39	0.043	1384	5038
	12	21.72	23.08	0.038	1382	4426
	14	13.14	22.28	0.031	1325	3140
	16	7.27	21.25	0.024	1226	1882

Run No. L20 Additive xylene

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
20	2	2.19	4.72	0.020	950	695
	4	4.38	8.05	0.027	1026	1194
	6	13.61	22.29	0.055	1143	3431
	8	22.51	24.05	0.081	1256	6867
	10	23.86	25.81	0.116	1322	11657
	12	24.77	27.06	0.140	1264	15594
	14	22.92	24.61	0.074	1350	7972
	16	23.04	24.72	0.102	1256	8665
15	2	2.68	5.43	0.022	964	799
	4	4.82	8.81	0.029	1033	1311
	6	13.13	22.25	0.053	1148	3359
	8	22.47	24.00	0.076	1271	6703
	10	23.65	25.54	0.103	1336	10729
	12	24.23	26.33	0.120	1356	13133
	14	23.76	25.69	0.107	1337	11168
	16	22.89	24.54	0.090	1277	8070
10	2	3.07	5.99	0.023	980	882
	4	5.05	9.21	0.031	1028	1377
	6	12.14	22.15	0.049	1157	3183
	8	22.43	23.96	0.071	1288	6539
	10	23.50	25.36	0.090	1364	10025
	12	23.83	25.81	0.098	1378	11305
	14	23.18	24.95	0.079	1365	8834
	16	22.41	23.92	0.074	1270	6513
5	2	3.31	6.37	0.025	976	946
	4	5.31	9.72	0.030	1052	1438
	6	7.19	21.22	0.040	1064	1987
	8	22.07	23.51	0.058	1297	5474
	10	23.07	24.81	0.073	1377	8405
	12	23.02	24.74	0.069	1389	8178
	14	22.48	24.05	0.058	1367	6511
	16	21.51	22.79	0.047	12767	4102
2.5	2	3.50	6.63	0.024	1000	977
	4	5.15	9.41	0.028	1063	1384
	6	9.34	21.71	0.037	1172	2508
	8	21.81	23.18	0.050	1302	4777
	10	22.68	24.31	0.059	1393	7060
	12	22.35	23.87	0.051	1390	6056
	14	21.67	23.01	0.042	1337	4384
	16	10.18	21.88	0.032	1247	2651

Run No. L21 Additive di-i-propyl ether

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.54	5.22	0.020	978	761
	4	5.42	9.95	0.030	1059	1466
	6	10.49	21.92	0.043	1160	2819
	8	22.07	23.50	0.059	1291	5478
	10	23.22	25.00	0.075	1389	8889
	12	23.00	24.71	0.072	1372	8178
	14	22.39	23.91	0.064	1316	6341
	16	21.36	22.61	0.052	1207	3872
15	2	3.00	5.89	0.022	988	863
	4	5.42	9.95	0.030	1059	1466
	6	10.13	21.86	0.041	1165	2724
	8	21.94	23.34	0.054	1299	5117
	10	22.89	24.57	0.067	1380	7774
	12	22.72	24.36	0.062	1382	7222
	14	21.97	23.38	0.051	1324	5145
	16	21.15	22.34	0.044	1220	3391
10	2	3.30	6.33	0.023	997	930
	4	5.31	9.72	0.030	1052	1438
	6	8.91	21.63	0.037	1157	2404
	8	21.84	23.22	0.049	1315	4886
	10	22.59	24.19	0.057	1391	6782
	12	22.23	23.72	0.050	1376	5746
	14	21.64	22.97	0.042	1331	4314
	16	10.96	22.01	0.036	1230	2852
5	2	3.23	6.23	0.023	992	916
	4	5.33	9.77	0.029	1064	1437
	6	8.54	21.55	0.024	1170	2289
	8	21.65	22.98	0.044	1316	4360
	10	22.39	23.94	0.051	1398	6174
	12	21.99	23.42	0.043	1388	5087
	14	21.37	22.63	0.035	1342	3697
	16	10.13	21.87	0.031	1256	2628
2.5	2	3.18	6.16	0.022	1001	901
	4	4.48	8.23	0.025	1055	1207
	6	7.90	21.40	0.032	1163	2112
	8	21.47	22.75	0.042	1297	3964
	10	22.24	23.74	0.046	1409	5719
	12	21.82	23.21	0.040	1383	4668
	14	21.26	22.50	0.033	1340	3472
	16	8.70	21.59	0.028	1239	2271

Run No. L22 **Additive** propionaldelyde

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.48	5.13	0.020	973	749
	4	4.84	8.85	0.027	1055	1303
	6	8.75	21.59	0.034	1178	2340
	8	21.55	22.86	0.040	1331	4109
	10	21.94	23.36	0.039	1415	4914
	12	21.55	22.86	0.034	1388	4022
	14	11.40	22.08	0.026	1352	2818
	16	7.20	21.24	0.021	1267	1833
15	2	2.74	5.51	0.021	980	805
	4	5.15	9.41	0.028	1063	1384
	6	8.79	21.60	0.034	1180	2350
	8	21.56	22.87	0.041	1324	4145
	10	22.02	23.46	0.041	1412	5127
	12	21.57	22.89	0.035	1383	4085
	14	13.04	22.27	0.028	1360	3088
	16	7.25	21.25	0.022	1254	1857
10	2	3.18	6.16	0.022	1001	901
	4	5.34	9.78	0.028	1074	1432
	6	8.58	21.56	0.034	1172	2299
	8	21.54	22.85	0.042	1312	4120
	10	22.05	23.50	0.042	1408	5202
	12	21.69	23.04	0.036	1395	4325
	14	13.77	22.33	0.029	1357	3180
	16	7.12	21.22	0.021	1263	1814
5	2	3.25	6.27	0.023	994	920
	4	5.30	9.72	0.027	1083	1417
	6	8.19	21.47	0.033	1165	2192
	8	21.47	22.76	0.041	1307	3965
	10	22.11	23.57	0.042	1418	5332
	12	21.77	23.14	0.037	1401	4513
	14	13.70	22.32	0.030	1344	3188
	16	7.47	21.31	0.023	1250	1921
2.5	2	3.22	6.21	0.022	1004	907
	4	4.91	8.97	0.026	1070	1313
	6	7.79	21.38	0.032	1158	2084
	8	21.43	22.70	0.041	1299	3886
	10	22.09	23.55	0.043	1407	5316
	12	21.80	23.17	0.038	1396	4582
	14	13.54	22.31	0.031	1331	3184
	16	7.36	21.28	0.023	1244	1893

Run No. L23 Additive ethanol

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.57	5.27	0.021	968	772
	4	4.97	9.09	0.028	1052	1342
	6	8.91	21.63	0.035	1175	2388
	8	21.55	22.86	0.038	1349	4086
	10	22.34	23.88	0.047	1420	5989
	12	22.07	23.53	0.043	1404	5275
	14	21.50	22.80	0.038	1339	3982
	16	9.16	21.68	0.031	1223	2410
15	2	3.03	5.94	0.023	978	875
	4	4.66	8.52	0.027	1044	1260
	6	8.48	21.54	0.033	1177	2266
	8	21.69	23.03	0.044	1324	4439
	10	22.25	23.76	0.046	1411	5741
	12	21.99	23.42	0.042	1396	5065
	14	21.43	22.71	0.036	1344	3818
	16	7.24	21.25	0.022	1253	1853
10	2	3.10	6.04	0.023	983	888
	4	4.86	8.89	0.027	1056	1309
	6	8.07	21.44	0.032	1170	2154
	8	21.61	22.93	0.043	1316	4261
	10	22.17	23.66	0.045	1405	5542
	12	21.94	23.35	0.040	1404	4917
	14	21.26	22.49	0.034	1329	3479
	16	9.17	21.69	0.029	1245	2392
5	2	3.24	6.25	0.022	1005	912
	4	4.76	8.72	0.026	1061	1279
	6	7.60	21.33	0.031	1160	2027
	8	21.53	22.83	0.042	1309	4087
	10	22.16	23.63	0.044	1410	5481
	12	21.83	23.22	0.039	1394	4676
	14	21.22	22.45	0.032	1343	3387
	16	8.44	21.53	0.028	1228	2209
2.5	2	3.16	6.13	0.022	1000	896
	4	4.88	8.93	0.026	1068	1307
	6	7.60	21.33	0.031	1160	2027
	8	21.51	22.81	0.041	1315	4046
	10	22.29	23.80	0.053	1367	5950
	12	21.73	23.09	0.038	1384	4452
	14	21.14	22.35	0.031	1337	3236
	16	7.75	21.37	0.026	1223	2021

Run No. L24 Additive formaldelyde

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (°C)	Rad. (Kcal. m^{-2}h.$^{-1}$ ster.$^{-1}$)
		1 flame	2 flames			
20	2	2.22	4.77	0.019	967	697
	4	4.74	8.67	0.026	1060	1273
	6	7.26	21.25	0.027	1188	1908
	8	21.47	22.76	0.037	1343	3916
	10	21.71	23.06	0.034	1420	4341
	12	21.48	22.78	0.031	1408	3840
	14	10.45	21.93	0.024	1354	2611
	16	6.71	13.49	0.020	1257	1703
15	2	2.32	4.91	0.019	975	715
	4	4.84	8.85	0.027	1055	1303
	6	7.89	21.40	0.030	1183	2092
	8	21.51	22.81	0.038	1340	3998
	10	21.83	23.22	0.036	1423	4622
	12	21.54	22.85	0.032	1408	3963
	14	10.30	21.91	0.024	1349	2580
	16	7.43	21.30	0.022	1263	1900
10	2	2.67	5.41	0.020	988	786
	4	4.94	9.04	0.027	1061	1329
	6	7.91	21.41	0.031	1173	2106
	8	21.49	22.79	0.038	1337	3966
	10	21.93	23.35	0.038	1423	4879
	12	21.63	22.97	0.034	1404	4179
	14	11.03	22.03	0.025	1356	2736
	16	7.19	21.23	0.022	1251	1842
5	2	3.00	5.89	0.021	1000	857
	4	5.06	9.26	0.027	1068	1357
	6	8.00	21.43	0.031	1177	2129
	8	21.53	22.83	0.040	1327	4068
	10	21.97	23.39	0.040	1410	4983
	12	21.70	23.05	0.036	1397	4350
	14	11.52	22.10	0.027	1342	2852
	16	7.65	21.35	0.024	1244	1976
2.5	2	3.19	6.18	0.022	1002	903
	4	4.94	9.05	0.026	1072	1323
	6	8.30	21.50	0.032	1180	2212
	8	21.55	21.86	0.041	1322	4120
	10	21.99	23.43	0.041	1406	5059
	12	21.70	23.06	0.038	1388	4377
	14	13.70	22.32	0.030	1344	3188
	16	7.91	21.41	0.026	1230	2060

Run No. L25 Additive trichloro-trifluoroethane

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
		1 flame	2 flames			
20	2	2.73	5.49	0.021	980	803
	4	4.45	8.17	0.025	1052	1198
	6	7.62	21.33	0.031	1160	2032
	8	21.45	22.72	0.039	1319	3888
	10	22.00	23.44	0.040	1417	5068
	12	21.75	23.11	0.037	1396	4462
	14	12.42	22.21	0.029	1336	3021
	16	7.63	21.34	0.024	1244	1971
15	2	2.80	5.60	0.021	985	817
	4	4.79	8.76	0.026	1063	1285
	6	7.76	21.37	0.030	1177	2060
	8	21.52	22.82	0.040	1325	4052
	10	22.00	23.44	0.041	1408	5078
	12	21.69	23.04	0.037	1386	4352
	14	21.13	22.34	0.030	1347	3207
	16	6.91	21.16	0.023	1222	1784
10	2	3.12	6.07	0.022	996	887
	4	4.65	8.51	0.026	1054	1252
	6	7.43	21.29	0.030	1162	1975
	8	21.46	22.74	0.040	1312	3924
	10	21.70	23.04	0.046	1311	4494
	12	21.77	23.14	0.038	1391	4521
	14	21.16	22.37	0.031	1341	3268
	16	8.07	21.45	0.026	1237	2100
5	2	3.31	6.40	0.022	1012	933
	4	4.81	8.81	0.026	1064	1292
	6	7.78	21.37	0.031	1168	2073
	8	21.45	22.73	0.040	1311	3908
	10	22.00	23.44	0.043	1391	5116
	12	21.73	23.09	0.038	1384	4443
	14	13.42	22.30	0.031	1329	3172
	16	7.86	21.40	0.024	1254	2026
2.5	2	3.19	6.18	0.022	1002	903
	4	4.93	9.02	0.026	1072	1320
	6	7.78	21.37	0.031	1168	2073
	8	21.47	22.76	0.041	1307	3965
	10	22.07	23.52	0.043	1402	5255
	12	21.70	23.06	0.038	1379	4392
	14	12.93	22.26	0.031	1322	3115
	16	8.09	21.45	0.026	1238	2104

Run No. G1   Additive nitrogen

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
20	2	2.59	5.29	0.020	982	770
	4	4.30	7.93	0.024	1055	1158
	6	6.77	13.67	0.029	1141	1801
	8	21.34	22.59	0.040	1289	3699
	10	21.81	23.19	0.042	1364	4678
	12	21.48	22.77	0.037	1344	3931
	14	11.52	22.09	0.030	1305	2890
	16	5.28	9.66	0.029	1060	1423
15	2	2.55	5.23	0.020	979	763
	4	4.56	8.36	0.025	1060	1224
	6	7.22	21.24	0.030	1152	1923
	8	21.40	22.67	0.041	1293	3830
	10	21.86	23.26	0.042	1373	4789
	12	21.54	22.85	0.037	1356	4049
	14	11.98	22.15	0.030	1316	2967
	16	6.43	12.47	0.022	1211	1656
10	2	2.88	5.72	0.021	992	834
	4	4.37	8.04	0.025	1048	1181
	6	7.34	21.27	0.030	1158	1953
	8	21.40	22.67	0.041	1293	3830
	10	21.95	23.37	0.043	1381	4999
	12	21.67	23.02	0.038	1372	4324
	14	12.83	22.25	0.031	1320	3103
	16	7.33	21.27	0.024	1229	1898
5	2	3.02	5.92	0.021	1002	862
	4	4.76	8.72	0.026	1061	1279
	6	7.78	21.37	0.031	1168	2073
	8	21.42	22.69	0.041	1297	3870
	10	22.24	23.74	0.047	1400	5722
	12	21.66	22.99	0.038	1369	4291
	14	21.15	22.35	0.031	1338	3242
	16	6.51	12.70	0.022	1215	1674
2.5	2	3.15	6.12	0.022	999	894
	4	4.84	8.86	0.026	1066	1298
	6	7.98	21.42	0.031	1176	2124
	8	21.46	22.75	0.041	1305	3949
	10	22.02	33.46	0.043	1394	5156
	12	21.67	23.02	0.038	1372	4234
	14	13.36	22.30	0.031	1328	3165
	16	7.19	21.23	0.024	1222	1862

Run No. G2 Additive argon

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.54	5.22	0.020	978	761
	4	4.18	7.73	0.024	1047	1131
	6	7.19	21.23	0.030	1151	1914
	8	21.38	22.63	0.040	1296	3768
	10	21.89	23.29	0.042	1377	4836
	12	21.54	22.85	0.037	1356	4049
	14	12.30	22.19	0.031	1311	3029
	16	6.54	12.80	0.022	1216	1681
15	2	2.65	5.39	0.021	974	789
	4	4.35	8.00	0.025	1046	1175
	6	7.39	21.28	0.030	1160	1966
	8	21.36	22.61	0.040	1292	3739
	10	21.93	23.35	0.042	1386	4940
	12	21.60	22.92	0.038	1358	4175
	14	11.99	22.15	0.031	1304	2980
	16	7.52	21.32	0.024	1238	1942
10	2	2.65	5.39	0.021	974	789
	4	4.50	8.25	0.025	1056	1210
	6	7.06	21.20	0.024	1176	1838
	8	21.46	22.74	0.041	1304	3933
	10	22.03	23.47	0.043	1396	5175
	12	21.66	22.99	0.038	1369	4291
	14	12.79	22.24	0.031	1320	3096
	16	6.93	21.17	0.023	1223	1788
5	2	3.05	5.97	0.022	992	874
	4	4.87	8.90	0.026	1068	1304
	6	7.85	21.39	0.031	1171	2092
	8	21.43	22.70	0.041	1299	3886
	10	22.06	23.51	0.043	1400	5235
	12	21.64	22.97	0.038	1366	4258
	14	13.48	22.30	0.031	1330	3178
	16	7.50	21.31	0.024	1237	1938
2.5	2	3.31	6.36	0.022	1011	928
	4	4.91	8.97	0.026	1070	1313
	6	7.78	21.37	0.031	1168	2073
	8	21.48	22.77	0.041	1309	3989
	10	22.09	23.55	0.043	1407	5316
	12	21.67	23.02	0.038	1372	4324
	14	13.36	22.30	0.031	1328	3165
	16	8.30	21.50	0.026	1247	2154

Run No. G3 Additive carbon dioxide

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
20	2	2.20	4.75	0.019	965	694
	4	4.06	7.53	0.023	1051	1097
	6	7.28	21.25	0.031	1145	1947
	8	21.46	22.74	0.043	1288	3968
	10	22.15	23.63	0.048	1378	5537
	12	21.79	23.16	0.042	1359	4624
	14	21.23	23.46	0.035	1313	3440
	16	7.82	21.39	0.028	1202	2058
15	2	2.26	4.83	0.019	970	704
	4	4.15	7.67	0.024	1044	1123
	6	7.14	21.21	0.030	1148	1901
	8	21.52	22.81	0.044	1289	4094
	10	22.08	23.53	0.045	1388	5313
	12	21.77	23.14	0.040	1373	4561
	14	21.20	22.42	0.034	1317	3376
	16	8.60	21.57	0.030	1202	2268
10	2	2.67	5.41	0.020	988	786
	4	4.59	8.40	0.026	1050	1237
	6	8.01	21.43	0.034	1148	2155
	8	21.49	22.78	0.042	1302	4013
	10	22.08	23.54	0.044	1397	5316
	12	21.79	23.16	0.039	1385	4578
	14	13.61	22.31	0.033	1310	3217
	16	7.90	21.41	0.028	1205	2075
5	2	2.87	5.70	0.022	978	837
	4	4.71	8.63	0.026	1058	1267
	6	7.77	21.37	0.032	1157	2079
	8	21.54	22.84	0.042	1311	4103
	10	22.10	23.57	0.043	1409	5346
	12	21.71	23.07	0.037	1390	4394
	14	12.88	22.25	0.031	1321	3109
	16	7.85	21.39	0.027	1215	2054
2.5	2	2.87	5.71	0.021	991	832
	4	5.05	9.23	0.027	1068	1354
	6	7.71	21.36	0.031	1164	2055
	8	21.52	22.81	0.041	1316	4054
	10	22.09	23.55	0.043	1407	5316
	12	21.87	23.27	0.040	1392	4777
	14	12.77	22.24	0.030	1195	3082
	16	7.60	21.33	0.025	1228	1972

Run No. G4 Additive commercial propane

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. m^{-2}h.$^{-1}$ ster.$^{-1}$)
		1 flame	2 flames			
20	2	2.53	5.21	0.021	964	765
	4	4.94	9.04	0.027	1061	1329
	6	21.38	22.62	0.055	1192	3929
	8	22.87	24.53	0.079	1319	7875
	10	23.82	25.81	0.090	1408	11147
	12	24.44	26.67	0.100	1448	13633
	14	23.73	25.67	0.092	1387	10841
	16	22.63	24.21	0.077	1291	7150
15	2	2.91	5.75	0.023	968	848
	4	4.96	9.06	0.027	1062	1332
	6	21.26	22.47	0.054	1175	3684
	8	22.65	24.25	0.070	1328	7133
	10	23.52	25.40	0.080	1409	9946
	12	24.02	26.10	0.086	1452	11812
	14	23.21	24.98	0.079	1369	8921
	16	22.34	23.84	0.067	1292	6247
10	2	3.15	6.11	0.024	975	904
	4	5.10	9.34	0.028	1060	1374
	6	11.68	22.10	0.045	1175	3070
	8	22.27	23.76	0.061	1313	5996
	10	23.17	24.95	0.069	1413	8661
	12	23.91	25.89	0.110	1347	11757
	14	22.42	23.96	0.059	1350	6356
	16	21.71	23.04	0.050	1283	4548
5	2	3.49	6.69	0.025	988	980
	4	5.24	9.59	0.028	1068	1408
	6	9.75	21.79	0.039	1169	2620
	8	21.74	23.09	0.048	1304	4605
	10	22.50	24.08	0.052	1409	6465
	12	22.18	23.67	0.044	1415	5544
	14	21.45	22.74	0.036	1348	3863
	16	9.86	21.82	0.030	1258	2559
2.5	2	3.42	6.51	0.024	994	960
	4	5.39	9.89	0.028	1077	1445
	6	8.25	21.48	0.033	1168	2207
	8	21.56	22.87	0.042	1316	4153
	10	22.25	23.75	0.046	1410	5730
	12	21.86	23.26	0.040	1391	4759
	14	21.21	22.44	0.032	1341	3373
	16	8.15	21.47	0.026	1240	2118

Run No. G5 Additive carbon monoxide

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
		1 flame	2 flames			
20	2	2.30	4.89	0.019	973	712
	4	4.66	8.54	0.026	1055	1255
	6	8.57	21.55	0.036	1153	2313
	8	21.69	23.02	0.048	1293	4484
	10	22.30	23.81	0.051	1382	5941
	12	21.96	23.38	0.045	1366	5042
	14	21.31	22.55	0.036	1319	3589
	16	8.14	21.46	0.029	1169	2145
15	2	2.35	4.96	0.019	977	721
	4	4.75	8.68	0.027	1049	1281
	6	8.78	21.60	0.038	1144	2381
	8	21.75	23.10	0.049	1297	4625
	10	22.21	23.70	0.048	1388	5678
	12	22.03	23.47	0.045	1380	5211
	14	21.29	22.53	0.036	1316	3567
	16	7.88	21.40	0.037	1216	2063
10	2	2.68	5.42	0.020	989	788
	4	4.86	8.89	0.027	1056	1309
	6	8.98	21.64	0.038	1152	2430
	8	21.67	23.01	0.048	1291	4457
	10	22.18	23.66	0.046	1398	5568
	12	22.06	23.51	0.045	1382	5282
	14	21.23	22.45	0.034	1323	3423
	16	7.88	21.40	0.026	1228	2051
5	2	3.01	5.91	0.021	1001	860
	4	5.08	9.28	0.028	1059	1368
	6	8.70	21.58	0.036	1158	2344
	8	21.66	23.00	0.046	1304	4413
	10	22.15	23.62	0.044	1408	5460
	12	21.92	23.32	0.042	1383	4902
	14	13.13	22.27	0.032	1314	3152
	16	8.74	21.60	0.028	1240	2281
2.5	2	3.31	6.36	0.022	1011	928
	4	5.24	9.59	0.028	1068	1408
	6	8.32	21.50	0.033	1171	2227
	8	21.52	22.81	0.043	1299	4075
	10	22.15	23.62	0.044	1408	5460
	12	21.92	23.33	0.041	1392	4887
	14	12.88	22.25	0.031	1321	3109
	16	7.98	21.43	0.025	1246	2067

Run No. G6 Additive oxygen

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.65	5.39	0.019	1001	778
	4	4.41	8.12	0.021	1101	1163
	6	7.58	21.33	0.025	1228	1968
	8	21.44	22.73	0.030	1412	3758
	10	13.69	22.33	0.026	1396	3129
	12	10.61	21.96	0.024	1359	2642
	14	8.02	21.44	0.021	1307	2031
	16	5.49	10.14	0.019	1203	1399
15	2	2.76	5.55	0.019	1010	799
	4	4.57	8.39	0.022	1098	1207
	6	7.76	21.37	0.027	1211	2032
	8	21.52	22.83	0.033	1393	3949
	10	21.54	22.85	0.032	1408	3963
	12	21.14	22.35	0.028	1373	3193
	14	8.11	21.46	0.021	1311	2052
	16	5.93	11.12	0.020	1213	1515
10	2	2.89	5.74	0.020	1006	831
	4	4.85	8.88	0.024	1090	1286
	6	7.95	21.42	0.029	1196	2099
	8	21.57	22.89	0.036	1372	4089
	10	21.83	23.22	0.036	1423	4622
	12	21.36	22.62	0.031	1383	3618
	14	9.11	21.68	0.023	1322	2311
	16	6.42	12.43	0.021	1225	1643
5	2	3.01	5.91	0.021	1001	860
	4	4.89	8.94	0.025	1080	1302
	6	8.15	21.46	0.031	1184	2167
	8	21.60	22.92	0.040	1340	4208
	10	22.00	23.44	0.039	1426	5045
	12	21.57	22.89	0.034	1392	4061
	14	10.65	21.96	0.026	1332	2676
	16	7.23	21.24	0.023	1238	1862
2.5	2	3.31	6.36	0.022	1011	928
	4	5.04	9.22	0.026	1078	1345
	6	8.26	21.49	0.032	1178	2202
	8	21.59	22.91	0.042	1322	4220
	10	22.01	23.45	0.041	1409	5097
	12	21.63	22.96	0.036	1383	4201
	14	12.30	22.19	0.029	1334	3003
	16	7.46	21.30	0.023	1249	1917

Run No. G7 Additive acetylene

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. m^{-2}h.$^{-1}$ ster.$^{-1}$)
		1 flame	2 flames			
20	2	2.72	5.48	0.021	979	801
	4	4.83	8.83	0.026	1065	1295
	6	10.16	21.87	0.038	1190	2703
	8	21.89	23.28	0.048	1330	4921
	10	22.48	24.05	0.053	1399	6428
	12	22.71	24.39	0.051	1452	7018
	14	22.42	23.95	0.063	1327	6407
	16	12.51	22.21	0.031	1315	3059
15	2	2.94	5.80	0.022	983	850
	4	4.93	9.02	0.026	1072	1320
	6	9.70	21.79	0.037	1184	2592
	8	21.76	23.12	0.046	1321	4613
	10	22.45	24.02	0.051	1408	6329
	12	22.54	24.13	0.048	1445	6495
	14	21.88	23.28	0.040	1394	4796
	16	11.90	22.14	0.032	1292	2977
10	2	3.20	6.18	0.023	990	909
	4	5.03	9.21	0.027	1067	1351
	6	9.00	21.65	0.035	1178	2409
	8	21.67	23.00	0.045	1312	4405
	10	22.33	23.86	0.049	1402	5988
	12	22.33	23.11	0.045	1433	5921
	14	21.64	22.97	0.037	1376	4244
	16	8.71	21.59	0.029	1228	2283
5	2	3.12	6.07	0.023	984	893
	4	5.03	9.21	0.027	1067	1351
	6	8.50	21.54	0.033	1178	2271
	8	21.57	22.88	0.043	1309	4184
	10	22.11	23.57	0.046	1385	5400
	12	21.92	23.33	0.041	1392	4897
	14	21.37	22.63	0.034	1352	3677
	16	9.78	21.81	0.028	1279	2521
2.5	2	3.18	6.16	0.022	1001	901
	4	4.94	9.05	0.026	1072	1323
	6	8.15	21.46	0.032	1173	2173
	8	21.48	22.76	0.042	1300	3988
	10	21.77	23.14	0.041	1364	4576
	12	21.76	22.13	0.039	1380	4525
	14	21.20	22.42	0.032	1339	3353
	16	7.72	21.37	0.023	1262	1983

Run No. G8 Additive methane

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (°C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
20	2	2.42	5.05	0.019	983	734
	4	6.90	21.15	0.029	1148	1834
	6	10.26	21.89	0.038	1193	2727
	8	21.58	22.89	0.040	1336	4158
	10	22.54	24.13	0.052	1416	6564
	12	22.67	24.30	0.049	1460	6856
	14	21.91	23.32	0.040	1400	4861
	16	12.46	22.21	0.032	1303	3064
15	2	2.68	5.42	0.020	989	788
	4	4.76	8.71	0.025	1072	1272
	6	9.53	21.75	0.036	1188	2544
	8	21.83	23.21	0.045	1342	4753
	10	22.42	23.97	0.050	1409	6216
	12	22.46	24.03	0.046	1448	6259
	14	21.35	22.61	0.031	1380	3597
	16	11.51	22.09	0.032	1283	2911
10	2	2.99	5.88	0.021	1000	855
	4	5.14	9.41	0.026	1084	1371
	6	9.15	21.68	0.035	1184	2446
	8	21.69	23.03	0.044	1324	4448
	10	22.22	23.72	0.047	1398	5689
	12	22.24	24.06	0.044	1425	5682
	14	21.53	22.83	0.036	1364	4010
	16	9.60	21.77	0.028	1272	2480
5	2	3.03	5.94	0.022	990	869
	4	5.06	9.26	0.026	1080	1351
	6	8.36	21.51	0.032	1182	2227
	8	21.59	22.91	0.042	1321	4212
	10	22.09	23.55	0.043	1406	5306
	12	21.69	23.04	0.039	1367	4378
	14	21.23	22.46	0.032	1344	3400
	16	9.19	21.70	0.026	1283	2365
2.5	2	3.31	6.36	0.022	1011	928
	4	4.94	9.05	0.026	1072	1323
	6	7.78	21.37	0.031	1168	2073
	8	21.46	22.75	0.041	1305	3949
	10	22.05	23.50	0.043	1400	5225
	12	21.70	23.05	0.038	1377	4375
	14	13.36	22.30	0.031	1328	3165
	16	7.91	21.41	0.024	1256	2039

Run No. G9 Additive air

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.36	4.97	0.019	978	723
	4	4.20	7.76	0.023	1060	1129
	6	6.91	21.16	0.028	1159	1827
	8	21.15	22.35	0.032	1327	3255
	10	21.53	22.84	0.031	1418	3935
	12	21.25	22.49	0.029	1384	3398
	14	8.34	21.51	0.021	1321	2106
	16	5.84	10.90	0.020	1208	1492
15	2	2.63	5.35	0.020	985	778
	4	4.33	7.97	0.024	1056	1164
	6	7.48	21.30	0.030	1164	1989
	8	21.28	22.51	0.035	1323	3524
	10	21.89	23.30	0.042	1379	4584
	12	21.43	22.71	0.032	1386	3764
	14	9.26	21.71	0.023	1328	2344
	16	6.33	12.17	0.021	1220	1622
10	2	2.76	5.54	0.020	996	804
	4	4.61	8.45	0.025	1063	1236
	6	7.02	21.18	0.029	1153	1863
	8	21.38	22.64	0.037	1324	3740
	10	21.94	23.36	0.038	1424	4898
	12	21.59	22.91	0.034	1396	4092
	14	10.35	21.92	0.025	1336	2604
	16	7.09	21.21	0.023	1231	1826
5	2	3.06	5.99	0.021	1005	870
	4	4.85	8.88	0.026	1067	1301
	6	7.78	21.37	0.031	1168	2073
	8	21.42	22.69	0.039	1313	3833
	10	22.01	23.45	0.040	1418	5078
	12	21.67	23.02	0.036	1392	4291
	14	12.12	22.17	0.028	1343	2963
	16	6.74	13.63	0.021	1243	1721
2.5	2	3.15	6.12	0.022	999	894
	4	4.85	8.88	0.026	1067	1301
	6	8.18	21.47	0.032	1175	2183
	8	21.50	22.79	0.041	1312	4014
	10	22.05	23.50	0.042	1408	5202
	12	21.71	23.07	0.038	1380	4409
	14	11.76	22.11	0.045	1176	3084
	16	7.09	21.21	0.023	1231	1826

Run No. G10 Additive hydrogen

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
20	2	2.29	4.87	0.019	972	710
	4	4.24	7.83	0.024	1051	1145
	6	6.40	12.31	0.026	1156	1682
	8	12.30	22.19	0.031	1311	3033
	10	21.63	22.96	0.033	1415	4158
	12	21.25	22.49	0.028	1396	3376
	14	8.88	21.63	0.021	1344	2231
	16	6.50	12.72	0.020	1246	1653
15	2	2.43	5.06	0.020	969	740
	4	4.46	8.19	0.025	1053	1201
	6	6.56	12.83	0.027	1152	1731
	8	12.68	22.23	0.032	1307	3095
	10	21.64	23.98	0.034	1407	4203
	12	21.37	22.64	0.030	1398	3632
	14	9.65	21.79	0.023	1342	2429
	16	8.16	21.53	0.033	1176	2261
10	2	2.55	5.23	0.020	979	763
	4	4.51	8.27	0.025	1056	1212
	6	6.91	21.16	0.028	1159	1827
	8	21.18	22.39	0.034	1312	3335
	10	21.77	23.14	0.036	1411	4493
	12	21.43	22.71	0.032	1386	3764
	14	10.35	21.92	0.025	1336	2604
	16	7.36	21.28	0.023	1244	1893
5	2	2.87	5.71	0.021	991	832
	4	4.66	8.54	0.026	1055	1255
	6	7.50	21.31	0.030	1165	1993
	8	21.28	22.52	0.037	1304	3557
	10	22.24	23.74	0.047	1400	5722
	12	21.56	22.87	0.035	1380	4053
	14	11.90	22.15	0.028	1338	2928
	16	7.82	21.39	0.024	1252	2018
2.5	2	3.17	6.15	0.022	1000	898
	4	5.09	9.31	0.026	1081	1358
	6	7.71	21.36	0.030	1175	2047
	8	21.34	22.60	0.039	1299	3696
	10	21.97	23.39	0.041	1401	5001
	12	21.63	22.96	0.037	1374	4227
	14	12.91	22.26	0.030	1333	3100
	16	8.17	21.47	0.026	1241	2122

Run No. G11 Additive helium

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
20	2	2.24	4.80	0.019	968	701
	4	4.18	7.73	0.024	1047	1131
	6	6.90	21.15	0.029	1148	1834
	8	21.25	22.47	0.039	1280	3519
	10	21.71	23.06	0.041	1353	4452
	12	21.41	22.68	0.036	1340	3780
	14	11.76	22.13	0.030	1311	2931
	16	5.81	10.84	0.020	1206	1486
15	2	2.37	4.98	0.019	979	724
	4	4.29	7.91	0.024	1054	1156
	6	7.10	21.21	0.029	1157	1884
	8	21.25	22.47	0.039	1280	3519
	10	21.77	23.14	0.041	1364	4576
	12	21.51	22.81	0.037	1350	3986
	14	11.49	22.09	0.030	1304	2884
	16	7.01	21.19	0.024	1213	1818
10	2	2.71	5.47	0.020	992	794
	4	4.42	8.13	0.025	1051	1192
	6	7.58	21.33	0.030	1169	2015
	8	21.33	22.57	0.040	1287	3676
	10	21.89	23.30	0.042	1379	4584
	12	21.57	22.89	0.037	1363	4113
	14	12.47	22.21	0.031	1314	3053
	16	6.91	21.16	0.023	1222	1783
5	2	2.96	5.83	0.021	997	849
	4	4.42	8.13	0.025	1051	1192
	6	7.80	21.38	0.030	1179	2069
	8	21.38	22.64	0.041	1289	3791
	10	21.91	23.31	0.042	1381	4883
	12	21.58	22.90	0.038	1355	4142
	14	12.74	22.24	0.031	1319	3090
	16	6.70	13.42	0.023	1211	1731
2.5	2	3.31	6.36	0.022	1011	928
	4	4.57	8.38	0.025	1060	1227
	6	7.73	21.36	0.031	1165	2059
	8	21.43	22.70	0.041	1299	3886
	10	22.01	23.45	0.043	1392	5136
	12	21.66	23.00	0.038	1370	4299
	14	21.14	22.35	0.031	1337	3236
	16	7.49	21.31	0.025	1224	1947

Run No. G12 Additive methyl bromide

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.70	5.46	0.022	965	803
	4	5.57	10.24	0.032	1048	1515
	6	21.32	22.54	0.060	1152	3846
	8	22.61	24.17	0.088	1244	7228
	10	23.67	25.54	0.116	1297	10948
	12	24.26	26.33	0.134	1320	13411
	14	23.86	25.87	0.119	1313	11696
	16	22.51	24.02	0.098	1193	7032
15	2	3.16	6.13	0.024	976	906
	4	5.57	10.24	0.032	1048	1515
	6	21.24	22.44	0.057	1154	3670
	8	22.50	24.04	0.080	1259	6839
	10	23.67	25.57	0.106	1329	10845
	12	24.10	26.14	0.118	1346	12587
	14	22.54	24.12	0.057	1382	6639
	16	22.26	23.72	0.084	1205	6227
10	2	3.49	6.62	0.025	988	980
	4	6.12	11.50	0.034	1060	1669
	6	13.49	22.28	0.052	1159	3393
	8	22.61	24.18	0.078	1284	7110
	10	23.68	25.60	0.097	1362	10762
	12	23.62	25.52	0.094	1364	10491
	14	22.77	24.39	0.075	1321	7521
	16	21.72	23.05	0.061	1219	4691
5	2	3.77	7.06	0.026	996	1048
	4	5.78	10.70	0.031	1069	1562
	6	11.15	22.03	0.044	1170	2962
	8	22.27	23.76	0.064	1297	6040
	10	23.21	24.99	0.072	1403	8816
	12	22.59	24.19	0.058	1385	6808
	14	22.04	23.47	0.050	1343	5292
	16	21.18	22.39	0.042	1242	3435
2.5	2	3.51	6.65	0.024	1000	980
	4	5.54	10.21	0.028	1086	1483
	6	10.19	21.87	0.039	1183	2720
	8	21.83	23.21	0.048	1320	4804
	10	22.83	24.50	0.059	1417	7476
	12	22.38	23.92	0.051	1396	6138
	14	21.65	22.99	0.040	1350	4309
	16	10.10	21.87	0.031	1255	2622

Run No. G13 Additive ethane

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (°C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
20	2	2.40	5.02	0.020	967	734
	4	4.84	8.86	0.026	1066	1298
	6	21.34	22.58	0.055	1185	3861
	8	22.68	24.28	0.070	1332	7205
	10	23.63	25.56	0.080	1425	10330
	12	24.12	26.25	0.086	1465	12189
	14	23.45	25.32	0.079	1404	9710
	16	22.31	23.81	0.065	1299	6160
15	2	2.65	5.39	0.021	974	789
	4	5.01	9.16	0.027	1065	1345
	6	21.30	22.52	0.054	1183	3766
	8	22.42	23.95	0.063	1327	6407
	10	23.31	25.13	0.072	1418	9140
	12	23.83	25.83	0.081	1448	11022
	14	23.01	24.72	0.071	1377	8175
	16	21.90	23.28	0.057	1272	5048
10	2	3.06	5.97	0.023	980	879
	4	5.20	9.52	0.028	1066	1398
	6	11.76	22.11	0.045	1176	3084
	8	22.06	23.50	0.014	1320	5394
	10	23.17	24.95	0.069	1413	8661
	12	22.96	24.67	0.061	1425	7877
	14	22.29	23.80	0.053	1367	5950
	16	21.32	22.56	0.041	1277	3676
5	2	3.53	6.69	0.025	991	990
	4	5.46	10.03	0.029	1071	1468
	6	9.46	21.74	0.037	1176	2535
	8	21.65	22.99	0.044	1317	4368
	10	22.36	23.89	0.049	1407	6057
	12	22.06	23.51	0.042	1409	5222
	14	21.38	22.65	0.034	1355	3706
	16	9.02	21.66	0.027	1264	2337
2.5	2	3.53	6.69	0.024	1002	985
	4	5.25	9.62	0.027	1080	1403
	6	8.05	21.44	0.032	1169	2150
	8	21.55	22.85	0.042	1313	4128
	10	22.16	23.63	0.045	1402	5500
	12	21.86	23.26	0.040	1391	4759
	14	21.21	22.44	0.032	1341	3373
	16	8.71	21.59	0.029	1228	2283

Run No. G14 Additive propane

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.47	5.12	0.021	960	753
	4	4.94	9.04	0.027	1061	1329
	6	21.38	22.62	0.056	1185	3931
	8	22.74	24.36	0.074	1321	7421
	10	23.81	25.80	0.087	1419	11066
	12	24.37	26.59	0.096	1456	13308
	14	23.64	25.56	0.088	1392	10490
	16	22.60	24.18	0.074	1300	7041
15	2	2.76	5.53	0.022	969	813
	4	5.01	9.16	0.027	1065	1345
	6	21.30	22.52	0.054	1182	3758
	8	22.87	24.53	0.079	1319	7875
	10	23.45	25.32	0.077	1414	9683
	12	23.85	25.87	0.082	1447	11137
	14	23.08	24.81	0.073	1378	8421
	16	22.30	23.79	0.063	1307	6093
10	2	3.14	6.09	0.024	974	901
	4	5.21	9.54	0.028	1067	1401
	6	12.74	22.22	0.047	1180	3256
	8	22.10	23.55	0.056	1314	5515
	10	23.73	25.67	0.092	1387	10841
	12	23.19	24.99	0.063	1450	8621
	14	22.31	23.83	0.054	1364	6015
	16	21.57	22.88	0.046	1287	4228
5	2	3.43	6.53	0.025	984	968
	4	5.53	10.17	0.029	1075	1486
	6	9.84	21.81	0.038	1180	2633
	8	21.66	22.99	0.045	1311	4396
	10	22.49	24.06	0.051	1415	6426
	12	22.19	23.69	0.044	1417	5575
	14	21.53	22.84	0.038	1345	4046
	16	9.73	21.80	0.029	1265	2521
2.5	2	3.36	6.43	0.023	1002	944
	4	4.99	9.13	0.027	1064	1341
	6	7.92	21.41	0.032	1164	2116
	8	21.53	22.83	0.042	1310	4095
	10	22.23	23.73	0.046	1407	5687
	12	21.94	23.36	0.040	1405	4926
	14	21.19	22.40	0.032	1336	3327
	16	7.41	21.29	0.023	1247	1905

Run No. 15 Additive butane

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
20	2	2.40	5.02	0.020	967	734
	4	5.05	9.23	0.028	1057	1361
	6	21.61	22.90	0.062	1194	4459
	8	22.96	24.64	0.084	1312	8223
	10	24.10	26.18	0.100	1405	12315
	12	24.73	27.08	0.110	1448	14968
	14	23.93	25.94	0.098	1391	11660
	16	22.85	24.49	0.085	1291	7893
15	2	2.87	5.63	0.022	974	826
	4	5.25	9.61	0.029	1059	1417
	6	21.47	22.74	0.057	1197	4135
	8	22.50	24.06	0.067	1319	6679
	10	23.76	25.72	0.087	1412	10878
	12	24.14	26.26	0.093	1438	12375
	14	23.39	25.22	0.083	1377	9556
	16	22.38	23.89	0.069	1288	6368
10	2	3.22	6.21	0.024	980	917
	4	5.45	10.00	0.030	1060	1473
	6	13.06	22.25	0.047	1185	3300
	8	22.18	23.65	0.057	1322	5728
	10	23.23	25.02	0.072	1406	8884
	12	23.03	24.76	0.068	1397	8216
	14	22.48	24.04	0.059	1360	6521
	16	21.64	22.96	0.049	1277	4394
5	2	3.70	6.95	0.026	992	1033
	4	5.40	9.91	0.029	1068	1454
	6	9.63	21.77	0.037	1182	2575
	8	21.79	23.16	0.048	1313	4718
	10	22.48	24.04	0.053	1398	6416
	12	22.14	23.61	0.045	1399	5458
	14	21.51	22.80	0.037	1349	3978
	16	10.36	21.91	0.031	1263	2678
2.5	2	3.57	6.76	0.024	1005	995
	4	5.15	9.43	0.027	1074	1380
	6	8.69	21.58	0.033	1185	2317
	8	21.56	22.87	0.043	1308	4167
	10	22.22	23.72	0.046	1406	5676
	12	21.81	23.20	0.040	1381	4650
	14	21.29	22.53	0.033	1345	3513
	16	8.90	21.63	0.026	1272	2298

Run No. G16 Additive ethylene

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (°C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.51	5.17	0.020	976	755
	4	4.82	8.83	0.025	1076	1287
	6	21.35	22.59	0.053	1198	3853
	8	22.63	24.22	0.066	1344	7013
	10	23.51	25.41	0.075	1432	9850
	12	23.98	26.05	0.080	1473	11548
	14	23.34	25.17	0.073	1417	9250
	16	22.33	23.83	0.061	1323	6142
15	2	2.71	5.47	0.022	966	805
	4	4.66	8.54	0.026	1055	1255
	6	21.29	22.51	0.052	1192	3723
	8	22.36	23.88	0.060	1335	6225
	10	23.25	25.06	0.070	1420	8920
	12	23.87	25.91	0.078	1468	11136
	14	23.03	24.76	0.068	1397	8216
	16	22.15	23.61	0.059	1305	5683
10	2	3.18	6.15	0.023	988	904
	4	4.82	8.82	0.027	1054	1300
	6	12.21	22.17	0.044	1192	3150
	8	22.02	23.44	0.052	1325	5267
	10	22.97	24.69	0.063	1416	7953
	12	23.11	24.88	0.059	1461	8285
	14	22.23	23.73	0.050	1377	5757
	16	21.28	22.52	0.040	1278	3594
5	2	3.51	6.65	0.024	1000	980
	4	5.12	9.36	0.028	1061	1378
	6	7.64	21.34	0.027	1205	2002
	8	21.67	23.01	0.043	1328	4391
	10	22.35	23.89	0.049	1406	6046
	12	22.09	23.55	0.040	1433	5263
	14	10.61	21.96	0.024	1359	2642
	16	8.52	21.55	0.025	1269	2196
2.5	2	3.41	6.50	0.023	1005	953
	4	5.06	9.26	0.027	1068	1357
	6	8.26	21.49	0.032	1178	2202
	8	21.59	22.91	0.042	1322	4220
	10	22.18	23.66	0.045	1406	5552
	12	21.82	23.21	0.039	1392	4658
	14	21.23	22.46	0.032	1345	3407
	16	7.79	21.38	0.024	1251	2009

Run No. G17 Additive nitrogen dioxide

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.47	5.12	0.020	972	747
	4	6.42	12.43	0.021	1225	1643
	6	8.93	21.63	0.036	1167	2402
	8	21.81	23.18	0.049	1308	4758
	10	22.43	23.99	0.052	1398	6294
	12	22.08	23.53	0.046	1380	5337
	14	21.57	22.89	0.040	1335	4150
	16	10.21	21.88	0.034	1228	2679
15	2	2.77	5.55	0.021	983	811
	4	5.36	9.83	0.029	1065	1444
	6	8.38	21.51	0.034	1164	2249
	8	21.70	23.04	0.046	1311	4494
	10	22.24	23.73	0.049	1385	5752
	12	21.96	23.38	0.043	1382	5009
	14	21.46	22.75	0.037	1340	3893
	16	9.80	21.81	0.031	1245	2557
10	2	2.69	5.43	0.021	976	795
	4	5.43	9.98	0.028	1080	1455
	6	8.46	21.53	0.033	1176	2261
	8	21.57	22.87	0.044	1300	4187
	10	22.24	23.74	0.047	1400	5722
	12	21.86	23.25	0.041	1380	4757
	14	21.29	22.54	0.034	1336	3542
	16	9.11	21.68	0.028	1255	2369
5	2	3.02	5.92	0.022	989	867
	4	4.97	9.08	0.027	1063	1335
	6	8.26	21.49	0.032	1178	2202
	8	21.47	22.76	0.042	1299	3980
	10	22.13	23.60	0.045	1398	5447
	12	21.82	23.20	0.039	1392	4649
	14	21.15	22.36	0.032	1328	3268
	16	8.20	21.48	0.026	1243	2131
2.5	2	3.22	6.21	0.022	1004	907
	4	5.03	9.21	0.027	1067	1351
	6	8.05	21.42	0.032	1169	2150
	8	21.52	22.82	0.042	1308	4070
	10	22.33	23.11	0.045	1433	5921
	12	21.76	23.13	0.038	1389	4504
	14	21.16	22.37	0.031	1340	3261
	16	7.07	21.20	0.023	1230	1822

Run No. G18 Additive hydrogen chloride

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.45	5.10	0.019	985	739
	4	4.39	8.07	0.024	1060	1178
	6	8.05	21.44	0.032	1169	2150
	8	21.52	22.82	0.043	1300	4092
	10	22.16	23.64	0.047	1388	5549
	12	21.87	23.26	0.042	1374	4798
	14	21.24	22.47	0.035	1316	3461
	16	7.76	21.37	0.027	1211	2032
15	2	2.75	5.53	0.020	995	802
	4	4.53	8.32	0.025	1058	1218
	6	8.42	21.52	0.032	1184	2242
	8	21.43	22.70	0.042	1291	3900
	10	22.17	23.65	0.046	1396	5547
	12	21.78	23.16	0.041	1367	4603
	14	21.24	22.47	0.034	1325	3444
	16	8.03	21.44	0.027	1223	2099
10	2	3.05	5.97	0.021	1004	868
	4	4.64	8.49	0.026	1053	1249
	6	7.96	21.42	0.032	1165	2126
	8	21.52	22.82	0.042	1308	4078
	10	22.19	23.68	0.045	1408	5584
	12	21.79	23.17	0.040	1377	4605
	14	21.24	22.47	0.033	1336	3431
	16	7.87	21.40	0.025	1241	2041
5	2	3.12	6.07	0.022	996	887
	4	4.83	8.83	0.026	1065	1295
	6	7.89	21.40	0.031	1172	2101
	8	21.45	22.73	0.042	1294	3932
	10	22.09	23.55	0.044	1398	5326
	12	21.76	23.13	0.039	1380	4525
	14	21.16	22.37	0.032	1330	3281
	16	7.65	21.35	0.025	1231	1985
2.5	2	3.24	6.25	0.022	1005	912
	4	4.75	8.69	0.026	1060	1276
	6	8.00	21.43	0.031	1177	2129
	8	21.50	22.79	0.041	1312	4014
	10	22.12	23.59	0.043	1412	5377
	12	21.74	23.10	0.038	1385	4461
	14	12.79	22.24	0.031	1320	3096
	16	7.16	21.23	0.022	1249	1834

Run No. G19 Additive chlorine

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	2.35	4.95	0.020	963	724
	4	7.52	21.30	0.044	1051	2098
	6	21.31	22.53	0.061	1147	3849
	8	22.63	24.20	0.079	1282	7172
	10	23.70	25.63	0.095	1372	10790
	12	23.91	25.89	0.110	1347	11757
	14	23.20	24.94	0.095	1303	9095
	16	22.22	23.67	0.080	1215	6086
15	2	2.83	5.64	0.022	975	828
	4	7.51	21.30	0.043	1057	2090
	6	11.90	22.14	0.032	1292	2977
	8	22.43	23.95	0.073	1278	6559
	10	23.50	25.37	0.087	1376	9997
	12	23.42	25.25	0.093	1341	9803
	14	22.72	24.33	0.077	1304	7402
	16	21.75	23.08	0.064	1208	4786
10	2	3.30	6.34	0.024	986	936
	4	7.19	21.22	0.040	1064	1987
	6	21.14	22.33	0.052	1165	3454
	8	22.31	23.80	0.067	1288	6170
	10	23.32	25.09	0.078	1385	9156
	12	22.92	24.61	0.074	1350	7972
	14	22.13	23.59	0.059	1302	5637
	16	21.33	22.57	0.049	1220	3776
5	2	3.73	6.99	0.025	1004	1034
	4	6.15	11.58	0.034	1062	1677
	6	10.73	21.96	0.044	1160	2878
	8	21.87	23.25	0.053	1292	4941
	10	22.69	24.32	0.059	1395	7087
	12	22.17	23.64	0.051	1359	5614
	14	21.63	22.96	0.044	1313	4325
	16	10.96	22.01	0.036	1230	2852
2.5	2	3.51	6.65	0.024	1000	980
	4	5.46	10.03	0.029	1071	1468
	6	9.15	21.68	0.037	1166	2463
	8	12.51	22.27	0.031	1315	3059
	10	22.42	23.97	0.050	1409	6216
	12	21.85	23.24	0.042	1370	4752
	14	21.22	22.45	0.034	1322	3417
	16	8.36	21.51	0.028	1225	2190

Run No. G20 Additive nitric oxide

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
		1 flame	2 flames			
20	2	2.43	5.06	0.020	969	740
	4	5.97	11.12	0.034	1052	1629
	6	9.95	21.83	0.042	1152	2692
	8	21.99	23.40	0.057	1289	5271
	10	22.71	24.34	0.063	1375	7211
	12	22.21	23.70	0.052	1360	5736
	14	21.59	22.90	0.043	1312	4218
	16	8.12	21.46	0.029	1204	2141
15	2	2.72	5.48	0.021	979	801
	4	5.72	10.55	0.032	1056	1552
	6	8.85	21.61	0.038	1147	2398
	8	21.84	23.21	0.052	1293	4858
	10	22.47	24.02	0.056	1376	6435
	12	22.06	23.50	0.048	1361	5315
	14	21.41	22.68	0.040	1303	3829
	16	8.43	21.53	0.031	1195	2234
10	2	2.85	5.68	0.021	989	828
	4	5.41	9.92	0.030	1052	1462
	6	8.35	21.50	0.035	1163	2248
	8	21.79	23.06	0.048	1306	4549
	10	22.29	23.80	0.051	1386	5918
	12	21.89	23.29	0.045	1361	4896
	14	21.38	22.64	0.038	1321	3750
	16	8.52	21.55	0.030	1209	2248
5	2	2.90	5.75	0.022	980	843
	4	5.14	9.40	0.029	1052	1390
	6	8.13	21.46	0.033	1163	2178
	8	21.64	22.96	0.045	1306	4343
	10	22.16	23.63	0.047	1386	5528
	12	21.80	23.18	0.042	1361	4651
	14	21.27	22.50	0.035	1321	3510
	16	8.31	21.50	0.028	1223	2176
2.5	2	3.11	6.05	0.022	996	885
	4	5.15	9.41	0.028	1063	1384
	6	8.18	21.47	0.032	1175	2183
	8	21.62	22.94	0.043	1319	4286
	10	22.13	23.59	0.045	1396	5426
	12	21.74	23.10	0.040	1367	4490
	14	21.17	22.38	0.032	1332	3294
	16	8.35	21.51	0.026	1249	2167

Run No. G21 Additive sulphur dioxide

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2} h.^{-1}$ $ster.^{-1}$)
20	2	2.53	5.20	0.020	977	759
	4	5.09	9.31	0.028	1060	1371
	6	8.72	21.59	0.036	1159	2349
	8	21.86	23.24	0.049	1317	4865
	10	22.50	24.07	0.054	1395	6487
	12	22.23	23.73	0.049	1384	5741
	14	21.62	22.94	0.042	1326	4263
	16	9.53	21.76	0.033	1216	2516
15	2	2.50	5.16	0.020	975	753
	4	5.16	9.44	0.028	1064	1388
	6	8.08	21.44	0.034	1152	2174
	8	21.67	23.00	0.046	1304	4422
	10	22.32	23.84	0.050	1392	5972
	12	22.03	23.47	0.045	1379	5201
	14	21.38	22.65	0.047	1325	3748
	16	8.91	21.63	0.030	1224	2342
10	2	2.75	5.52	0.021	981	807
	4	4.95	9.06	0.027	1062	1332
	6	7.99	21.42	0.033	1157	2144
	8	21.56	22.86	0.044	1299	4170
	10	22.26	23.76	0.048	1396	5788
	12	21.94	23.36	0.042	1388	4959
	14	21.26	22.50	0.034	1330	3486
	16	8.84	21.62	0.028	1244	2305
5	2	3.00	5.89	0.022	988	863
	4	4.92	9.00	0.026	1071	1317
	6	7.88	21.40	0.032	1162	2107
	8	21.52	22.81	0.042	1307	4062
	10	22.08	23.53	0.045	1388	5313
	12	21.77	23.14	0.040	1372	4552
	14	21.44	22.71	0.032	1326	3857
	16	8.18	21.47	0.025	1255	2115
2.5	2	4.71	8.60	0.022	999	1300
	4	4.88	8.93	0.026	1068	1307
	6	7.78	21.37	0.031	1168	2073
	8	21.49	22.78	0.042	1303	4021
	10	22.12	23.58	0.044	1403	5388
	12	21.72	23.08	0.039	1373	4447
	14	21.13	22.33	0.031	1335	3216
	16	7.87	21.40	0.025	1241	2041

Run No. G22 Additive ammonia

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
		1 flame	2 flames			
20	2	2.56	5.25	0.020	980	765
	4	3.94	7.34	0.022	1056	1064
	6	6.70	13.36	0.027	1160	1766
	8	21.37	22.63	0.038	1312	3727
	10	21.58	22.89	0.040	1336	4158
	12	21.67	23.02	0.036	1392	4300
	14	10.58	21.96	0.025	1344	2651
	16	6.55	12.87	0.020	1248	1664
15	2	2.47	5.12	0.020	972	747
	4	4.06	7.53	0.023	1051	1097
	6	7.13	21.21	0.029	1159	1892
	8	21.39	22.66	0.038	1317	3773
	10	22.02	23.46	0.042	1403	5143
	12	21.70	23.05	0.037	1388	4368
	14	11.49	22.09	0.027	1341	2846
	16	6.35	12.22	0.020	1237	1615
10	2	2.73	5.49	0.021	980	803
	4	4.48	8.23	0.025	1055	1207
	6	7.53	21.31	0.031	1156	2009
	8	21.44	22.71	0.040	1308	3884
	10	22.07	23.53	0.043	1404	5275
	12	21.73	23.10	0.037	1394	4436
	14	21.55	22.86	0.038	1349	4086
	16	7.24	21.25	0.022	1253	1853
5	2	2.87	5.71	0.021	991	832
	4	4.81	8.81	0.026	1064	1292
	6	7.65	21.34	0.031	1162	2041
	8	21.47	22.76	0.041	1307	3965
	10	22.06	23.51	0.043	1401	5245
	12	21.73	23.08	0.038	1383	4435
	14	9.60	21.77	0.028	1272	2480
	16	7.28	21.26	0.023	1240	1873
2.5	2	3.20	6.20	0.022	1003	905
	4	4.87	8.90	0.026	1068	1304
	6	7.78	21.37	0.031	1168	2073
	8	21.42	22.69	0.041	1296	3862
	10	22.03	23.47	0.043	1395	5165
	12	21.74	23.10	0.038	1385	4461
	14	13.80	22.33	0.031	1334	3210
	16	7.86	21.40	0.026	1228	2047

Run No. G23 Additive sulphur trioxide

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (°C)	Rad. (Kcal. m^{-2} $h.^{-1}$ $ster.^{-1}$)
20	2	2.45	5.09	0.020	971	743
	4	4.73	8.65	0.026	1059	1270
	6	7.10	21.21	0.029	1157	1884
	8	21.33	22.58	0.039	1296	3673
	10	22.06	23.51	0.042	1410	5232
	12	21.68	23.02	0.037	1383	4318
	14	12.33	22.20	0.030	1323	3021
	16	6.16	11.70	0.021	1211	1581
15	2	2.80	5.60	0.021	985	817
	4	4.93	9.01	0.027	1060	1325
	6	7.27	21.25	0.030	1155	1936
	8	21.33	22.58	0.039	1296	3673
	10	22.04	23.49	0.042	1407	5192
	12	21.69	23.04	0.037	1386	4352
	14	12.46	22.21	0.030	1325	3039
	16	6.88	21.15	0.023	1220	1776
10	2	2.80	5.60	0.021	985	817
	4	4.93	9.01	0.027	1060	1325
	6	7.36	21.27	0.030	1159	1958
	8	21.39	22.66	0.040	1300	3798
	10	22.07	23.53	0.043	1404	5275
	12	21.73	23.09	0.038	1384	4452
	14	12.65	22.23	0.031	1317	3078
	16	7.06	21.20	0.024	1216	1830
5	2	3.17	6.15	0.022	1000	898
	4	4.67	8.56	0.026	1056	1258
	6	7.78	21.37	0.031	1168	2073
	8	21.54	22.84	0.041	1320	4095
	10	22.01	23.45	0.043	1392	5138
	12	21.70	23.05	0.038	1377	4375
	14	21.15	22.35	0.032	1327	3255
	16	7.89	21.41	0.026	1229	2056
2.5	2	3.17	6.15	0.022	1000	898
	4	4.85	8.88	0.026	1067	1301
	6	7.78	21.37	0.031	1168	2073
	8	21.49	22.78	0.041	1311	4006
	10	22.03	23.47	0.043	1395	5165
	12	21.73	23.09	0.038	1384	4452
	14	13.80	22.33	0.031	1334	3210
	16	7.82	21.39	0.025	1239	2028

Run No. G24 Additive sulphur trioxide

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ ster.$^{-1}$)
40	2	2.50	5.16	0.020	975	753
	4	4.46	8.19	0.025	1053	1201
	6	6.92	21.16	0.029	1148	1838
	8	21.34	22.60	0.039	1299	3696
	10	21.98	23.40	0.041	1403	5020
	12	21.67	23.02	0.036	1392	4291
	14	11.98	22.15	0.030	1316	2967
	16	5.92	11.07	0.021	1196	1520

Run No. G25 Additive sulphur trioxide on a rich flame

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. m^{-2}h.$^{-1}$ ster.$^{-1}$)
20	2	2.66	5.39	0.020	988	784
	4	4.72	8.65	0.025	1070	1263
	6	7.50	21.31	0.030	1165	1993
	8	21.52	22.82	0.041	1316	4062
	10	22.11	23.58	0.045	1394	5395
	12	21.74	23.10	0.041	1358	4505
	14	21.24	22.47	0.034	1325	3444
	16	7.25	21.55	0.024	1225	1877
15	2	2.91	5.77	0.021	994	840
	4	4.72	8.65	0.025	1070	1263
	6	7.65	21.34	0.031	1162	2041
	8	21.54	22.84	0.041	1320	4095
	10	22.13	23.60	0.045	1397	5437
	12	21.77	23.14	0.042	1356	4596
	14	21.32	22.56	0.036	1321	3610
	16	7.49	21.31	0.026	1211	1957
10	2	3.01	5.91	0.021	1001	860
	4	4.65	8.51	0.025	1065	1245
	6	7.82	21.38	0.031	1169	2082
	8	21.52	22.82	0.042	1308	4070
	10	22.21	23.71	0.046	1404	5654
	12	21.82	23.20	0.042	1364	4687
	14	21.28	22.52	0.036	1314	3546
	16	7.70	21.36	0.026	1220	2008
5	2	3.23	6.23	0.022	1004	910
	4	5.04	9.22	0.026	1078	1345
	6	7.76	21.37	0.031	1167	2069
	8	21.60	22.92	0.042	1324	4237
	10	22.10	23.56	0.046	1384	5389
	12	21.85	23.24	0.043	1363	4780
	14	21.31	22.56	0.037	1311	3615
	16	7.99	21.43	0.028	1209	2098
2.5	2	3.41	6.51	0.022	1018	949
	4	5.12	9.36	0.026	1083	1364
	6	8.18	21.47	0.032	1175	2183
	8	21.64	22.97	0.042	1331	4314
	10	22.15	23.63	0.046	1393	5505
	12	21.82	23.20	0.043	1357	4715
	14	21.27	22.51	0.037	1303	3542
	16	7.99	21.43	0.028	1209	2098

Run No. G26

Additive sulphur trioxide on a simulated town gas

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (°C)	Rad. (Kcal. m^{-2} $h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	3.40	6.50	0.022	1017	947
	4	10.33	21.90	0.039	1187	2750
	6	21.72	23.06	0.049	1292	4658
	8	12.74	22.23	0.036	1268	3149
	10	4.76	8.73	0.022	1111	1253
	12	2.78	5.58	0.018	1027	798
0	2	4.29	7.91	0.024	1054	1156
	4	11.08	22.02	0.039	1207	2904
	6	21.86	23.24	0.050	1311	4885
	8	21.23	22.45	0.038	1284	3471
	10	5.00	9.17	0.022	1126	1309
	12	2.80	5.60	0.020	999	813

Run No. G27 Additive sulphur trioxide on town gas

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	5.57	10.20	0.039	992	1553
	4	21.83	23.22	0.081	1154	5215
	6	23.23	24.95	0.116	1240	9448
	8	22.71	24.28	0.104	1204	7677
	10	21.58	22.84	0.090	1075	4612
	12	10.18	21.84	0.074	992	2946
0	2	4.18=	7.73	0.024	1047	1131
	4	10.93	22.00	0.040	1195	2883
	6	21.83	23.20	0.051	1299	4833
	8	21.18	22.39	0.039	1266	3397
	10	5.09	9.33	0.022	1132	1330
	12	2.83	5.65	0.019	1016	814

Run No. G28

Additive sulphur trioxide on town gas after passing through silica gel and carbosorb

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	3.64	6.86	0.024	1010	1010
	4	10.71	21.96	0.041	1181	2847
	6	21.81	23.18	0.053	1283	4821
	8	13.54	22.30	0.039	1252	3279
	10	4.70	8.62	0.027	1107	1238
	12	2.97	5.85	0.020	1012	846
0	2	4.23	7.81	0.024	1050	1142
	4	11.25	22.04	0.040	1203	2946
	6	21.82	23.19	0.050	1303	4787
	8	21.20	22.41	0.040	1262	3448
	10	4.79	8.79	0.021	1127	1252
	12	2.83	5.65	0.020	1001	819

Run No. G29

Additive sulphur trioxide on town gas after passing through carbosorb

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
20	2	5.56	10.20	0.037	1007	1541
	4	21.91	23.27	0.080	1164	5303
	6	23.34	25.10	0.116	1255	9813
	8	22.72	24.28	0.106	1198	7706
	10	21.57	22.82	0.092	1067	4603
	12	11.11	21.99	0.076	1007	3166
0	2	4.18	7.73	0.024	1047	1131
	4	10.93	22.00	0.040	1195	2883
	6	21.83	23.20	0.050	1305	4816
	8	21.20	22.41	0.039	1269	3425
	10	5.09	9.33	0.022	1132	1330
	12	2.97	5.85	0.021	998	851

Run No. G30

Additive sulphur trioxide on town gas after passing through silica gel

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. m^{-2} $h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20	2	3.71	6.97	0.024	1015	1025
	4	10.71	21.96	0.040	1189	2839
	6	21.78	23.14	0.053	1277	4752
	8	21.19	22.39	0.040	1259	3419
	10	4.70	8.62	0.022	1107	1238
	12	3.14	6.10	0.021	1011	886
0	2	4.18	7.73	0.024	1047	1131
	4	10.93	22.00	0.040	1195	2883
	6	21.83	23.20	0.051	1299	4833
	8	21.19	22.39	0.040	1259	3419
	10	5.09	9.33	0.022	1132	1330
	12	2.79	5.59	0.020	998	810

Run No. G31

Additive sulphur trioxide and
tri-ethylene glycol on town
gas passed through
silica gel

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (°C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
20% SO_3	2	3.67	6.90	0.024	1012	1015
	4	10.67	21.95	0.041	1180	2841
	6	21.84	23.21	0.054	1281	4892
	8	21.27	22.50	0.044	1244	3622
	10	4.80	8.78	0.024	1087	1274
	12	3.33	6.39	0.021	1025	926

Run No. G32

Additive sulphur trioxide and tetrahydrothiophene on town gas, passed through silica gel

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	2 flames	Emiss.	Flame Temp. (^{o}C)	Rad. (Kcal. m^{-2}h.$^{-1}$ ster.$^{-1}$)
20% SO_3	2	5.62	10.33	0.037	1010	1557
	4	21.84	23.19	0.077	1165	5115
	6	23.11	24.80	0.108	1247	8946
	8	22.67	24.24	0.098	1217	7504
	10	21.55	22.80	0.084	1090	4502
	12	10.29	21.86	0.069	1015	2947

Run No. G33 Additive tetrahydrothiophene

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output 1 flame	Pyrometer Output 2 flames	Emiss.	Flame Temp. (°C)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
	2	2.90	5.75	0.021	993	838
	4	4.94	9.04	0.027	1061	1329
	6	8.11	21.45	0.033	1162	2173
	8	21.58	22.89	0.043	1311	4201
	10	22.08	23.53	0.045	1388	5313
	12	21.72	23.08	0.039	1372	4438
	14	21.14	22.34	0.033	1315	3257
	16	7.58	21.33	0.026	1215	1978

Run No. G34

Additive sulphur trioxide and tetrahydrothiophene

Pyrometer

Add. Conc. (%)	Ht. above Burner (cm)	Pyrometer Output		Emiss.	Flame Temp. (^oC)	Rad. (Kcal. $m^{-2}h.^{-1}$ $ster.^{-1}$)
		1 flame	2 flames			
20% SO_3	2	3.69	6.92	0.027	980	1035
	4	8.20	21.46	0.049	1047	2309
	6	21.29	22.50	0.060	1148	3794
	8	22.48	24.02	0.071	1296	6674
	10	23.21	24.99	0.080	1365	8946
	12	22.73	24.35	0.069	1344	7331
	14	21.48	22.76	0.044	1284	4011
	16	7.96	21.42	0.030	1186	2111

Appendix 7

Table 16

The visual effects of the addition of sulphur trioxide.

	Fuel	SO_3 added to	other additive before absorber	fuel through		other additive after absorber	visual effect	conclusion
				carbo-sorb	silica gel			
a.	CH_4	air	no	yes	yes	no	none	may need richer initial flame
b.	rich CH_4	air	no	yes	yes	no	none	may need SO_3 in fuel supply
c.	rich CH_4	CH_4	no	yes	yes	no	none	check earlier with town gas
d.	town gas	air	no	no	no	no	strongly luminous throughout flame	may be due to C_2H_6 or C_3H_8 in town gas
e.	CH_4	air	C_2H_6	yes	yes	no	none	luminosity not due to C_2H_6
f.	CH_4	air	C_3H_8	yes	yes	no	none	luminosity not due to C_3H_8
g.	sim. town gas	air	no	yes	yes	no	none	luminosity due to a trace component
h.	town gas	air	no	yes	yes	no	none	trace component removed by carbosorb or silica gel

Table 16 (cont.)

	Fuel	SO_3 added to	other additive before absorber	fuel through		other additive after absorber	visual effect	conclusion
				carbo-sorb	silica gel			
i.	town gas	air	no	no	yes	no	none	trace component absorbed by silica gel
j.	town gas	air	no	yes	no	no	strongly luminous	trace component not absorbed by carbo-sorb
k.	town gas	air	no	no	yes	H_2O	none	trace component not H_2O
l.	town gas	none	no	no	yes	t.e.g.[1]	sl. yellow tip	
m.	town gas	air	no	no	yes	t.e.g.	sl. yellow tip	trace component not t.e.g.
n.	town gas	none	no	no	yes	C_6H_6	sl. yellow tip	
o.	town gas	air	no	no	yes	C_6H_6	sl. yellow tip	trace component not C_6H_6
p.	town gas	none	no	no	yes	t.h.t.[2]	sl. yellow tip	

1 triethylene glycol

2 tetrahydrothiophene

Table 16 (cont.)

Fuel	SO_3 added to	other additive before absorber	fuel through		other additive after absorber	visual effect	conclusion
			carbo-sorb	silica gel			
q. town gas	air	no	no	yes	t.h.t.	strongly luminous throughout flame	trace component is similar to t.h.t.
r. CH_4	none	no	yes	yes	t.h.t.	sl. yellow tip	t.h.t. alone has little effect
s. CH_4	air	no	yes	yes	t.h.t.	luminous throughout flame	

14. References to the Literature

1. Monaghan M.T. and McGrath J.A., Gaswarme Int., 17 (10), 376, 1968.
2. Finlayson P.C. and Durrant A.W., J.Inst. F., 37, 543, 1964.
3. J. Soc. Glass Tech., 41, 58A, 1957.
4. Monagham M.T. and McGrath J.A., Shell Research Ltd. "The Industrial Applications of Luminous Flames from Natural Gas", 1968.
5. Jennings J.L. and Patton J.R., Proc.Am.I.Min.E., Nat. Open Hearth Comm., 37, 320, 1954.
6. Andoniev S.M., Levitasov Y.M., Makarov K.I., Potshtman A.M., Pokras L.M. and Tesner P.A. Int. Gas Union, I.G.U./E.16-67, 10th Int. Gas Conference, Hamburg, 1967.
7. Levitasov Y.M., Makarov K.I., Pokras L.M., Potshtman A.M., Podoprigova I.D., Sapiro V.S., Tesner P.A. and Sheinfain F.I., Izv.Vyssh.Ucheb. Zaved., Chern. Met., 12, 157-61, 1969.
8. Kapustin E.A., Kaloshin N.A., Rudman V.D., and Leparskii V.V., Stal, 5, 420, 1963.
9. Lhospied P and Reveillard Y., G.E.F.G.N., "Investigations carried out about the radiation of the flames on behalf of the G.E.F.G.N." 1966.
10. Jaegle J. and Malmezat P., I.G.U./E.15, 67. "Radiation from natural gas flames. Industrial experience and research in pilot plant." 1967.
11. Siemens F., J. Iron and Steel Inst., (ii), 434, 1884.

12. Hudson J.G., Engineer, 70, 523, 1890.

13. Sherman R.A., Trans. A.S.M.E., 56, 177, 1934.

14. Trinks W. and Keller J.D., ibid., 58, 203, 1936.

15. Thring M.W., J. Iron and Steel Inst., 171, 381, 1952.
Ibid., 173, 168, 1954.

16. Pearson S.W., Chesters J.H. and Thring M.W., Paper to Joint Conference on Combustion, A.S.M.E. June 1955., and I.Mech.E., October 1955.

17. Kruszeuski S., J.Soc.Glass Tech., 35, 164, 1959.

18. Robert G., I.Gas.E., Autumn Res.Meeting 1966.

19. Datschefski G., Glass Tech., 8, 148, 1967.

20. Agather V.N., Proc.Am.I.Min.E., Nat. Open Hearth Comm. 38, 215, 1955.

21. Thring M.W. and Hubbard E.H., Iron and Coal Trades Rev., 175, 1251, 1957.

22. Thring M.W., Chemical and Process Engineering, 46, 544, 1965.

23. Hottel H.C., "Heat Transmission", McAdams W.H. , (McGraw-Hill, 1954).

24. Schack A., Arch.Eisenhiittenw, 13, 241, 1939.

25. "The Science of Flames and Furnances", Thring M.W., (Chapman and Hall, 1952).

26. Saleh M.A., Ph.D. thesis, University of London 1952, "Heat Transfer from Luminous Flames in Vertical Tubes".

27. Bone W.E., Trans. Fuel Conf. (London), 2, 151, 1928.

28. Brodia H.P. and Gaydon A.G., Trans.Fara.Soc., 49, 1190, 1953.

29. Hottel H.C. and Broughton F.P., Ind.Eng.Chem., Anal.Ed., 4, 166, 1932.

30. The International Flame Radiation Research Joint Committee (Ijmuiden), See reports in:
J. Inst. F., 24, S1, 1951.
Ibid., 25, S17, 1952.

31. Schack A., Z. Tech.Phys., 6, 530, 1925.

32. Mayorcas B. and Riviere M., "Descriptioh of Trials and Results," Flame Radiation Research Doc.D3/b/8, 1952.

33. Daws L.F. and Thring M.W., J.Inst.F., 25, S28, 1952.

34. Hottel H.C., "Heat Transmission", McAdams W.H., 104 (McGraw-Hill, 1954).

35. Sherman R.A., Trans. A.S.M.E., 79, 1727, 1957.

36. Creasey D.E., Ph.D. thesis, University of London, 1960. "Heat Transfer from Vertical Luminous Flames in Cooled Envelopes".

37. Sato T., Kunitomo T., Nakashima F. and Fujii I., Bulletin of Jap.Soc.Mech.E, 9, 768, 1966.

38. Thring M.W., Chemical and Process Engineering, 46, 544, 1965.

39. Beer J.M. and Howarth C.R., 12th Symposium (Int.) on Combustion, The Combn.Inst., Pittsburgh, Penn. 1969.

40. Gill D.W., B.C.U.R.A. Monthly Bulletin, 14, (4 and 5), 1952.

41. Kaskan W.E., Combustion and Flame, 5, 93, 1961.

42. Lee K.B., Thring M.W. and Beer J.M., Combustion and Flame, 6, 1962.

43. Kurlbaum F., Phys.Z., 3, 332, 1902.

44. Angstrom K., Phys.Rev., 17, 302, 1903.

45. Ladenburg R., Phys.Z., 7, 697, 1906.

46. Leder F., Ann.Phys.Lpz., 24, 305, 1907.

47. Beckar A., ibid., 28, 1017, 1909.

48. Datschefski G., Glass Tech. 10, 107, 1969.

49. Stull V.R. and Plass G.N., J.Opt.Soc.Am., 50, 121, 1960.

50. Haslam R.T. and Boyer M.W., Indus. and Eng. Chemistry, 19, 4, 1927.

51. Lhospied P. and Reveillard Y., Compt. Rend.Congr. Ind.Gaz. 82, 1034, 1966.

52. Gas Council M.R.S., External Report 98, "Burning Natural Gas in Industrial Burners," 1966.

53. Guenebant H. and Gaydon A.G., The 6th Symposium (Int.) on Combustion, The Combn. Inst., (New York) 1957.

54. Diederichsen J. and Gould R.D., Combustion and Flame, 9, 25, 1965.

55. Gillings J., Metal Progress, 66, 91, 1954.

56. Power and Works Eng. 50, 225, 1955.

57. Glinkov M.A., Iron and Coal Trades Rev. 173, 89, 1956.

58. Zakharikov N.A. and Rozhanskii A.I., Steklo Keram, 15, 4, 1958.

59. Dewerth D.W. and Zalavadia J.V., Trans.A.S.M.E., J.Eng. Power, 88A, 111, 1966.

60. "Flames, their Structure, Radiation and Temperature", Gaydon A.G. and Wolfhard H.G., (Chapman and Hall, 1960).

61. Ray S.K. and Long R., Combustion and Flame, 8, 139, 1964.

62. Chakraborby B.B. and Long R., ibid., 12, 168, 1969.
Ibid., 12, 226, 1968.
Ibid., 12, 237, 1968.
Ibid., 12, 469, 1968.

63. Porter G., Combn. Researches and Reviews, A.G.A.R.D., 108, 1955.

64. Booth F., Proc. Phys. Soc., A62, 95, 1949.

65. Thomas A., Combustion and Flame, 6, 46, 1961.

66. Millikan R.C., J.Phys.Chem., 66, 794, 1962.

67. Foster P.J., J.Inst.F., 38, 297, 1965.

68. Tesner P.A., The 7th Symposium (Int.) on Combustion, The Combn. Inst., (Butterworths) 1959.

69. Francies W.E., The 10th Symposium (Int.) on Combustion, The Combn. Inst., (Cambridge) 1965.

70. Narasimham K.S. and Foster P.J., The 10th Symposium (Int.) on Combustion, The Combn. Inst., (Cambridge) 1965.

71. Homann K.H. and Wagner H.G., Proc. Roy.Soc., 307A, 414, 1968.
Ber. Bunsengesellschaft Phys.Chem., 69, 20, 1965.
The 11th (Int.) Symposium on Combustion, The Combn. Inst. (Pittsburgh) 1966.

72. Homann K.H., Combustion and Flame, 11, 265, 1967.

73. Bonne U., Homann K.H. and Wagner H.G., The 10th Symposium (Int.) on Combustion, The Combn. Inst., 1965.

74. Gaydon A.G. and Whittingham G., Proc. Roy. Soc., 189, 313, 1947.

75. Dooley A. and Whittingham G., Trans. Faraday Soc., 46, 354, 1946.

76. Whittingham G., Nature, 156, 207, 1945.

77. Wolfhard A,G, and Parker W.G., Fuel, 29, 235, 1950.
Proc.Phys.Soc., A62, 722, 1949.

78. Wolfhard A.G. and Parker W.G., Proc.Phys.Soc., A65, 2, 1952.

79. Wolfhard A.G. and Parker W.G., The 4th Symposium (Int.) on Combustion, The Combn. Inst. (Massachusetts) 1953. The 5th Symposium (Int.) on Combustion, The Comb. Inst. 1955.

80. Arthur J.R., Nature, 165, 557, 1950.

81. Thring M.W., J. Inst. F., 29, 23, 1956.

82. Mellish C.E. and Linnett J.W., The 4th Symposium (Int.) on Combustion, The Combn. Inst., (Massachusetts) 1953.

83. Clingman W.H., Brokaw R.S. and Pease R.N., ibid.

84. Arthur J.R. and Napier D.H., The 5th Symposium (Int.) on Combustion, The Combn. Inst., 1955.

85. Street J.C. and Thomas A., Fuel, 34, 4, 1955.

86. Rust F.F. and Vaughan W.E., Indus.Eng.Chem., 41, 2595, 1949.

87. Skirrow G. and Wolfhard H.G., Proc.Roy.Soc., A232, 78, 1955.

88. Stephens E.R., Scott W.E., Golden J.A. and Faunce B., The 6th Symposium (Int.) on Combustion, The Combn. Inst. (New York) 1957.

89. Fenimore C.P., Jones G.W. and Moore G.E., ibid.

90. Smith S.R. and Gordon A.S., J. Phys. Chem., 60, 1059, 1956.

91. Breisacher P., Dembrow D. and Berl W.G., The 7th Symposium (Int.)

on Combustion, The Combn. Inst., (London) 1959.

92. Cole D.J. and Minkoff G.J., Proc.Roy.Soc., A239, 280, 1957.

93. Tesner P.A., Robinovitch H.J. and Rafalkes I.S., The 8th Symposium (Int.) on Combustion, The Combn. Inst. (Baltimore) 1961.

94. Schirmer R.M., McReynolds L.A. and Daley J.A., Soc. Automotive Engrs., Preprint 114B, 1960.

95. Jennings K.R. and Linnett J.W., Trans.Faraday Soc., 56, 1737, 1960.

96. Schmidt K.H. and Schulze V., Gas-Wasserfach, 103, 418, 1962.

97. Bonne U.,Jost W. and Wagner H.G., Am.Chem.Soc., Division of Fuel Chemistry, Preprints, 1, 6, 1961.

98. Rosser W.A., Inami S.H. and Wise H., Combustion and Flame, 7, 107, 1963.

99. Fenimore C.P. and Jones G.W., Combustion and Flame 7, 323, 1963.

100. Ibiricu M.M. and Gaydon A.G., Combustion and Flame, 8, 51, 1964.

101. Pearson G.S., Nature, 208, 283-4, 1965.

102. Scully D.B., J.Inst. F., 39, 266, 1966.

103. Mason D.M., Am.Chem.Soc., Division of Fuel Chemistry, Preprints 11, 540, 1967.

104. Blake A.R., Hilton D.A. and Robins I.H., J. appl. Chem., 17, 321, 1967.

105. Miller W.J., U.S. Clearinghouse Fed.Sci.Tech.Info., P.B. 173993, 1967.

106. Fenimore C.P. and Jones G.W., Combustion and Flame, 12, 196, 1968.

107. Fenimore C.P. and Jones G.W., J.Phys.Chem., 63, 1834, 1959.

108. McLintock I.S., Combustion and Flame, 12, 217, 1968.

109. Dearden P. and Long R., J. appl. Chem., 18, 243, 1968.

110. Tischer R.L. and Scheller K., Combustion and Flame, 12, 307, 1968.

111. Kaskan W.E. and Millikan R.C., J.Chem.Phys., 32, 1273, 1960.

112. Kaskan W.E., Mackenzie J.D. and Millikan R.C., J.Chem.Phys., 34, 570, 1961.

113. Kaskan W.E. and Millikan R.C., The 8th Symposium (Int.) on Combustion, The Combn. Inst. (Baltimore) 1961.

114. Tesarik B., Hutricke Listy, 24, 362, 1969.

115. Schmidt H., Ann. Physik, 29, 998, 1909.

116. Pengelly A.E.S., J.Inst.F., 35, 210, 1962.

117. Wolfhard H.G. and Parker W.G., Proc.Phys.Soc.(London) B62, 523, 1949.

118. Topper L., Indus.Eng.Chem., 46, 2551, 1954.

119. Maesawa M., Tanaka Y. and Ogisu Y., The 12th Symposium (Int.) on Combustion, The Combn. Inst., 1969.

120. Reynolds P.M., Brit. J. Appl. Physics., 15, 579, 1964.

121. Dyne P.J. and Penner S.S., J. Am. Rocket Soc., 23, 165, 1953.

122. Hett J.H. and Gilstein J.B., J.Opt.Soc.Am., 39, 909, 1949.

123. Penner S.S., J.Chem.Phys., 19, 272, 1951.

124. Sanderson J.A., Curcio J.A. and Estes D.V., Physcial Review, 74, 1221, 1948.

125. Comerford F.M., Fuel, 35, 333, 1956.

126. Kurlbaum F., Physik. Z., 3, 187, 1902.

127. Wurster C.F., Smith J.O. and Satterfield C.N., Journal of Chemical and Engineering Data, 6, 626, 1961.

128. Instrument Soc. America., "The Effect of Water Vapour Absorption on the Accuracy of Temperature Measurement by Pyrometers", 68-563, 1968.

129. "Heat Transmission", W.H. McAdams, 60, (McGraw-Hill) 954.

130. Hoffmann K., Z. Physik, 14, 310, 1923.

131. Schmidt H. and Furthmann E., Mitt. Kaiser-Wilhelm-Inst. Eisenforsch. Dusseldorf, Adhandl, 109, 225 (1928).

132. Davies O.L., "Statistical Methods in Research and Production", 366 (Oliver and Boyd, 1967).