RADIATION FROM A LINE FIRE

by

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Submitted to the Department of Chemical Engineering on May 19, 1961 in partial fultillment of the requirements for the degree of Master of Science.

ABSTRACT

This thesis is a study of the radiation from a fire front. The intensity of radiation was measured with a thermopile at different distances from a fire front for different heat liberation rates, different source widths and different fuels. Modeling laws were derived and the results were used to correlate the data.

The intensity of radiation was found to be independent of source width when the heat liberation rate per unit length of source remains constant.

It was also found that in the heat liberation range of 50,000 to 200,000 Btu/hr-ft length of fire front the intensity at a distance Z from the source centerline is approximated by:

$$I = 6{,}400 \left(1 - \frac{1.16 \times 10^5 \; (Z/(Q/L))}{\sqrt{1 + \left[1.16 \times 10^5 \frac{Z}{Q/L}\right]^2}} \right) \quad \text{Btu/hr-ft}^2$$

to within 10%, where Q/L is the heat liberation rate per unit length of fire front.

Correlation of the data when different fuels were studied, showed that Q/L is not sufficient to characterize the fuel; temperature level and gas absorption coefficient have also to be considered.

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May 19, 1961

Professor P. Franklin
Secretary of the Faculty
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Dear Sir:

The attached thesis entitled "Radiation from a Line Fire", is submitted in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering.

Respectfully submitted,

Charles-Louis de Rochechouart

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I SUMMARY

Each year forest and city fires prove to be costly in human lives and money. Very little is known about the mechanism of uncontrolled combustion associated with these fires. Uncontrolled combustion involves all modes of heat transfer; in order to thoroughly investigate its mechanism one has to attempt to isolate the effect of each mode of heat transfer. The purpose of this thesis is to study the radiation from a line fire when other modes of heat transfer are made unimportant.

Gaseous fuel was fed through a long narrow rectangular slot and fired; the intensity of radiation was measured at different distances from the slot for different heat liberation rates, different slot widths and different fuels.

It was found that the intensity of radiation is independent of slot width, confirming the theory that all properties of the fire are only dependent on local conditions and not on the past "history" of the fire.

In the case of a single fuel and for heat liberation rates Q/L ranging from 50,000 to 200,000 Btu/hr.ft length of slot the intensity of radiation at a distance Z from the slot centerline was found to be approximated within 10% by:

$$I = 6{,}400\left(\frac{1.16 \times 10^5 \left\langle Z/(Q/L)\right\rangle}{\sqrt{1 + \left\{1.16 \times 10^5 \left\langle Z/(Q/L)\right\rangle\right\}^2}}\right)$$

When different fuels were used, it was found that Q/L was not sufficient to characterize the fuel since the temperature level and the attenuation factor changed when the fuel changed. Because of time limitation only a few qualitative results were found. These results warrent further investigation of fuel mixtures the compositions of which could be varied in order to obtain a given Q/L, a given temperature level and/or a given attenuation factor K. Correlations would then be possible using the dimensionless groups emerging from the modeling analysis.

II. INTRODUCTION

Each year in the U. S. there are between 12 and 13 million acres of forest land destroyed by fire. During the Second World War various bombing raids turned cities into raging infernos; in the case of nuclear attack, damage from wide spread uncontrolled combustion in areas where large amounts of potential fuel are densely located, can be easily foreseen. At the present time very little is known about the process of uncontrolled combustion; for instance no one can answer such questions as the effect of fuel density loading and surface - volume ratio of the fuel on the rate of movement of a fire front. A simple mathematical model of the process of fire spread in the case of a flat surface has been derived (1) (4) (7) with some simplifying assumptions (see Appendix). The results show that the velocity of flame spread V is directly proportional to the height of the flame H, inversely proportional to the thickness of the fuel L and directly proportional to an effective heat transfer to the surface by radiation minus an effective heat transfer away from the surface by radiation and convection.

$$V = (M - N) \frac{H}{L} \qquad \text{(A-4)}$$

where M and N represent the heat transfer expressions. However, the assumptions necessary to obtain the above solution make it of doubtful value except as a qualitative understanding of the process.

Uncontrolled conbustion involves four different modes of heat transfer.

1) Heat transfer by conduction within the fuel itself.

2) Heat transfer by convection to and away from the fuel; as the fire burns hot gases are formed producing a chimney effect which draws cool air across the unburned fuel into the flame. Also near the fire the flame will lick at fuel near by because of turbulent disturbances, transferring heat by convection at short distances.

3) One mode of heat transfer particular to solid fuels referred to as the fire brand, consists of an ember being swept from the burning fuel to an area of unburned fuel.

4) The last mode of heat transfer is radiant heat transfer which consists of gas radiation from the flame to the unburned fuel and surface radiation from the fuel to the ambient surroundings and other fuel.

It is believed that for a thorough analysis of the problem of uncontrolled combustion it will be necessary to determine which particular modes of heat transfer are important under specific conditions by attempting to study them individually.

The main purpose of this thesis is to study the mechanism of radiant heat transfer from a fire front, and verify the modeling laws which can be established from theoretical considerations. The intensity of radiation from a fire was measured at different distances from this fire front, for different rates of heat liberation, different source widths and different fuels. The results were then correlated in the form of dimensionless groups of variables which appeared in the modeling analysis.

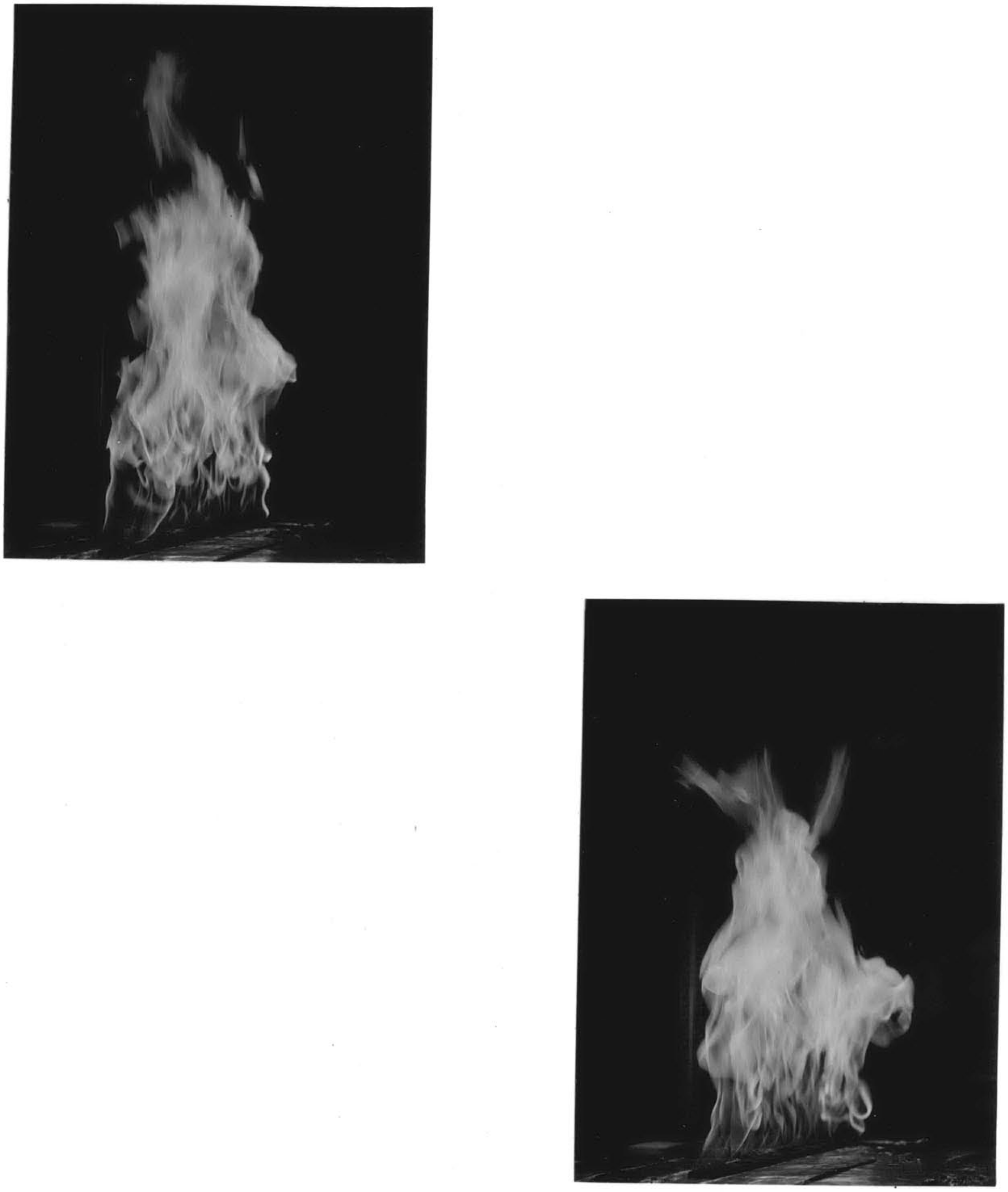


FIGURE I

PHOTOGRAPHS OF LINE FIRE

III. MODELING

Modeling of radiation from a natural convection jet rising from a line source.

Let us consider a process subject to change in space or time. One can write quantitative statements about force, energy and mass. If each statement is divided throughout by one of the terms a set of force, energy or mass ratios will emerge. These ratios must be the same in similar systems. If all the different variables pertaining to a particular system are therefore arranged in the three catagories of mass, force and energy, and if ratios are taken within each catagory, one will be provided with a number of dimensionless groups representing the particular system under consideration.

This method has been applied (3) to a natural convection jet rising from a line source with an energy liberation rate Q/L Btu/hr. perft. length of line source. To describe the system the following statements were made:

Forces:

Momentum due to steady flow: $U^2 \rho Z^2$ (1)

(Turbulent stress)(Area) : $\rho \, \overline{1v} \, Z^2 \, U/Z$

If one makes the assumption that the velocity v in the transport coefficient $\overline{1v}$ is measured by the local steady velocity U, and that 1 is measured by the distance the jet has risen, the group becomes the same as (1).

Buoyancy: $Z^3 g(\rho - \rho_o)$

which by use of the perfect gas law becomes:

$$Z^3 g\rho \frac{(T - T_o)}{T_o} \qquad (2)$$

Viscous forces: μUZ (3)

These three force statements can be replaced by two dimensionless ratios:

(1)/(3) $\frac{UZ\rho}{\mu}$ (A) Reynolds number

(2)/(1) $\frac{Zg(T - T_o)}{U^2 T_o}$ (B) Froude number

Energy Rates:

Convection flux: $Z^2 U\rho C_p (T - T_o)$ (4)

Turbulant transport which with the same assumption as in (2) becomes identical to (4)

Heat liberation rate: $(Q/L)(Z)$ (5)

Conduction: $\lambda Z(T - T_o)$ (6)

Radiation flux: $\sigma(T^4 - T_o^4)\, f(\epsilon's, KPZ)$ (7)

These four energy statements can be replaced by three dimensionless ratios:

(5)/(4) $\frac{Q/L}{UZ\rho C_p (T - T_o)}$ (C)

(6)/(4) $\frac{\lambda}{UZ\rho C_p}$ (D)

(7)/(4) $\frac{\sigma(T^4 - T_o^4)\, f(\epsilon's, KPZ)}{U\rho C_p (T - T_o)}$ (E)

Mass Rates:

Bulk flow: $UZ^2 \rho \, fi$ (8)

Diffusion: $\mathfrak{D} \, Z\rho \, fi$ (9)

These two mass statements can be replaced by a dimensionless ratio:

$$(8)/(9) \quad \frac{UZ}{\mathfrak{D}} \qquad \text{(F)}$$

Any one ratio can be combined with another and replaced by the resulting ratio. For instance, by combining (A) and (D) one obtains $\lambda/\mu C_p$, the Prandtl number and by combining (A) and (F) one obtains $\mu/\rho\mathfrak{D}$ the Schmidt number.

The dimensionless groups representing the system under study are therefore:

The Reynolds number

The Schmidt number

The Prandtl number

$$\frac{Q/L}{UZ\rho C_p(T - T_o)} \qquad \text{(C)}$$

$$\frac{Zg(T - T_o)}{U^2 T_o} \qquad \text{(B)}$$

$$\frac{\sigma(T^4 - T_o^4) \; f(\epsilon's, KPZ)}{U\rho C_p(T - T_o)} \qquad \text{(E)}$$

The Schmidt number and the Prandtl number are constant for gases. By inspection of data gained in the litterature (2) the Reynolds number is not believed to be a factor when experimenting in the turbulent region; therefore, only the groups (C), (B) and (E) will be considered for modeling.

Combining these three groups, the system can then be defined by the three new groups:

$$\frac{Q/L}{\rho C_p}\left(\frac{T_o}{g}\right)^{1/2} Z^{-3/2}\ (T - T_o)^{-3/2}$$

$$\frac{Q/L\ \ g}{T_o \rho C_p}\ U^{-3}$$

$$\frac{\sigma(T^4 - T_o^4)}{(\rho C_p)^{2/3}} \frac{f(\epsilon's, KPZ)}{\left(\frac{Q/L\ g}{T_o}\right)^{1/3} (T - T_o)}$$

Any ratio must be identified with a position in relation to the axis through the heat source expressed in non-dimensional terms. If R is the distance from the center line of the slot:

$$\frac{Q/L}{\rho C_p}\left(\frac{T_o}{g}\right)^{1/2} Z^{-3/2}\ (T - T_o)^{-3/2} = f_1\ (R/Z)$$

$$\frac{Q/L}{T_o \rho C_p}\ g\ U^{-3} = f_2\ (R/Z) \qquad (3-1)$$

$$\frac{\sigma(T^4 - T_o^4)\ f(\epsilon's, KPZ)}{(\rho C_p)^{2/3}\left(\frac{Q/L\ g}{T_o}\right)^{1/3} (T - T_o)} = f_3(R/Z)$$

This means that if the three left-hand groups are kept constant conditions (velocity, intensity of radiation, $T - T_o$) will be the same at corresponding values of R/Z.

1) If only one fuel is of interest and the temperature level remains constant, substitution of proportionality of ρ to P and elimination of all constant quantities yields the three following groups:

$$\frac{(Q/L)Z^{-3/2}}{P}$$

$$\frac{Q/L}{PU^3}$$

$$\frac{f(\epsilon's, KPZ)}{P^{2/3}\ (Q/L)^{1/3}}$$

The function involving ϵ's and KPZ is not one of direct proportionality, therefore ϵ's and KPZ have to be kept independently constant and one is left to model with:

$$\frac{Q/L}{PZ^{3/2}}\ ,\ \epsilon\ ,\ PZ\ ,\ P^{2/3}\ \ (Q/L)^{1/3}$$

The group $\frac{Q/L}{PU^3}$ is a function of all others and therefore remains constant when the others are constant. The third group yields $P \propto Z^{-1}$; combining the first and the last groups yields $P \propto Z^{-3/2}$; this indicates that not enough degrees of freedom are left for modeling. However, within the flame itself the radiation fluxes are small compared to other fluxes, and therefore it is possible to model the radiation process and its space-distribution over nearby surfaces if one is not intent on allowing for interaction of radiation with other fluxes. This eliminates the fourth group and one is left to model with the following groups:

$$\frac{Q/L}{PZ^{3/2}}\ \ ,\ \epsilon\ ,\ PZ$$

2) If it is desired to model with different types of fuel the temperature level will not remain the same when switching from one fuel to another. Going back to equations (3-1) the groups to be kept constant are:

$$\frac{(Q/L)(T_o/g)^{1/2}(T - T_o)^{-3/2}}{\rho C_p Z^{3/2}}$$

ϵ's

KPZ

$$\frac{\sigma\ (T^4 - T_o^4)}{(\rho C_p)^{2/3}(T - T_o)(Q/L)^{1/3}(g/T_o)^{1/3}}$$

The velocity group being a function of all others remains constant when the others are constant. Combining the first and fourth groups yields:

$$\frac{(Q/L)(T_o/g)^{1/2}(T - T_o)^{-3/2}}{\rho C_p\ Z^{3/2}}$$

ϵ's

KPZ

$$\frac{Z\ \sigma\ (T^4 - T_o^4)}{Q/L}$$

Substituting $p = \rho RT$ and after elimination of all quantities which remain unchanged one is left to model with:

$$\frac{Q/L}{P} Z^{-3/2} \quad \underline{(T - T_o)^{-3/2}} \; T$$

ϵ's

KPZ

$$\frac{Z \sigma (T^4 - T_o^4)}{Q/L}$$

With the assumptions made one is left to model with three or four groups depending if one or several fuels are of interest. The group containing the ϵ's remains constant since the surface was not changed throughout the experimental study.

The modeling of pressure is not attractive; unfortunately it can only be avoided if the flame is opaque in which case KPZ is infinite; in the general case pressure should be varied accordingly with Z. However, in this study, pressure was not modeled for practical reasons and the conclusions of the analysis had to be adjusted to fit the actual procedure.

1) In the case where only one fuel is of interest the two groups left to model with are:

$$\frac{Q/L}{PZ^{3/2}} \quad \text{and PZ}$$

A plot of any property of the system versus $\frac{Q/L}{Z^{3/2}}$ should yield similar curves of constant Z.

2) In the case where different fuels are of interest the three groups left to model with are:

$$\frac{(Q/L)}{PZ^{3/2}} \quad T(T - T_o)^{-3/2}$$

KPZ

$$\frac{Z\sigma(T^4 - T_o^4)}{Q/L}$$

Eliminating P and Z from the first group yields:

$$K^2(Q/L)\ \frac{\sigma\ (T^4 - T_o^4)\ T^2}{(T - T_o)^3}$$

KPZ

$$\frac{Z\ \sigma\ (T^4 - T_o^4)}{Q/L}$$

Any property of the system is a function of these three groups, none of which remain nearly constant when fuel is changed.

IV. PROCEDURE

Alternatively city gas or propane, pure or diluted in nitrogen was fed through a 24 by 2 inches slot and fired. The slot width was chosen at 2 inches in order to be as close as possible to turbulent conditions while momentum to the gases remains negligeable. The intensity of radiation from the flame was measured by means of a calibrated thermopile and the signal recorded on a Sanborn 150 Recorder.

The validity of the modeling laws was verified by four different experimental procedures.

1) The reproducibility of the data was verified by taking measurements of the radiation intensity at identical distances and for identical heat liberation rates on different days.

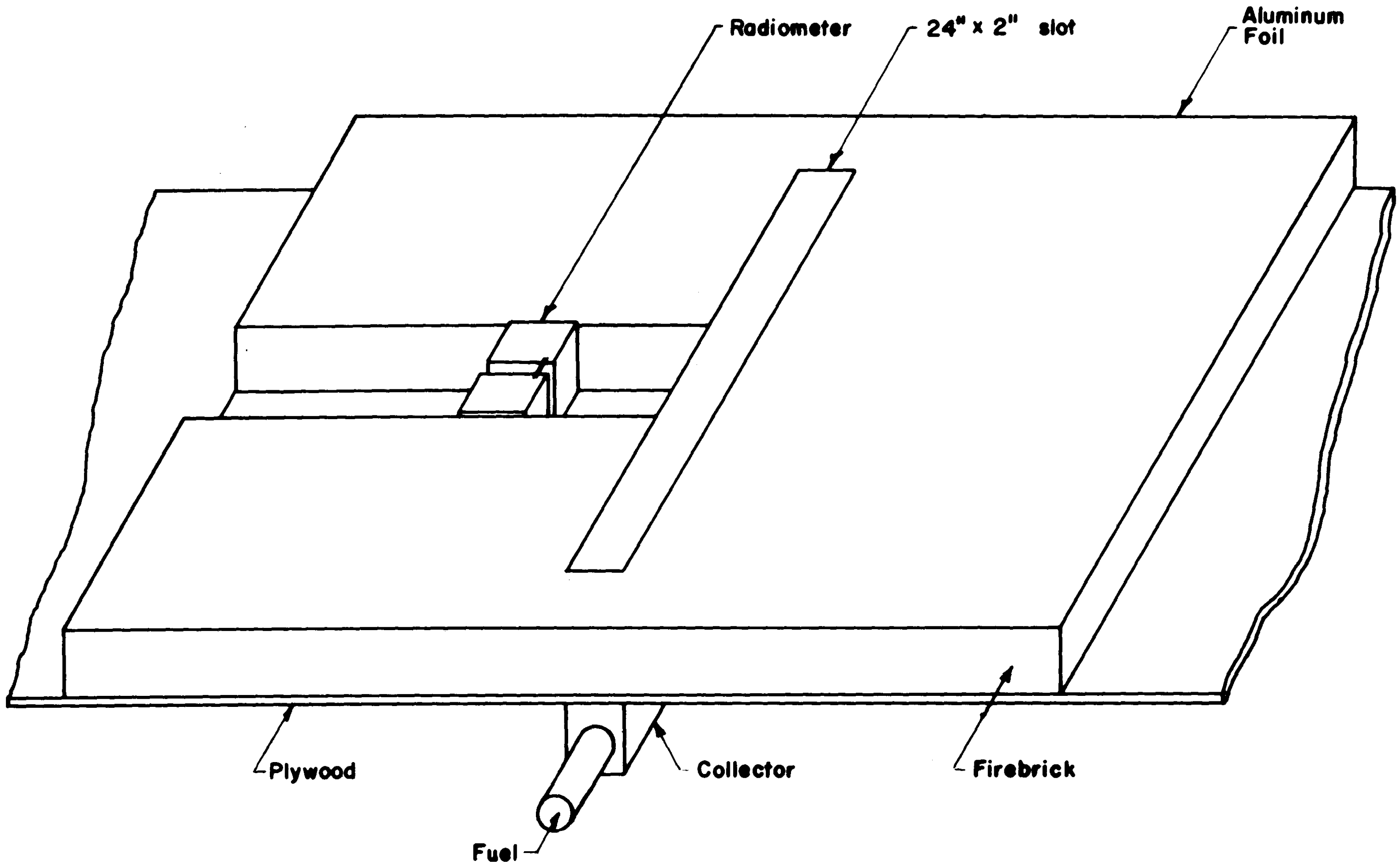
2) Variation of the radiation intensity with distance from the fire front was studied for different heat liberation rates ranging from 50,000 to 200,000 Btu/hr-ft. length of fire front.

3) The slot width was halved and the intensity of radiation was measured at different distances from the fire front.

4) In the first series of experiments nitrogen was added to the city gas in proportions ranging from 10 to 25%; in a second series of experiments the fuel was switched to propane. For each case the intersity of radiation was measured at different distances from the fire front. A theoretical flame temperature was calculated for each mixture to be inserted in the temperature modeling group.

FIGURE 15

APPARATUS



V RESULTS AND DISCUSSION OF RESULTS

Reproducibility and sources of error.

Four runs were taken on different days for a heat liberation rate of 148,500 Btu/hr.ft. length of slot. The results are recorded on Table 1 (Appendix) and plotted as intensity I in Btu/hr.ft^2, versus distance from the slot centerline Z, in feet, on Figure 2.

The data can be considered reproducible within 5%, since all the points except two fall within 5% of the best curve which can be fitted through the data points. Since the maximum convection to the radiometer is less than 2% (see Appendix), the additional error is probably due to drafts in the room.

There are three ways in which an error can be introduced in the experimental procedure.

1) Drafts in the room may increase or decrease the intensity reading, depending on whether the flame is bent towards or away from the radiometer. Every thing was done to prevent drafts but they could not be completely eliminated.

2) When the radiometer was calibrated the strip was exposed to normal incident radiation. When the intensity of radiation from the flame was measured the radiometer was exposed to grazing radiation, part of which is not absorbed by the strip; the reading recorded is therefore lower than the true value. (It would have been desirable to verify the variation of absorptivity of the metal strip with angle of incidence and introduce a correction factor.)

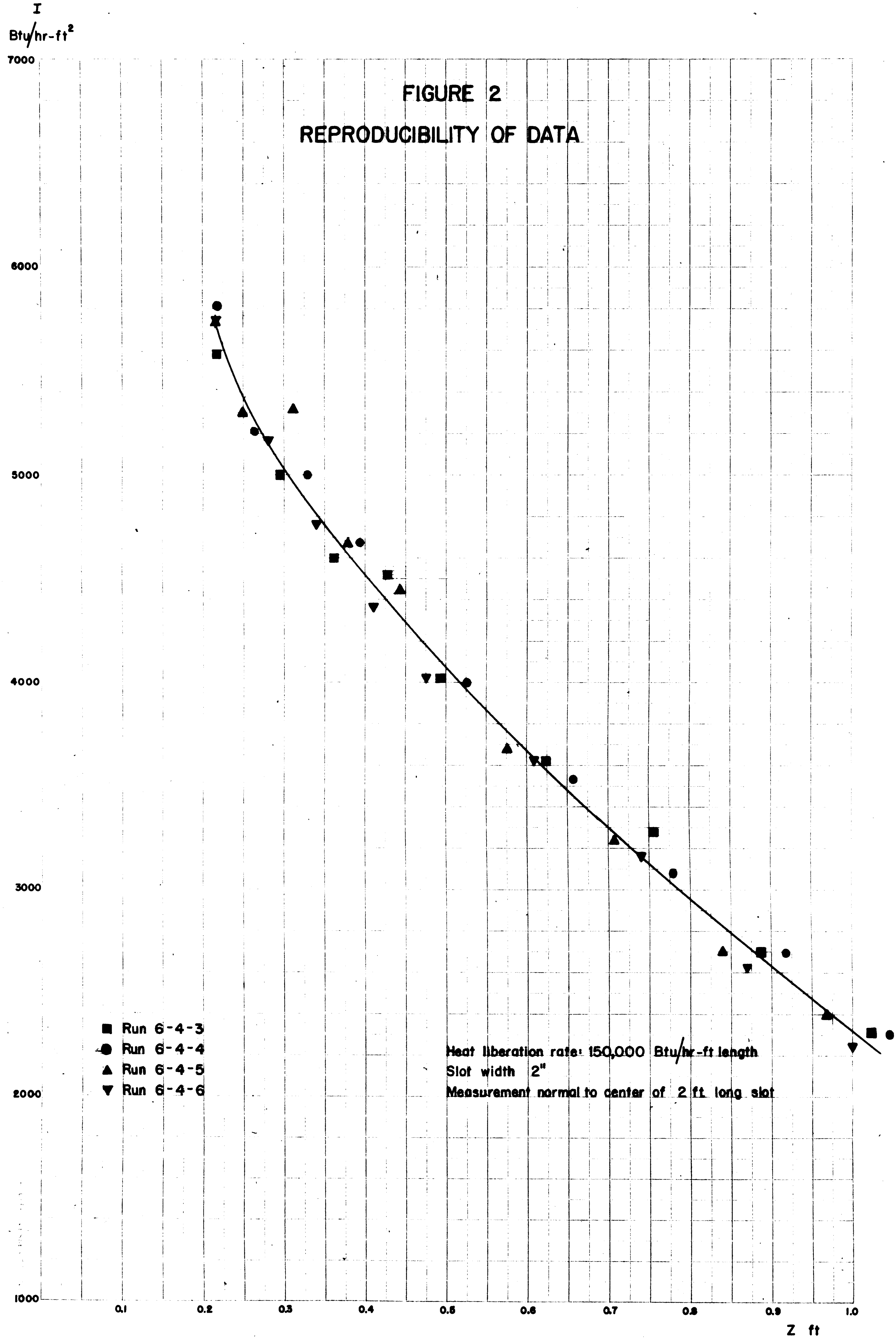


FIGURE 2
REPRODUCIBILITY OF DATA
I
Btu/hr-ft²
7000
6000
5000
4000
3000
2000
1000
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Z ft
Run 6-4-3
Run 6-4-4
Run 6-4-5
Run 6-4-6
Heat liberation rate: 150,000 Btu/hr-ft length
Slot width 2"
Measurement normal to center of 2 ft long slot

3) For points distant from the slot, the flame does not act like an infinite fire front. The error introduced is a function of the heat liberation rate as well, because of the effect of the latter on flame height and the effect of flame height on error due to departure from infinite lateral extent of flame. A study of this error is being made at the present time (8) and the first results seem to indicate an error of about 20% for points beyond a distance of one foot away from the fire and corresponding to heat liberation rates used in this study. To force the error to be less than 5% at a distance of one foot from the fire front, the fire front would have to be twelve feet long. An approximate method of correcting for departure from infinite lateral extent of flame is included in the Appendix and shows how this correction varies fro two different heat liberation rates.

Effect of heat liberation rate for a single fuel and slot width.

Ten runs were taken at different heat liberation rates ranging from 50,000 to 200,000 Btu/hr.ft. length of slot, and the intensity of radiation I was measured at different distances from the slot center-line. The results are recorded on Table 2 (Appendix) and plotted on Figure 3.

The ten intensity profiles have the same characteristic features and correspond qualitatively to what could be expected from theoretical considerations: decaying lines which go to 0 when Z goes to infinity.

It has been seen in a previous chapter that when a single fuel is considered, any property of the system is a function of two groups

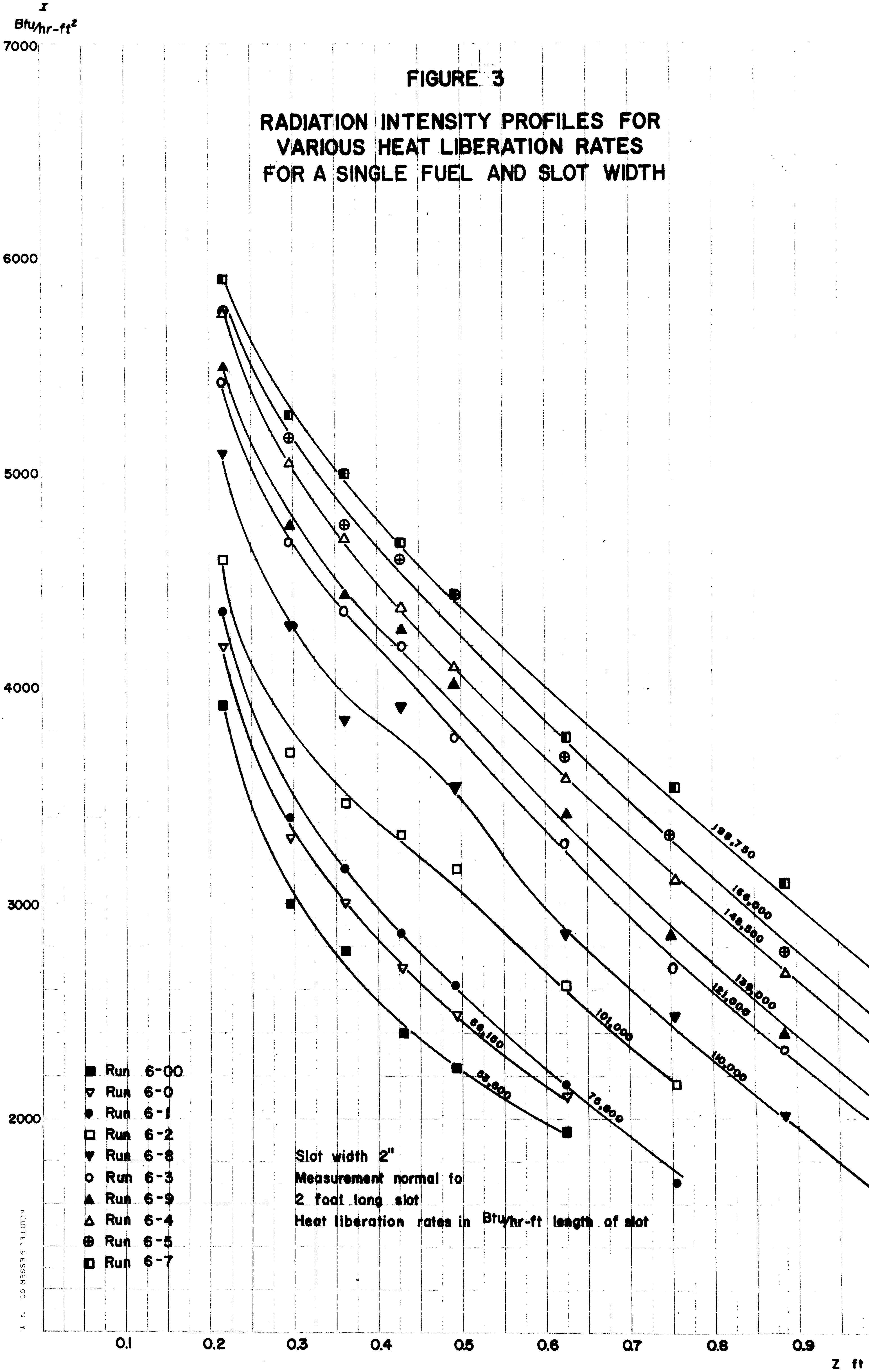


FIGURE 3

RADIATION INTENSITY PROFILES FOR VARIOUS HEAT LIBERATION RATES FOR A SINGLE FUEL AND SLOT WIDTH

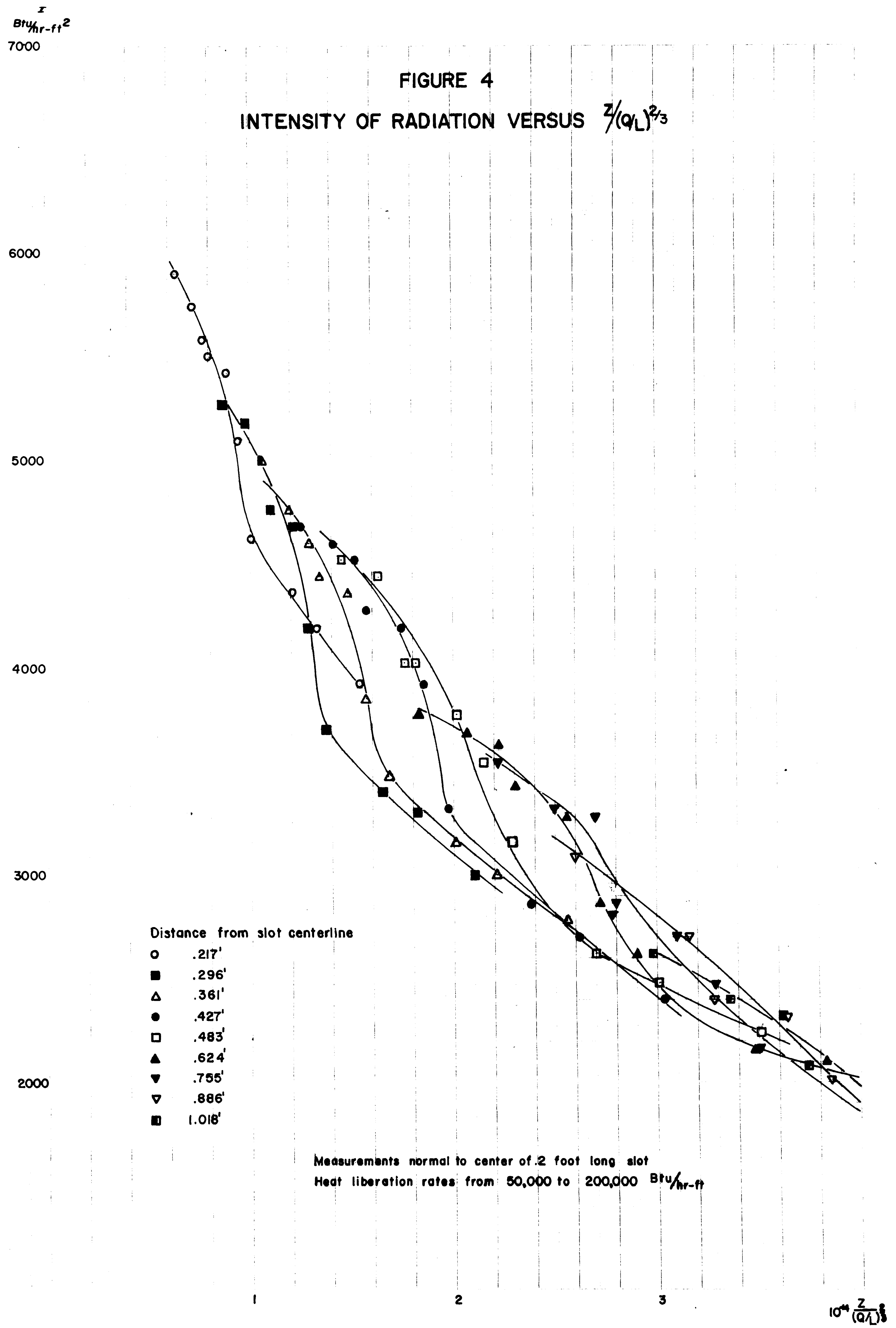
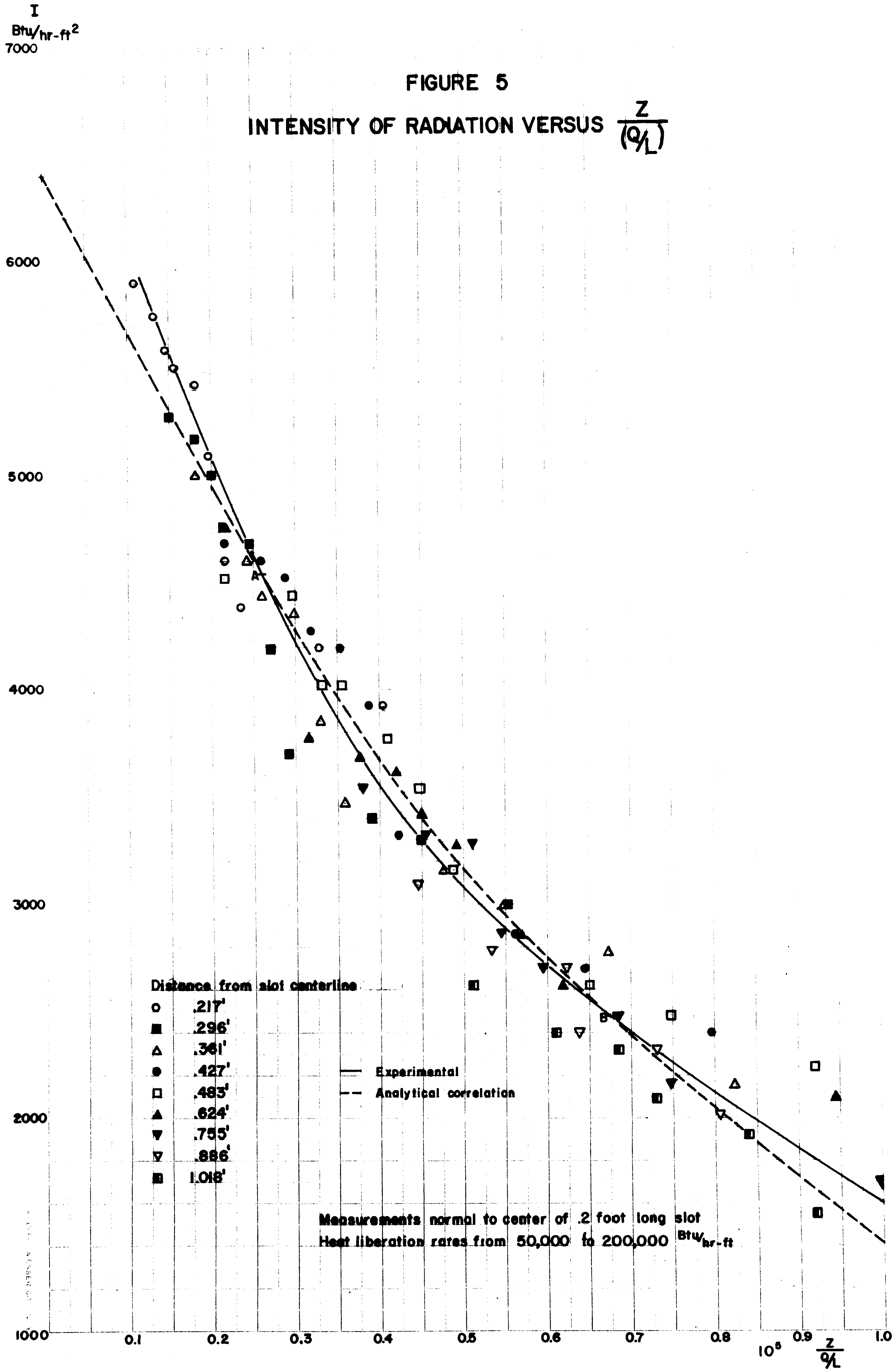
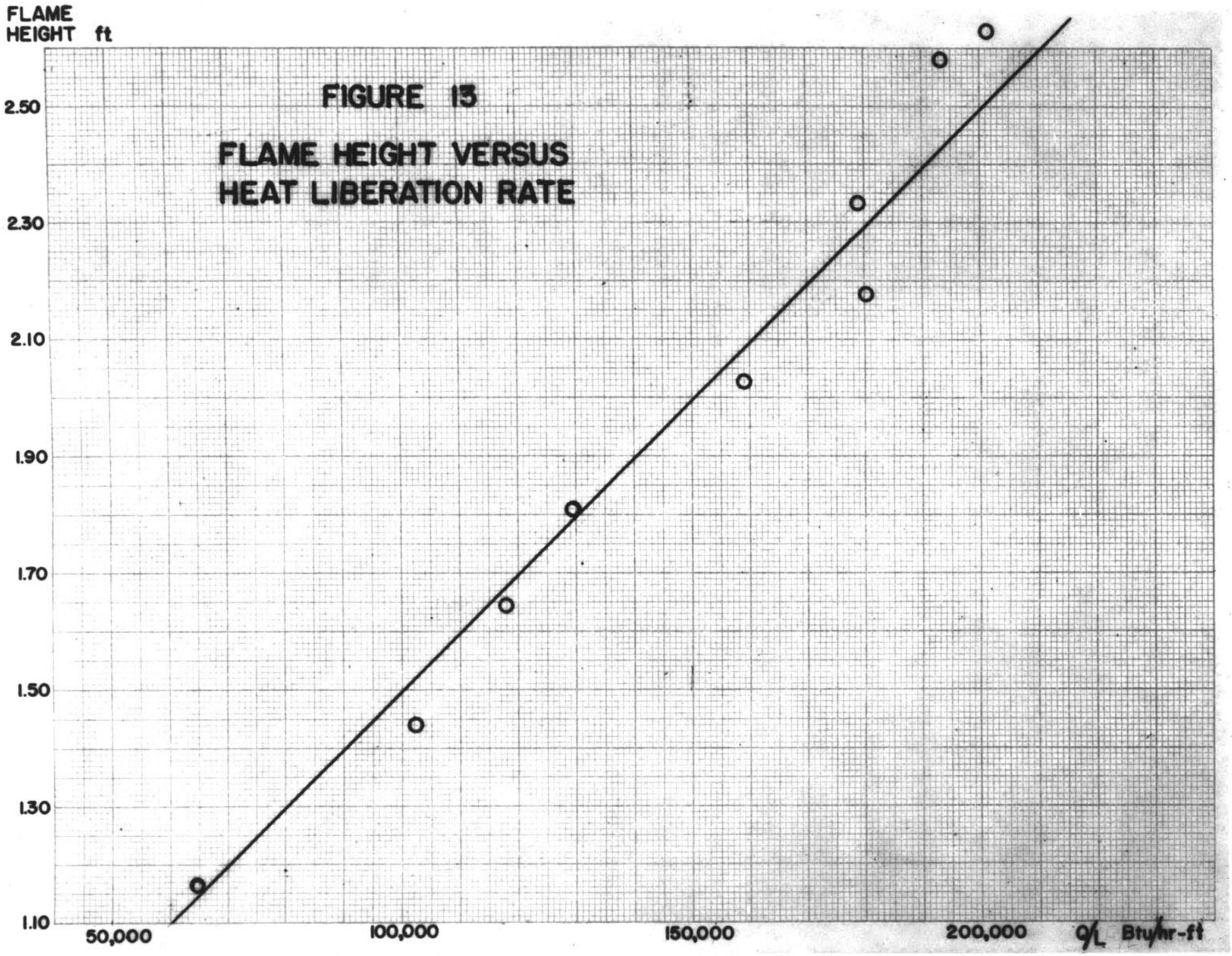

I
Btu/hr-ft²
7000
6000
5000
4000
3000
2000
FIGURE 4
INTENSITY OF RADIATION VERSUS Z/(Q/L)^2/3
Distance from slot centerline
.217'
.296'
.361'
.427'
.483'
.624'
.755'
.886'
1.018'
Measurements normal to center of 2 foot long slot
Heat liberation rates from 50,000 to 200,000 Btu/hr-ft
1
2
3
10^14 Z/(Q/L)^2/3

FIGURE 5

INTENSITY OF RADIATION VERSUS $\frac{Z}{(Q/L)}$




FLAME HEIGHT ft
FIGURE 13
FLAME HEIGHT VERSUS HEAT LIBERATION RATE
2.50
2.30
2.10
1.90
1.70
1.50
1.30
1.10
50,000
100,000
150,000
200,000
Q/L Btu/hr-ft

$\frac{Z^{3/2}}{P(Q/L)}$ and KPZ; in as much as pressure was not modeled, one way to correlate the data is to plot the intensity I versus $\frac{Z^{3/2}}{P(Q/L)}$ for lines of constant KPZ. P being kept constant, I was plotted versus $\frac{Z}{(Q/L)^{2/3}}$ for lines of constant Z. Figure 4 presents the family of curves obtained in this way from Figure 3. From theoretical considerations these curves should go to 0 when Z is infinite and I should be a maximum when Z is zero. The trend indicated by the curves of Figure 4 confirms those expectations; but the curves indicate plainly that the correlation is not perfect, i.e., that either more groups are involved than those based on the assumptions made in the modeling analysis or that the data are incorrect. The certainity of the latter has been indicated when attention was called to the effect of finite lateral extent of flame. The writer cannot visualize which of these effects is the main reason for the imperfection of the correlation.

An attempt was then made to correlate the data appearing on Figure 4 in order to bring the family of curves together in a single curve by an appropriate change in the exponent of the modeling group. Inspection of Figure 4 indicated that $Z/(Q/L)$ might correlate better than $Z/(Q/L)^{2/3}$. I was therefore plotted versus $Z/(Q/L)$, yielding Figure 5.

It is interesting to speculate on the possible meaning of the newer correlation. The total energy from an infinite flame of uniform emissive power I_u over its height would be:

$$(I_u)\,\frac{1}{2}\left(1 - \frac{Z/H}{\sqrt{1 + (Z/H)^2}}\right)$$

If flame height is proportional to heat liberation rate and if I_u was not to change as flame height H is changed by changing heat liberation rate then:

$$H = K'\left(Q/L\right)$$

and

$$I = \frac{1}{2}\,I_u\left(1 - \frac{Z/K'(Q/L)}{\sqrt{1 + \left[\frac{Z}{K'(Q/L)}\right]^2}}\right)$$

or

$$I = I_u\, f(Z/(Q/L))$$

in agreement with the correlation method used to obtain Figure 5. Whether I_u is in fact fixed or whether a correction is necessary to the data on account of the failure to use an infinite line of fire is not known at this time.

Equation (   ) was fitted to two points A and B of the best experimental curve which could be drawn through the data points. The constants were found to be:

$$I_u = 12{,}800$$

$$1/K' = K = 1.16 \times 10^5$$

Flame height was then measured for different heat liberation rates. The results appear on Figure 13. In the range of this study flame height is directly proportional to the heat liberation rate and the inverse of the slope of the line is: $(Q/L)/H = 1.03 \times 10^5$ which compares well with the value of K.

In the range of study therefore and with the limitations previously stated the intensity of radiation from a fire front at distance Z normal to the centerline of the fire front can be approximated by the expression:

$$I = 6{,}400 \left(1 - \frac{1.16 \times 10^5 \langle Z/(Q/L) \rangle}{\sqrt{1 - \left[1.16 \times 10^5 \langle Z/(Q/L) \rangle\right]^2}} \right) \qquad (5\text{-}1)$$

Q/L is the heat liberation rate per unit length of fire.

Effect of slot width at a fixed heat liberation rate.

Dimensional analysis indicates that, for systems with negligible primary or feed momentum, the shape of the system high enough above the source to make the wedge of flame and hot gases "forget" their origin, is independent of feed slot-width and dependent only on the feed rate per unit length; but it was not known, however, whether this generalization extended down into the flame itself. To test the point the slot width was cut down to one-inch and the intensity measurements were carried out for two different heat liberation rates. The results were compared to those obtained for identical heat liberation rates with a two-inch wide slot. The results appear on Table 3 (Appendix) and are plotted on Figure 6.

Within 5% the results are the same for the one-inch slot and for

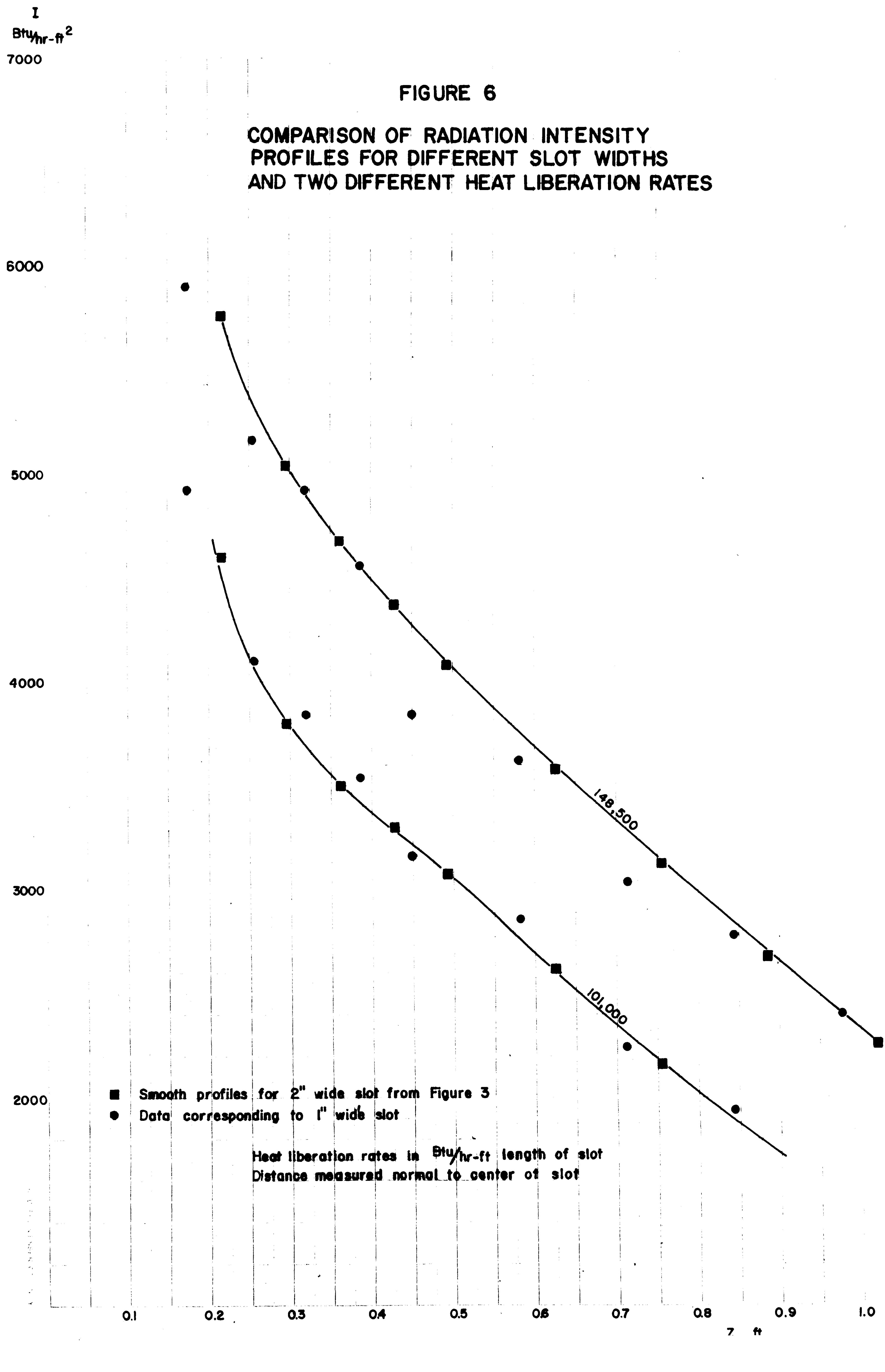


FIGURE 6

COMPARISON OF RADIATION INTENSITY PROFILES FOR DIFFERENT SLOT WIDTHS AND TWO DIFFERENT HEAT LIBERATION RATES the two-inch slot. Therefore, slot width does not change the intensity profiles providing the heat liberation rates remain the same and that the increase in initial velocity does not contribute significantly to the momentum flow through horizontal levels at which the main part of the radiation originates. Qualitatively this also confirms that the Reynolds number of the feed is of little effect in this range of study.

Effect of change of fuel at a fixed heat liberation rate.

Five different mixtures were studied:

Pure City Gas

90% City Gas - 10% Nitrogen

80% City Gas - 20% Nitrogen

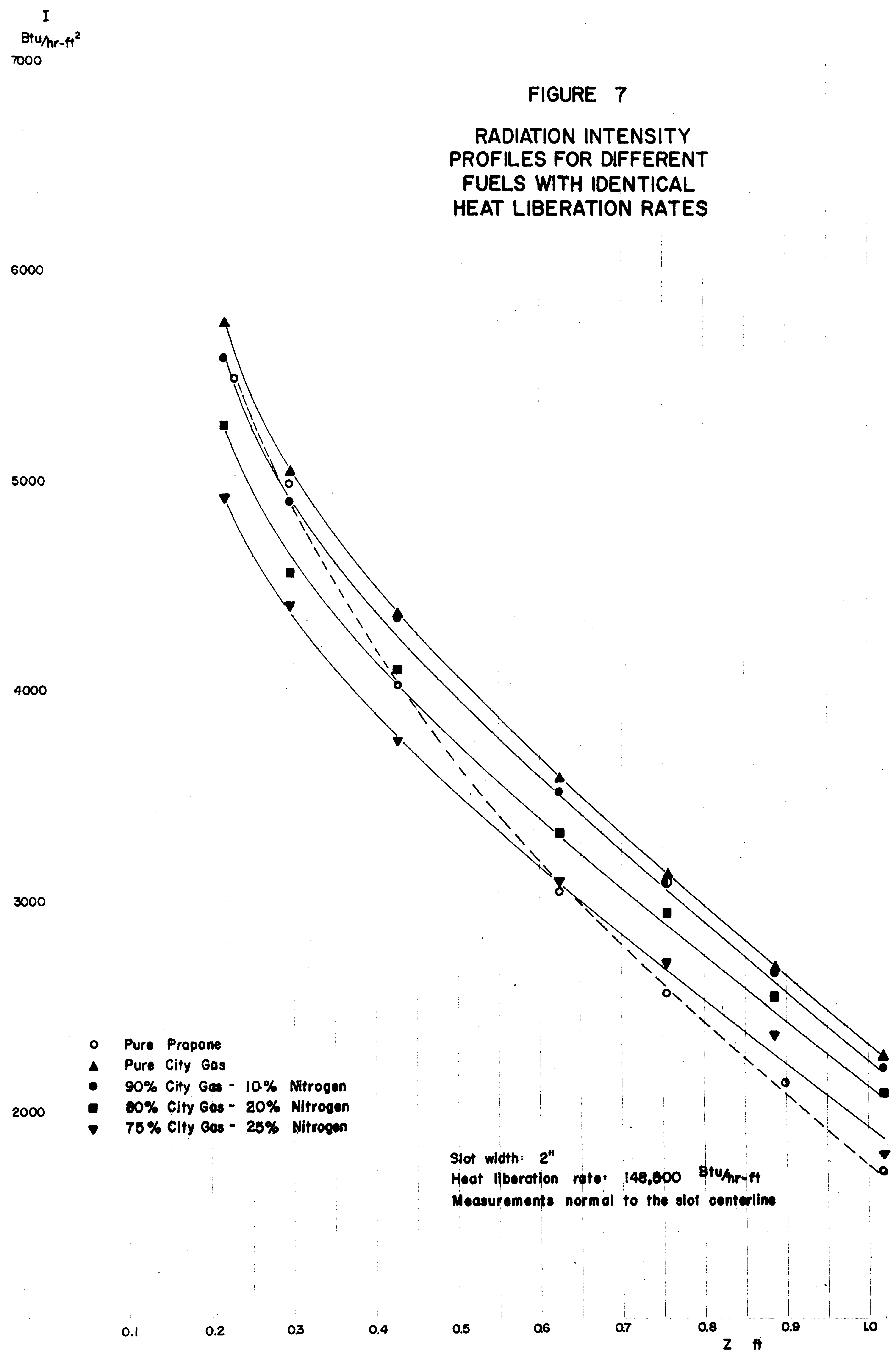
75% City Gas - 25% Nitrogen

Pure Propane

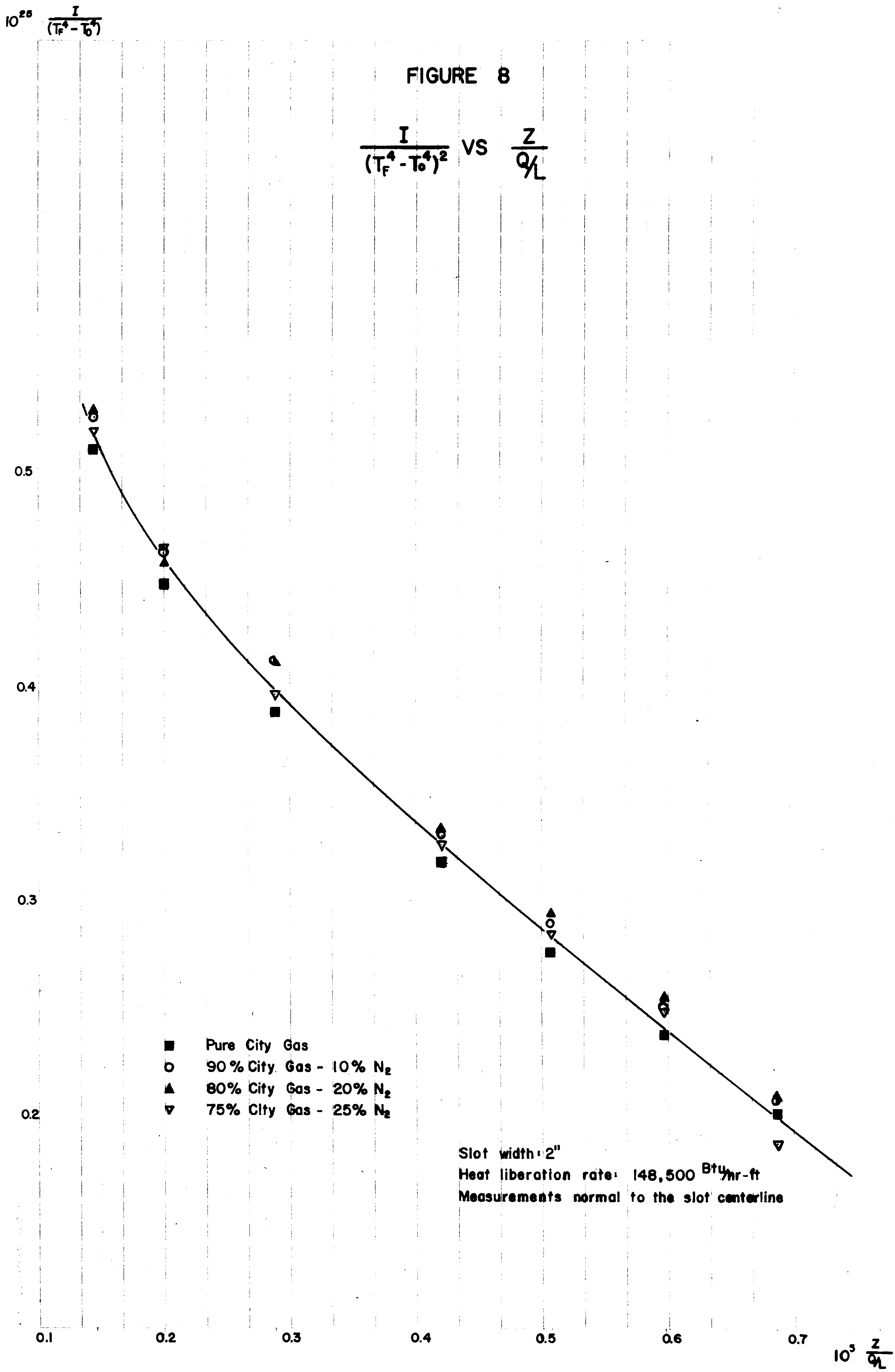
Flow rates were adjusted so that the heat liberated was 178,500 Btu/hr.ft. length of slot. For each mixture the intensity of radiation was measured at different distances from the fire front. The data are recorded in Table 4 (Appendix); the intensity profiles appear on Figure 7.

The City-Gas-Nitrogen mixtures all give intensity profiles having the same characteristic features. However, with Propane the intensity profile is somewhat different. It was noticed that the flame height for identical heat liberation rates is smaller for Propane than for City Gas and almost independent of nitrogen percent in the City-Gas-Nitrogen mixtures. The adiabatic flame temperature of Nitrogen-City Gas mixtures decreases with increasing percent Nitrogen, and the adiabatic flame temperature of Propane is higher than that of pure City-gas. If for qualitative purposes one crudely approximates the intensity from the flame to a spot on the floor, as the product of a uniform flame emissive power I_u by the geometrical "view" the floor-spot has of the flame, the trend indicated by the Nitrogen-City Gas mixture agrees with theoretical considerations: as the percent Nitrogen is increased the flame gets "colder" and I_u decreases, and, since the flame height is constant, I also decreases. However in the case of Propane the writer cannot visualize whether the different features can be explained by the same considerations or if the effect of the attenuation constant K is of primary importance.

In as much as a change of fuel means a change in the temperature level, the heating value, and a change in the attenuation factor K, the three groups resulting from the modeling analysis of Chapter III vary independently. Different correlations were attempted. The best fit for the Nitrogen-City Gas mixtures was obtained when plotting $\frac{I}{(T_F^4 - T_o^4)}$ versus Z/(Q/L); the results appear on Figure 8 (The propane data could not be correlated on the same basis) This correlation is not supported by the modeling analysis but lack of data did not allow for a more thorough study and the last result is presented only as tentative, and almost certain to be modified when more or better data become available.



I
Btu/hr-ft²
7000
6000
5000
4000
3000
2000
FIGURE 7
RADIATION INTENSITY PROFILES FOR DIFFERENT FUELS WITH IDENTICAL HEAT LIBERATION RATES
Pure Propane
Pure City Gas
90% City Gas - 10% Nitrogen
80% City Gas - 20% Nitrogen
75% City Gas - 25% Nitrogen
Slot width: 2"
Heat liberation rate: 148,800 Btu/hr-ft
Measurements normal to the slot centerline
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Z ft



10^{25} $\frac{I}{(T_F^4 - T_0^4)}$
FIGURE 8
$\frac{I}{(T_F^4 - T_0^4)^2}$ VS $\frac{Z}{Q/L}$
0.5
0.4
0.3
0.2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
10^3 $\frac{Z}{Q/L}$
Pure City Gas
90% City Gas - 10% N_2
80% City Gas - 20% N_2
75% City Gas - 25% N_2
Slot width: 2"
Heat liberation rate: 148,500 Btu/hr-ft
Measurements normal to the slot centerline

VI CONCLUSIONS AND RECOMMENDATIONS

Conclusions

It was found that for heat liberation rates ranging from 50,000 to 200,000 Btu/hr-ft length of fire front and 300,000 to 2,400,000 Btu/hr-ft^2 of source, the intensity of radiation I for a given Q/L is independent of slot width and therefore of the feed Reynolds number, provided that the increase in initial velocity does not contribute significantly to the momentum of the gases.

In the same range of study and when **only** one fuel is of interest the intensity of radiation I from the flame to the surroundings can be approximated by the expression:

$$I = 6{,}400\left(1 - \frac{1.16 \times 10^5 \left(Z/(Q/L)\right)}{\sqrt{1 + \left\{1.16 \times 10^5 \frac{Z}{Q/L}\right\}^2}}\right) \qquad (5\text{-}1)$$

where Z is the distance measured normal to the fire front centerline and Q/L is the heat liberation per unit length of fire.

Equation (5-1) does not hold when different fuels are studied since Q/L does not characterize completely the fuel; the temperature level and the attenuation factor varying also in the process. Because of time limitation a complete study of this case could not be done and the results obtained were only qualitative.

Recommendations

The precision of the data could be improved by **working** in a completely draft-free room. However as it has already been stated the largest error comes from the fact that for points distant from the fire-front the assumption of an infinite line fire is a poor one, and the data should be corrected for this error. Work is being done at the present time in this direction and the results should be available presently.

Further study on this problem of intensity measurements from a line fire can be done in two directions:

a) When increasing the heat liberation rate per foot length of fire, find if Equation (5-1) still holds. Increasing the heat liberation rate per unit length of slot brings the fire closer to turbulent conditions. This presents location problems since at these rates it is impossible to operate in a laboratory and on the other hand working outdoors is not appealing because of wind.

b) It would be interesting to extend results of the form of Equation (5-1) to different fuels. By mixing basic fuels one could compare mixtures which have a given heating value, a given flame temperature and a given attenuation factor; and it should be possible to evaluate each effect independently.

VII. APPENDIX

A/ Apparatus

The apparatus consisted mainly of a large piece of plywood (6' x 3' x 1/2") on top of which was disposed a layer of refractory brick covered by a sheet of aluminum foil. This formed a satisfactory "isothermal surface" under steady-state conditions. The slot dimensions were fixed at 24 x 2-inches for three sets of experiments and 24 x 1-inches for the other set. A collector was sealed to the bottom of the plywood, and fuel, pure or premixed with nitrogen was fed to the collector through a one-inch pipe. The collector was fitted with a rectangular chimney, which at firebrick level was topped by a layer of 200 mesh copper screen. At different levels in the chimney, layers of copper screen were placed in order to obtain a flat gas velocity profile.

Nitrogen and fuel flow rates were obtained by measuring the pressure drop across calibrated orifices. Plots for these orifices appear on Figure 14. Fuel temperature was checked by means of a thermocouple set into the feed pipe.

The radiometer will be discussed in detail in the next chapter. It was mounted on tracks and the distance from the strip to the slot could be precisely measured.

The signal from the radiometer was recorded on a Sanborn 150. Scale 2 was used (full scale deflection 1 M_v).

APPENDIX (Cont.)

B. Radiometer

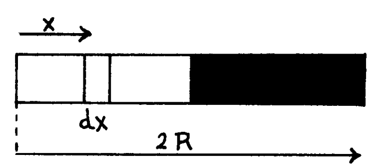
a) Physical description.

The heat sink consisted of two 2 x 2 x 2 inch copper blocks one quarter on an inch apart. The metal strip was chromel-constantan 0.012-inch thick on the constantan side and 0.018-inch thick on the chromel side.

The following calculation will give an idea of the magnitude of the convection associated with such a radiometer.

b) Convection contribution.

Consider a bimetallic strip of length 2R and thickness t and on this strip an element dx situated at a distance x from one end. If K_1 and K_2 are the conductivities of each metal and q is the heat transfer by radiation to the strip the energy balance can be written:



$$K_i t_i \frac{d^2T}{dx^2} = -q \qquad \text{assuming convection can be neglected}$$

let: $Z = x/R \qquad dZ^2 = \frac{dx^2}{R^2}$

$\theta = (T - T_o)/T_0 \qquad d^2\theta = \frac{d^2T}{T_o}$

where T_o is ambient temperature and R is the center to end distance.

So:

$$\frac{d^2\theta}{dZ^2} = -\frac{R^2}{T_o}\frac{q}{K_i t_i} = B_i$$

It follows that:

$$\theta_1 = C_1 + C_2 Z + C'_1 Z^2 \qquad 0 \leq Z \leq 1$$

$$\theta_2 = C_3 + C_4 Z + C'_2 Z^2 \qquad 1 \leq Z \leq 2$$

The boundary conditions are:

1) At the center of the strip:

$$\theta_1 = \theta_2 \qquad \frac{d\,\theta_1}{dZ} = \frac{d\,\theta_2}{dZ}$$

2) At both ends of the strip the temperature is the ambient temperature

$$\theta_1 = 0 \quad \text{at } Z = 0$$

$$\theta_2 = 0 \quad \text{at } Z = 2$$

Application of the boundary conditions yields

$$C_1 = 0$$

$$2C'_1 = -B_1$$

$$2C'_2 = -B_2$$

$$0 = C_3 + 2C_4 + 4C'_2$$

$$C_2 + 2C'_1 = C_4 + 2C'_2$$

$$C_1 + C_2 + C'_1 = C_3 + C_4 + C'_2$$

Solving:

$$C_1 = 0 \qquad C_3 = (B_1/2) - (B_2/2) \qquad C'_1 = -(B_1/2)$$

$$C_2 = \frac{3B_2}{4} + \frac{B2}{4} \qquad C_4 = (5B_2/4) - (B_1/4) \qquad C'_2 = -(B_2/2)$$

So:

$$\theta_1 = \frac{3B_1}{4} + \frac{B_2}{4} Z - \frac{B_1}{2} Z^2$$

$$\theta_2 = \frac{B_1}{2} - \frac{B_2}{2} + \frac{5B_2}{4} - \frac{B_1}{4} Z - \frac{B_2}{2} Z^2$$

At the center of the strip:

$$\theta = \frac{B_1 + B_2}{4} \qquad (A-1)$$

If the convection coefficient is U, the convection contribution at a point becomes

$$q_c = 2U(T - T_o)$$

So:

$$q_c = 2U\theta T_o = (U/2)(B_1 + B_2)T_o$$

By using the following properties:

K_1 = 13 Btu/hr-ft ^{2} - ^oF/ft for constantan

K_2 = 10 Btu/hr-ft ^{2} - ^oF/ft for chromel

T_o = 530 ^oR

t_1 = 0.012 inch

t_2 = 0.018 inch

R = 1/8 inch = 1.04×10^{-2} ft.

Find:

$$B_1 = q \frac{(1.04 \times 10^{-2})^2 (12)}{(530)(10^{-3})(12)(13)} = 1.54 \times 10^{-5} q$$

$$B_2 = q \frac{(1.04 \times 10^{-2})^2 (12)}{(530)(10^{-3})(18)(10)} = 1.34 \times 10^{-5} q$$

And:

$$q_c = 1/2 \times 530 \times 2.88 \times 10^{-5}\ q\ U$$

A calculation on U (5) yields a value of approximately 2, So:

$$q_c/q = 1.55\ \%$$

So the assumption that convection could be neglected is reasonable if 2% precision is satisfactory. Under these conditions eq. (A-1) indicates that a plot of the intensity of radiation I versus the millivolt reading should yield a straight line.

c) Calibration

The radiometer was calibrated using a constant temperature furnace as a black body radiation source at different temperature levels. The radiometer was moved in a direction perpendicular to a square opening in the front part of the furnace and the voltage signal was recorded as a function of distance. The temperature of the plate was maintained at ambient temperature by means of water cooling.

If:

T_F = Furnace temperature ^oR

T_o = Ambient temperature ^oR

M_v = signal in millivolts

A_2F_{21} = View factor between the metal strip and the front plate, $ft.^2$

The radiative heat transfer is:

$$q = A_2F_{21}\sigma(T_F^4 - T_o^4)$$

q/M_v is plotted versus M_v on Figure 10. Values are recorded on table 5.

1) View factor calculation.

Consider a metal strip of length 2 1 and width t, a rectangle of dimensions 2q and 2w, separated by a distance D. Let Ox, Oy, Oz be three coordinate axes.

$$d(AF) = (dA_1 \cos \Phi_1) \times (dA_2 \cos \Phi_2) \times 1/r^2$$

Assuming the strip is black and that black body radiation is coming out of the furnace, from Figure 9,

$$d(AF) = 1/\pi(t dz) \cos \Phi_1 \quad \times \quad (dx dy) \cos \Phi_2 \quad \times \quad 1/r^2$$

$$\text{With : } r^2 = x^2 + (y - z)^2 + D^2$$

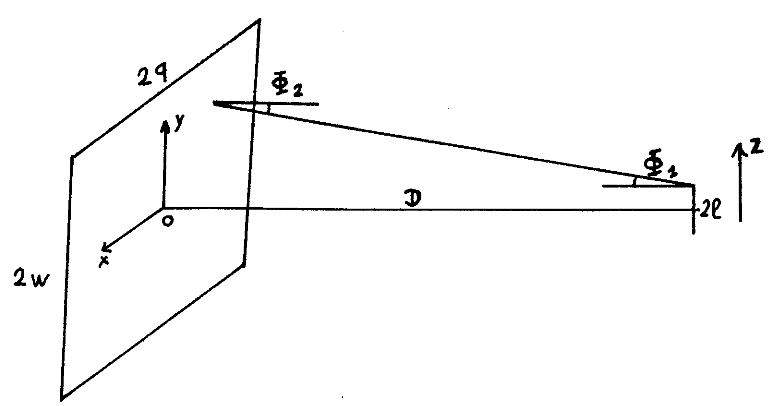
and

$$\cos \Phi_1 = \cos \Phi_2 = \frac{D}{\left(x^2 + (y - z)^2 + D^2\right)^{1/2}}$$

So:

$$AF = \frac{8}{\pi} \int_0^1 \int_0^w \int_0^q (t dz) \cos \Phi_1 \quad (dy dx \cos \Phi_2) \times 1/r^2$$

$$= \int_0^q \int_0^w \int_0^1 \frac{8D^2 \ t \ dx \ dy \ dz}{\pi(x^2 + (y - z)^2 + D^2)^2}$$



integrating with respect to x gives,

$$= \frac{8D^2 t}{\pi} \int_0^w \int_0^1 \left\{ \frac{x \, dydz}{2\left[(y-z)^2 + D^2\right]\left[x^2 + (y-z)^2 + D^2\right]} \right.$$

$$\left. + \frac{dy \, dz}{2\left[(y-z)^2 + D^2\right]^{3/2}} \tan^{-1} \frac{x}{\left[(y-z)^2 + D^2\right]^{1/2}} \right\}_0^q$$

$$= \int_0^w \int_0^1 \frac{8t}{\pi} \left(\frac{D^2 \, q \, dy \, dz}{2\left[(y-z)^2 + D^2\right]\left[q^2 + (y-z)^2 + D^2\right]} \right.$$

$$\left. + \frac{D^2 \, dy \, dz}{2\left[(y-z)^2 + D^2\right]^{3/2}} \tan^{-1} \frac{q}{\left[(y-z)^2 + D^2\right]^{1/2}} \right\}$$

Using the change of variables

$$dv = \frac{D^2 \, dy}{2(y^2 - 2yz + z^2 + D^2)^{3/2}} \qquad u = \tan^{-1} \frac{q}{\left[y^2 - 2yz + z^2 + D^2\right]^{1/2}}$$

$$v = \frac{(y-z)}{2\left[(y-z)^2 + \cancel{q^2} + D^2\right]^{1/2}} \qquad du = - \frac{(y-z)q}{\left[(y-z)^2 + D^2 + q^2\right]\left[(y-z)^2 + D^2\right]^{1/2}}$$

Find:

$$AF = \int_0^w \int_0^1 \frac{8t}{\pi} \frac{q \, dy \, dz}{2\left[(y-z)^2 + q^2 + D^2\right]}$$

$$+ \int_0^1 \left\{ \frac{(y-z)}{2\left[(y-z)^2 + D^2\right]^{1/2}} \tan^{-1} \frac{q}{\left[(y-z)^2 + D^2\right]^{1/2}} \, dz \right\}_0^w$$

$$AF = \frac{8t}{\pi}\left\{\int_0^1 \frac{q}{2\left[(D^2 + q^2)\right]^{1/2}} \tan^{-1} \frac{(y - z)}{\left[(D^2 + q^2)\right]^{1/2}} \, dz\right]_0^w$$

$$+ \int_0^1 \frac{(y - z)}{\left[(y - z)^2 + D^2)\right]^{1/2}} \tan^{-1} \frac{q}{\left[(y - z)^2 + D^2\right]^{1/2}} \, dz \Bigg\}_0^w$$

$$AF = \frac{8t}{\pi}\left\{\int_0^1 \frac{(w - z)}{2\left[(w - z)^2 + D^2\right]^{1/2}} \tan^{-1} \frac{q}{\left[(w - z)^2 + D^2\right]^{1/2}} \, dz\right.$$

$$+ \int_0^1 \frac{z}{2(z^2 + D^2)^{1/2}} \tan^{-1} \frac{q}{(z^2 + D^2)^{1/2}} \, dz$$

$$+ \int_0^1 \frac{q}{2\,(q^2 + D^2)^{1/2}} \tan^{-1} \frac{(w - z)}{(D^2 + q^2)^{1/2}} \, dz$$

$$\left. - \int_0^1 \frac{q}{2(q^2 + D^2)^{1/2}} \tan^{-1} \frac{-z}{(D^2 + q^2)^{1/2}} \, dz \right\}$$

Consider the expression:

$$A = \int \frac{x}{(x^2 + D^2)^{1/2}} \tan^{-1} \frac{q}{(D^2 + x^2)^{1/2}} \, dx$$

$$\text{let } dv = \frac{x}{(x^2 + D^2)^{1/2}} \, dx \qquad u = \tan^{-1} \frac{q}{(x^2 + D^2)^{1/2}}$$

$$v = (x^2 + D^2)^{1/2} \qquad du = -\frac{qx \, dx}{x^2 + D^2 + q^2}$$

Therefore:

$$A = (x^2 + D^2)^{1/2} \tan^{-1} \frac{q}{(x^2 + D^2)^{1/2}} + \frac{q}{2} \ln(x^2 + D^2 + q^2)$$

Using this result:

$$AF = \frac{4t}{\pi} \Bigg\{ - \left[(w - z)^2 + D^2 \right]^{1/2} \tan^{-1} \frac{q}{\left[(w - z)^2 + D^2 \right]^{1/2}}$$

$$- \frac{q}{2} \left[(w - z)^2 + D^2 + q^2 \right] + (z^2 + D^2)^{1/2} \tan^{-1} \frac{q}{(z^2 + D^2)^{1/2}}$$

$$+ \frac{q}{2} \ln(z^2 + D^2 + q^2) \quad + \frac{q}{(q^2 + D^2)^{1/2}} \Bigg(-(w - z) \tan^{-1} \frac{(w - z)}{(D^2 + q^2)^{1/2}}$$

$$+ \frac{(D^2 + q^2)^{1/2}}{2} \ln \left[1 + \frac{(w - z)^2}{D^2 + q^2} \right] + z \tan^{-1} \frac{z}{(D^2 + q^2)^{1/2}}$$

$$- \frac{(D^2 + q^2)^{1/2}}{2} \ln \left(1 + \frac{z^2}{D^2 + q^2} \right) \Bigg) \Bigg\}_0^1$$

And finally, noting that $q = w$

$$\frac{\pi AF}{4t} = - \left[(w - 1)^2 + D^2 \right]^{1/2} \tan^{-1} \frac{w}{\left[(w - 1)^2 + D^2 \right]^{1/2}}$$

$$+ (w^2 + D^2)^{1/2} \operatorname{Tan}^{-1} \frac{w}{(w^2 + D^2)^{1/2}} - \frac{w}{2} \ln \left[(w - 1)^2 + D^2 + w^2 \right]$$

$$+ \frac{w}{2} \ln (2w^2 + D^2) - D \tan^{-1} \frac{w}{D} + (D^2 + 1^2)^{1/2} \tan^{-1} \frac{w}{(D^2 + 1^2)^{1/2}}$$

$$+ \frac{w}{2} \ln (1^2 + w^2 + D^2) - \frac{w}{2} \ln (D^2 + w^2) - \frac{w(w - 1)}{(D^2 + w^2)^{1/2}} \tan^{-1} \frac{(w-1)}{(D^2 + w^2)^{1/2}}$$

$$+ \frac{w^2}{(D^2 + w^2)^{1/2}} \tan^{-1} \frac{w}{(D^2 + w^2)^{1/2}} + \frac{w}{2} \ln \left[\frac{D^2 + w^2 + (w - 1)^2}{D^2 + w^2} \right]$$

$$- \frac{1w}{(D^2 + w^2)^{1/2}} \tan^{-1} \frac{1}{(D^2 + w^2)^{1/2}} - \frac{w}{2} \ln \left[\frac{D^2 + 2w^2}{D^2 + w^2} \right]$$

$$- \frac{w}{2} \ln \left[\frac{D^2 + w^2 + 1^2}{D^2 + w^2} \right] \qquad \text{(A-2)}$$

it is to be noted that in the above expression, all "ln" terms cancel.

An approximate solution can also be found by considering the metal strip as a point receiver. Referring to Figure

$$d(AF) = \frac{\cos \Phi_2 \cos \Phi_1 \, (dx\, dy)}{\pi r^2}$$

where $r^2 = D^2 + x^2 + y^2$

and

$$AF = \int \int \frac{D^2 \, dx \, dy}{(D^2 + x^2 + y^2)^2}$$

So:

$$AF = \frac{1}{\pi}\left[\int_0^w \frac{2D^2\ x\ dy}{(D^2+\ y^2)(D^2+\ x^2+\ y^2)} + \frac{4D^2}{2(D^2+\ y^2)^{3/2}} \tan^{-1} \frac{x\ dy}{(D^2+\ y^2)^{1/2}}\right]_0^w$$

$$AF = \frac{1}{\pi}\int_0^w \frac{2\ D^2 w\ dy}{(D^2+\ y^2)(D^2+\ w^2+\ y^2)} + \frac{1}{\pi}\int_0^w \frac{2D^2}{(D^2+\ y^2)^{3/2}} \tan^{-1} \frac{w}{(D^2+\ y^2)^{1/2}}\ dy$$

let: $dv = \dfrac{2D^2 dy}{(D^2 + y^2)^{3/2}}$ $\qquad u = \tan^{-1} \dfrac{w}{(D^2+\ y^2)^{1/2}}$

With: $v = \dfrac{2y}{(D^2+\ y^2)^{1/2}}$ $\qquad du = \dfrac{wy\ dy}{(D^2+\ w^2+\ y^2)(D^2+y^2)^{1/2}}$

And:

$$AF = \frac{1}{\pi}\int_0^w \frac{2D^2 w\ dy}{(D^2+\ y^2)(D^2+\ w^2+\ y^2)} + \frac{1}{\pi}\frac{2y}{(D^2+\ y^2)^{1/2}} \tan^{-1} \frac{w}{(D^2+\ y^2)^{1/2}}$$

$$+ \frac{1}{\pi}\int_0^w \frac{2wy^2 dy}{(D^2 + y^2)(D^2+\ w^2+\ y^2)}$$

So:

$$AF = \frac{1}{\pi}\int_0^w \frac{2w\ dy}{(D^2+\ w^2 + y^2)} + \frac{1}{\pi}\frac{2y}{(D^2+\ y^2)^{1/2}} \tan^{-1} \frac{w}{(D^2+\ y^2)^{1/2}}$$

And finally:

$$AF = \frac{1}{\pi}\frac{4w}{(D^2+\ w^2)^{1/2}} \tan^{-1} \frac{w}{(D^2+\ w^2)^{1/2}} \qquad (A-3)$$

Both F corresponding to (A-2) and (A-3) are plotted on Figure 10 for the following values:

$2w = 3.50$ inches

$2\,l = 6/10$ of an inch

The data are recorded on Table 6 (Appendix). The values of F used for this particular radiometer corresponding to a strip one quarter of an inch long were interpolated from data obtained for the two cases of a source point and of a strip 6/10 of an inch long.

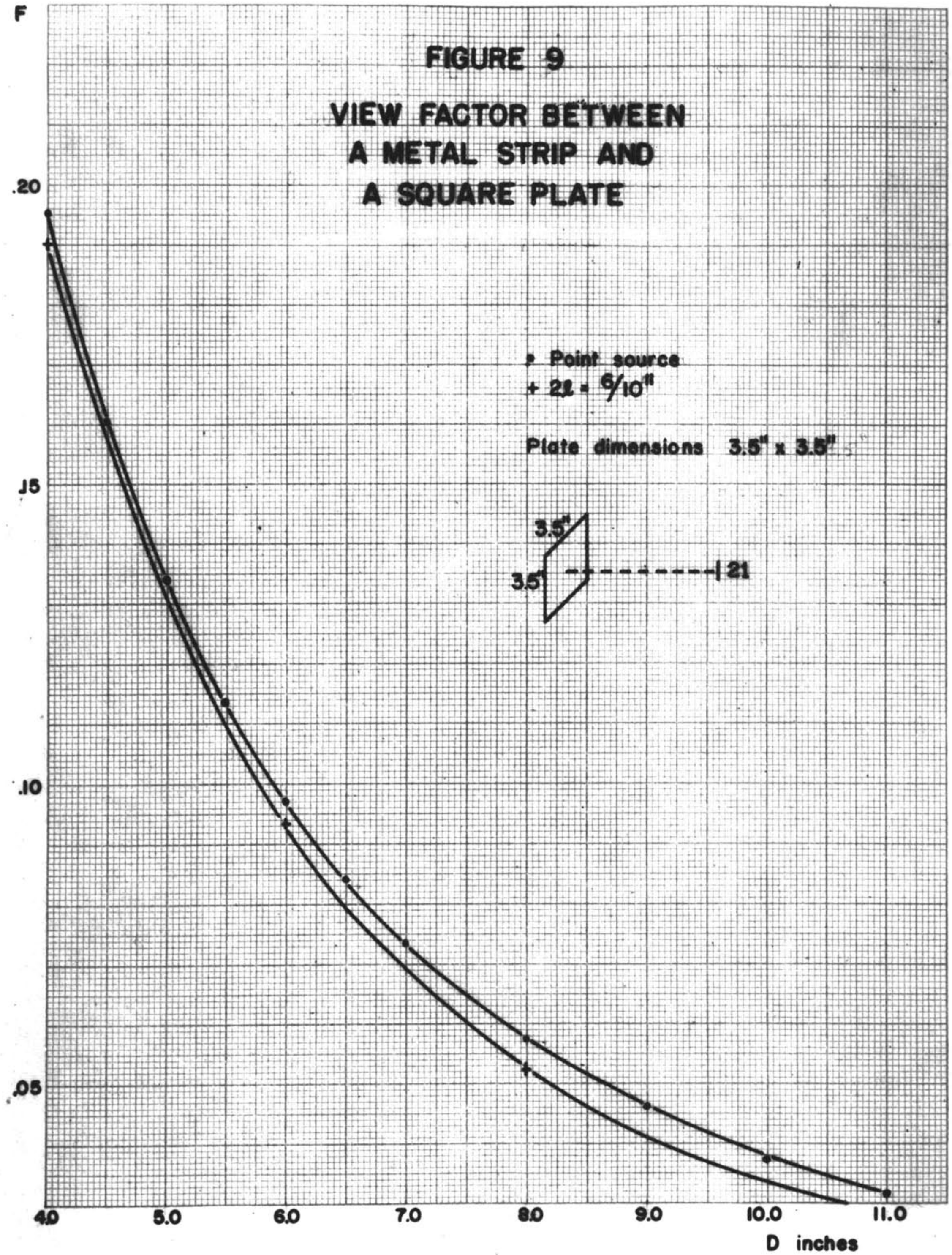


FIGURE 9

VIEW FACTOR BETWEEN A METAL STRIP AND A SQUARE PLATE

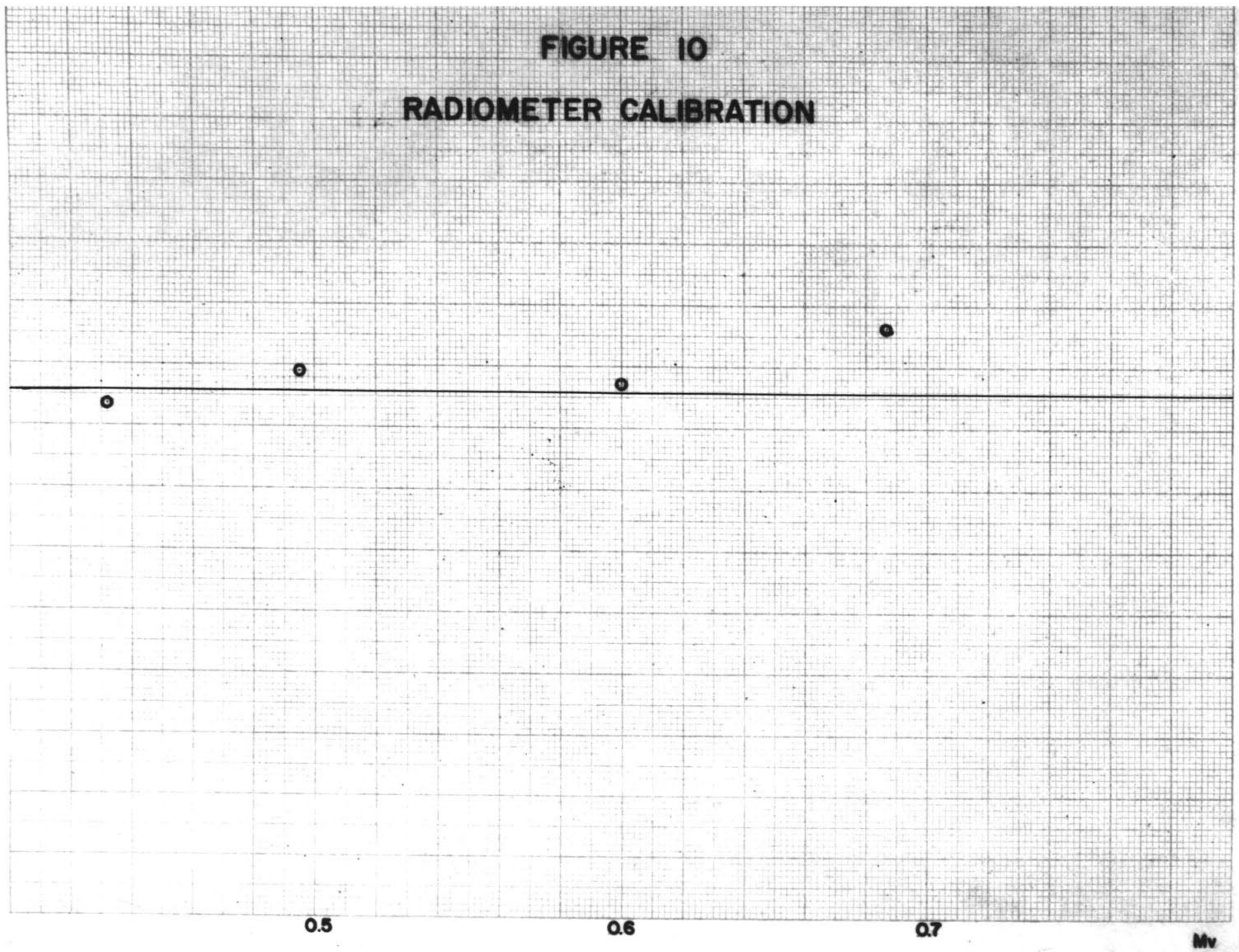
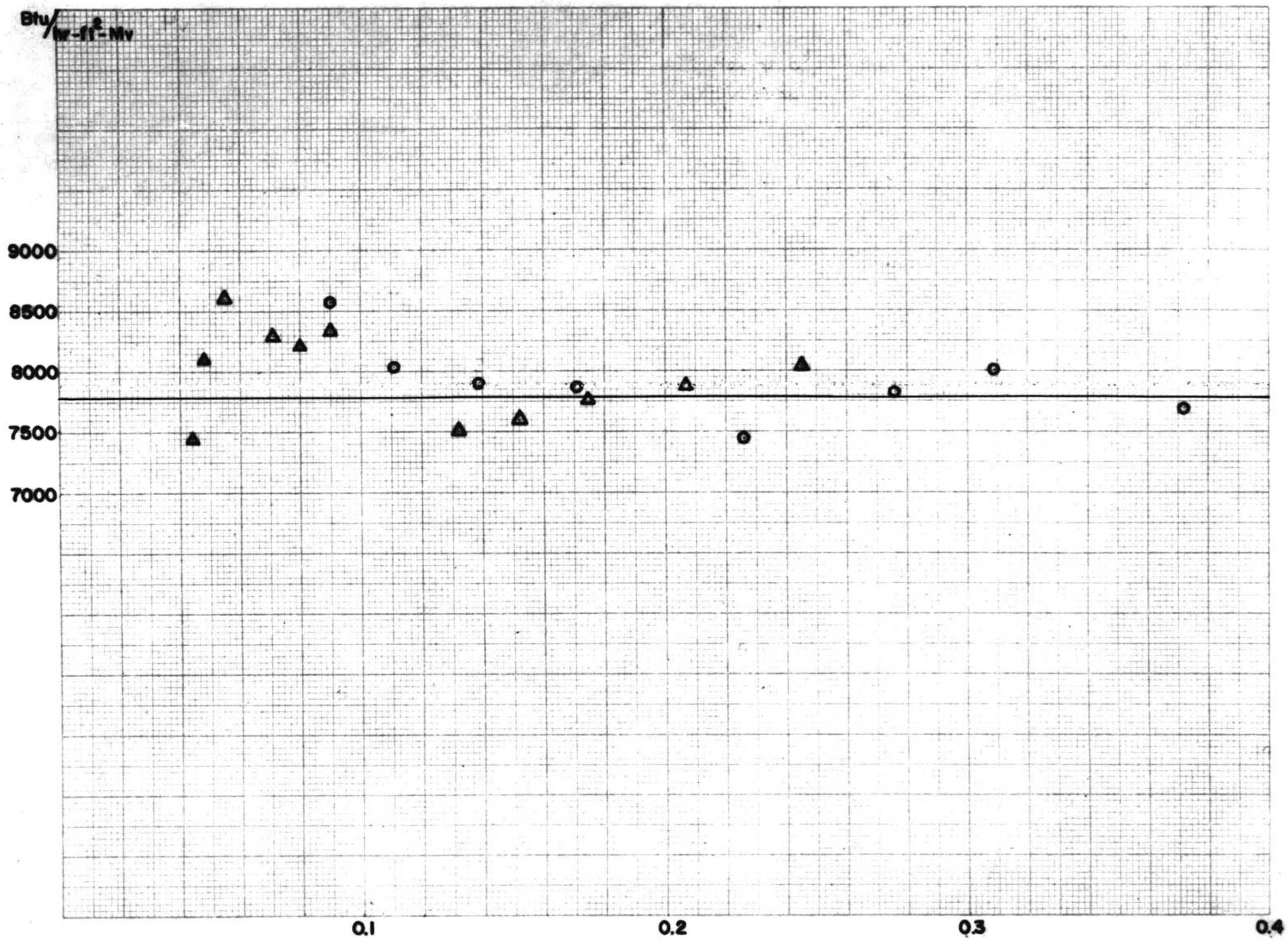


FIGURE 10
RADIOMETER CALIBRATION
0.5
0.6
0.7
Mv


Btu/hr-ft²-Mv
9000
8500
8000
7500
7000
0.1
0.2
0.3
0.4

APPENDIX (Cont.)

C/ Sample Calculation

Calculation of intensity of radiation.

$$I = M_v \left(\frac{I}{M_v}\right)_{\text{calibration}}$$

For run 6-4 at Z = .427 ft.

$M_v = .58$ millivolt

$\left(\frac{I}{Mv}\right)_{cal} = 7,790\ (.58)$ Btu/hr.ft.^{2} mv

So $I = 4,518$ Btu/hr.ft.^{2}

Calculation of $Z/(Q/L)^{2/3}$

For run 6-4 at Z = .427 ft.

$Q/L = 148,000$ Btu/hr.ft. length of slot

$(Q/L)^{2/3} = 2,811$

$Z/(Q/L)^{2/3} = .427/2,811$

$= 1.520 \times 10^4$

APPENDIX (Cont.)

D. Calculation of the Adiabatic Flame Temperature for City-Gas Nitrogen Mixtures

Consider a mixture of "a" moles of City Gas and (1-a) moles of Nitrogen. Assuming City Gas is almost pure methane, the combustion reaction is:

$$a\ CH_4 + A(\text{air}) \longrightarrow a\ CO_2 + 2a\ H_2O + \frac{79}{100}\ A$$

The following simplifying assumptions were made.

- Stoichiometric combustion mixture.
- No dissociation. This is not a good assumption since at the flame temperature of City Gas, dissociation occurs; but this calculation is only aimed at giving qualitative rather than quantitative results and therefore the assumption is justified.
- The heating value (high) of City Gas was taken as 1,040 Btu/cu.ft. at room temperature.

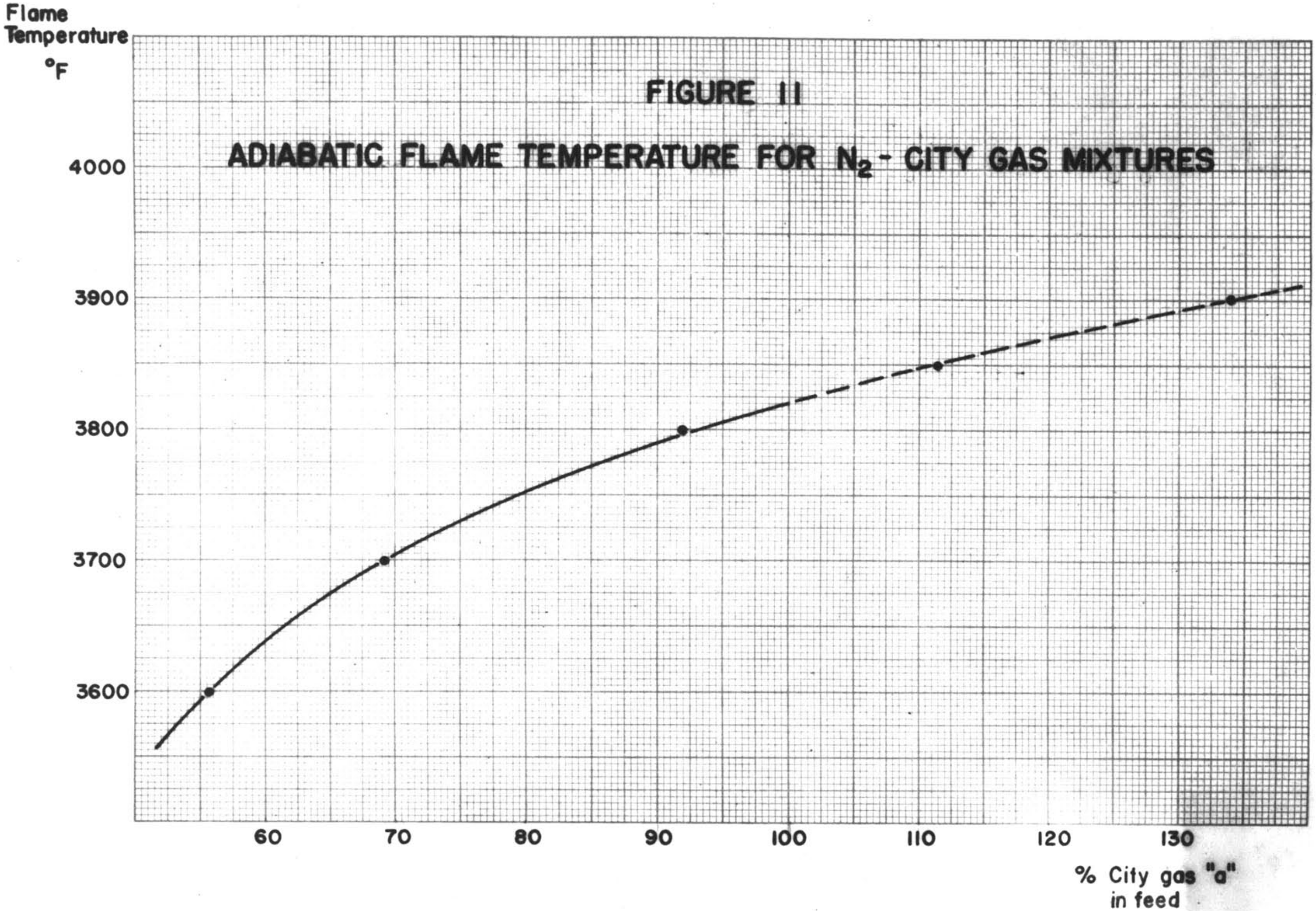
A plot of adiabatic flame temperature T_F versus percent Nitrogen "a" for City Gas-Nitrogen mixtures was then constructed; it appears on Figure 11.

Table 6

T °F	a
3600	.558
3700	.692
3800	.920
3850	1.114 *
3900	1.34 *

* (The last two values of "a" have no physical meaning since "a" cannot be greater than 1)

All these adiabatic flame temperatures are a little high since

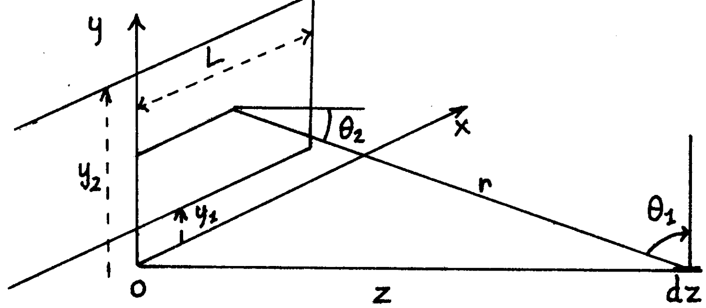

Flame Temperature °F
FIGURE 11
ADIABATIC FLAME TEMPERATURE FOR N_2 - CITY GAS MIXTURES
4000
3900
3800
3700
3600
60
70
80
90
100
110
120
130
% City gas "a" in feed

no allowance was made for dissociation of the combustion products. Nevertheless these values are only to be used for correlation purposes and their use is justified.

APPENDIX (Cont.)

E./ Sample Correction for Finite Lateral Extent of Fire.

Let us assume (8) that the flame can be represented by a flat wall of fire of height y_2 with a gap of height y_1 between the lower part of the flame and the surface. Let dZ be a spot on the surface at a distance Z from the slot centerline and let 2L be the lateral extent of the flame.



$$\mathcal{F}_{12} = \iint \frac{\cos\theta_1 \cos\theta_2 \, dA_2}{\pi r^2}$$

Where $r = (x^2 + y^2 + z^2)^{1/2}$

and $\cos\theta_1 = y/r$

$\cos\theta_2 = z/r$

$$\mathcal{F}_{12} = 2 \int_0^L \int_{y_2}^{y_1} \frac{zy \, dx \, dy}{\pi(x^2 + y^2 + z^2)^2}$$

$$\mathcal{F}_{12} = 2 \int_0^L \frac{Z}{\pi} dx \int_{y_2}^{y_1} \frac{y \, dy}{\left[y^2 + (x^2 + z^2)\right]^2}$$

Find:

$$\mathcal{F}_{12} = \frac{Z}{\pi} \int_0^L dx \left[- \frac{1}{x^2 + (y^2 + z^2)} \right]_a^b$$

For: $y_1 = b$

$y_2 = a$

$$\mathcal{F}_{12} = \frac{Z}{\pi} \left\{ \int_0^L \frac{dx}{x^2 + (z^2 + a^2)} - \int_0^L \frac{dx}{x^2 + (z^2 + b^2)} \right\}$$

Find:

$$\mathcal{F}_{12} = \frac{Z}{\pi} \left\{ \frac{1}{(z^2 + a^2)^{1/2}} \tan^{-1} \frac{L}{(z^2 + a^2)^{1/2}} - \frac{1}{(z^2 + b^2)^{1/2}} \tan^{-1} \frac{L}{(z^2 + b^2)^{1/2}} \right\}$$

$$R = \frac{\text{View factor for } L = 1 \text{ ft.}}{\text{View factor for } L = \infty}$$

$$R = \frac{\frac{1}{(z^2+a^2)^{1/2}} \tan^{-1} \frac{1}{(z^2+a^2)^{1/2}} - \frac{1}{(z^2+b^2)^{1/2}} \tan^{-1} \frac{1}{(z^2+b^2)^{1/2}}}{\frac{\pi}{2} \left[\frac{1}{(z^2+a^2)^{1/2}} - \frac{1}{(z^2+b^2)^{1/2}} \right]}$$

The correction factor R was calculated for two different heat liberation rates and for a spot on the surface at a distance of 1 foot from the slot centerline.

For Q/L = 75,800 Btu/hr.ft.

$y_1 = 1.25'$

$y_2 = .2'$

$z = 1'$

Find R = .75

For Q/L = 166,000 Btu/hr.ft.

$y_1 = 2.15'$

$y_2 = .35'$

$z = 1'$

Find R = .67

This is a rather crude way of correcting for finite lateral extent of fire; work being done (8) at the present time will give a better answer to this problem. The flame is broken down in cubes of radiating gas and the contribution of each cube is calculated as a function of position with respect to a spot on the surface.

APPENDIX (Cont.)

F. / Mathematical Model of Fire Spread

The simplest case of fuel combustion is that of a flat surface with the fire moving across it in a line, as shown on Figure 12. If the fuel is infinite in two dimensions the flame can be approximated as a flat wall heat source. Hottel ( ) derived the equation for heat transfer by radiation, convection and conduction to an element dx of the fuel bed of thickness L with the assumptions:

1) The density ρ, the heat capacity of the fuel C_p, the thermal conductivity K and the emissivity of the fuel ϵ are independent of temperature.

2) The heat transfer coefficient for the surface U is independent of x.

3) The emissivity ϵ_F of the flame is a constant and independent of the height of the flame.

4) The flame is gray.

5) The fuel at the base of the flame is at ignition temperature T_b.

In this particular mathematical model conduction was neglected.

The energy balance gives:

$$VC_p\rho \frac{dT}{dx} - \frac{U}{L} (T - T_a) - \frac{\sigma\epsilon}{L} (T^4 - T_a^{\,4}) \left[1 - \epsilon_F F(x)\right]$$

$$= -\frac{\sigma\epsilon \;\epsilon_F}{L} F(x) (T_F^{\,4} - T_a^{\,4})$$

Where F(x) is the geometric "view" the element dx has of the flame.

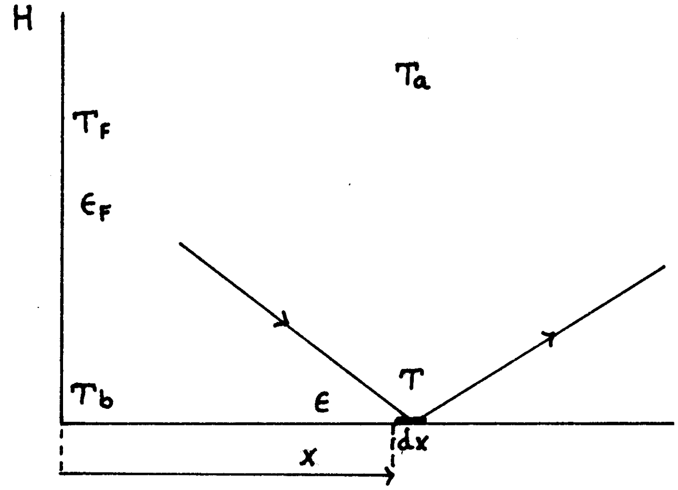


Figure 12

So:

$$\frac{dT}{dx} - \frac{U}{LVC_p\rho}\ (T - T_a) - \frac{\sigma\epsilon}{LVC_p\rho}\ (T^4 - T_a^4)\ \left[1 - \epsilon_F\ F(x)\right]$$

$$= - \frac{\sigma\epsilon\epsilon_F}{LVC_p\rho}\ (T_F^4 - T^4)\ F(x)$$

approximate $T^4 - T_a^4$ by

$$T^4 - T_a^4 = (T - T_a)\ \frac{T_b^4 - T_a^4}{T_b - T_a}$$

let

$$\theta = \frac{T - T_a}{T_b - T_a} \qquad \text{i.e.,} \quad \frac{dT}{dx} = (T_b - T_a)\ \frac{d\theta}{dx}$$

$$z = x/H$$

So:

$$\frac{d\theta}{dx} - \frac{U}{LVC_p\rho}\ \frac{(T - T_a)}{T_b - T_a} - \frac{\sigma\epsilon}{LVC_p\rho}\ (T - T_a)\ \frac{T_b^4 - T_a^4}{(T_b - T_a)}$$

$$= - \frac{\sigma\epsilon\epsilon_F}{LVC_p\rho}\ \frac{(T_F^4 - T^4)}{T_b - T_a}\ F(z)$$

And:

$$\frac{d\theta}{dz} - A'\theta = - B'\ F(z)$$

where:

$$A' = \frac{UH}{LVC_p\rho} + \frac{\sigma\epsilon H}{LVC_p\rho} \quad \frac{T_b^4 - T_a^4}{T_b - T_a}$$

$$B' = \frac{\sigma\epsilon\epsilon_F H}{LVC_p\rho} \left[\frac{T_F^4 - T_a^4}{T_b - T_a}\right]$$

A rigorous expression for F(z) by the cross string method gives:

$$F(z) = 1/2\left(1 - \frac{z}{\sqrt{1 + z^2}}\right)$$

However it can be approximated by a simpler expression (7)

$$F(z) = (1/2)\ e^{-z}$$

So:

$$\frac{d\theta}{dz} - A'\theta = -(1/2)\ B'\ e^{-z}$$

Multiply this equation by the integrating factor $e^{\int -A'\,dz} = e^{-A'z}$.

The solution is then:

$$\theta e^{-A'z} = -\int e^{-A'z}\left(\frac{1}{2} B' e^{-z}\right) dz + C$$

So:

$$\theta e^{-A'z} = +\frac{1}{2} B' \times \frac{1}{A' + 1}\ e^{-(A'z + z)} + C$$

The boundary condition $\theta = 0$ at $z = \infty$ yields $C = 0$. Therefore:

$$\theta = +\frac{1}{2}\left(\frac{B'}{1 + A'}\right) e^{-(A'z + z)}$$

Imposing $\theta = 1$ at $z = 0$

$$1 = + \frac{B'}{2(1 + A')} \quad \text{or} \quad 2 + 2A' = B'$$

Replacing A' and B' by their values, yields:

$$2 = - \frac{2UH}{LVC_p\rho} - 2\frac{\sigma\epsilon H}{LVC_p\rho} \cdot \frac{T_b^4 - T_a^4}{T_b - T_a} + \frac{\sigma\epsilon\epsilon_F H}{LVC_p\rho} \cdot \frac{T_F^4 - T_a^4}{T_b - T_a}$$

or:

$$V = \frac{\sigma\epsilon\epsilon_F(T_F^4 - T_a^4)}{C_p\rho\ (T_b - T_a)} \frac{H}{L} \left[\frac{1}{2} - \frac{1}{\epsilon_F} \cdot \frac{T_b^4 - T_a^4}{T_F^4 - T_a^4} - \frac{U(T_b - T_a)}{\sigma\epsilon\epsilon_F(T_F^4 - T_a^4)}\right]$$

So:

$$V = C_1 \frac{H}{L}\left(\frac{1}{2} - C_2\right)$$

Or alternatively:

$$V = \frac{H}{L}(M - N)$$

where:

$$M = \frac{1}{2}\ \frac{\sigma\epsilon\epsilon_F(T_F^4 - T_a^4)}{C_p\rho\ (T_b - T_a)} \qquad (A-4)$$

and

$$N = \frac{\sigma\epsilon\ (T_b^4 - T_a^4)}{C_p\rho\ (T_b - T_a)} + \frac{U}{C_p\rho}$$

APPENDIX

G/ Tables of Data

and

Calculated Values

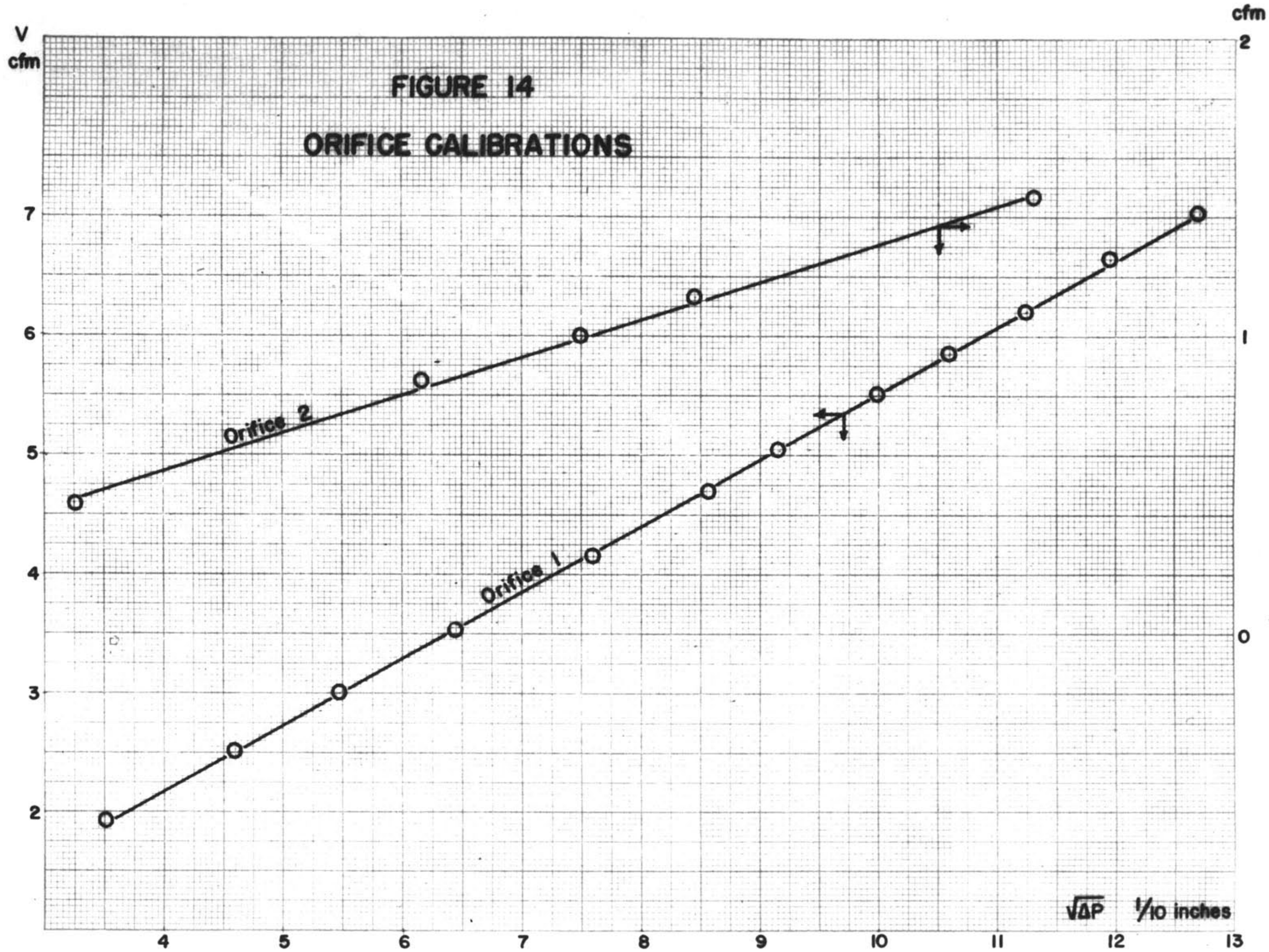


FIGURE 14
ORIFICE CALIBRATIONS
V
cfm
cfm
Orifice 2
Orifice 1
7
6
5
4
3
2
2
1
0
4
5
6
7
8
9
10
11
12
13
√ΔP 1/10 inches

Table 1

Reproducibility of Data

ΔP = 7.40-inches Q/L = 148,500 Btu/hr.ft.

Run 6-4-3			Run 6-4-4			Run 6-4-5			Run 6-4-6		
Dist. ft	Read mv	Intensity Btu/hr.ft^2	Dist. ft	Read mv	Intensity Btu/hr.ft^2	Dist. ft	Read mv	Intensity Btu/hr.ft^2	Dist. ft	Read mv	Intensity Btu/hr.ft^2
.217	.71	5,580	.217	.74	5,820	.217	.73	5,740	.217	.73	5,740
.296	.64	5,000	.263	.665	5,210	.247	.675	5,300	.279	.66	5,160
.361	.59	4,600	.329	.64	5,000	.312	.68	5,320	.345	.61	4,760
.427	.58	4,520	.394	.60	4,680	.378	.60	4,670	.411	.56	4,360
.493	.53	4,020	.525	.52	4,000	.443	.57	4,440	.476	.52	4,020
.624	.47	3,620	.657	.46	3,540	.575	.48	3,680	.607	.47	3,620
.755	.42	3,280	.788	.40	3,080	.706	.42	3,240	.739	.41	3,160
.886	.35	2,700	.919	.35	2,700	.837	.35	2,700	.870	.34	2,620
1.018	.30	2,320	1.050	.30	2,320	.968	.31	2,400	1.001	.29	2,240

Table 2

Intensity Values for Different Heat Liberation Rates

Run 6-00

$\Delta P = 1.02$
$Q/L = 53,600$ Btu/hr.ft.
$(Q/L)^{2/3} = 1,406$

Dist. Z ft.	Read mv	Intensity Btu/hr.ft^2	$Z/(Q/L)^{2/3}$
.217	.51	3,920	1,540
.296	.39	3,000	2,100
.361	.36	2,780	2,560
.427	.31	2,400	3,040
.493	.29	2,240	3,510
.624	.25	1,940	4,440

Run 6-0

$\Delta P = 1.50$
$Q/L = 66,150$
$(Q/L)^{2/3} = 1,636$

Dist. Z ft.	Read mv	Intensity Btu/hr.ft^2	$Z/(Q/L)^{2/3}$
.217	.54	4,190	1,330
.296	.435	3,300	1,820
.361	.39	3,000	2,210
.427	.35	2,700	2,620
.493	.32	2,480	3,020
.624	.28	2,100	3,830

Table 2 (Cont.)

Run 6-1

ΔP = 2.00
Q/L = 75,800
$(Q/L)^{2/3}$ = 1,791

Dist. Z ft	Read mv	Intensity Btu/hr.ft^2	$Z/(Q/L)^{2/3}$
.217	.56	4,360	1,210
.296	.44	3,400	1,650
.361	.41	3,160	2,010
.427	.37	2,860	2,380
.493	.34	2,620	2,750
.624	.28	2,160	3,490
.755	.22	1,700	4,220

Run 6-2

ΔP = 3.42
Q/L = 101,000
$(Q/L)^{2/3}$ = 2,155

Dist. Z ft.	Read mv	Intensity Btu/hr.ft^2	$Z(Q/L)^{2/3}$
.217	.59	4,600	1,010
.296	.48	3,700	1,374
.361	.45	3,470	1,675
.427	.43	3,320	1,980
.493	.41	3,160	2,290
.624	.34	2,620	2,900
.755	.28	2,160	3,500

Table 2 (Cont.)

Run 6-8

$\Delta P = 4.15$
$Q/L = 110{,}100$
$(Q/L)^{2/3} = 2{,}298$

Dist. Z ft.	Read mv	Intensity Btu/hr.ft^2	$Z(Q/L)^{2/3}$
.217	.65	5,090	948
.296	.54	4,190	1,290
.361	.50	3,850	1,570
.427	.51	3,920	1,860
.493	.46	3,540	2,150
.624	.37	2,860	2,720
.755	.32	2,470	3,290
.886	.26	2,010	3,860
1.018	.20	1,550	4,430

Run 6-3

$\Delta P = 5.02$
$Q/L = 121{,}000$
$(Q/L)^{2/3} = 2{,}447$

Dist. Z ft.	Read mv	Intensity Btu/hr.ft^2	$Z(Q/L)^{2/3}$
.217	.69	5,420	890
.296	.60	4,680	1,210
.361	.56	4,360	1,480
.427	.54	4,190	1,750
.493	.48	3,770	2,020
.624	.43	3,280	2,550
.755	.35	2,700	3,090
.886	.30	2,320	3,630
1.018	.25	1,920	4,160

Table 2 (Cont.)

Run 6-9

ΔP = 5.90
Q/L = 139,000
$(Q/L)^{2/3}$ = 2,701

Dist. Z ft	Read mv	Intensity Btu/hr.ft^2	$Z(Q/L)^{2/3}$
.217	.70	5,500	802
.296	.61	4,760	1,100
.361	.57	4,440	1,340
.427	.55	4,270	1,575
.493	152	4,020	1,820
.624	144	3,420	2,310
.755	.37	2,860	2,800
.886	.31	2,400	3,280
1.018	.27	2,090	3,760

Run 6-4

ΔP = 7.40
Q/L = 148,500
$(Q/L)^{2/3}$ = 2,811

Dist. Z ft.	Read mv	Intensity Btu/hr.ft^2	$Z(Q/L)^{2/3}$
.217	.71	5,580	775
.296	.64	5,000	1,055
.361	.59	4,600	1,285
.427	.58	4,520	1,520
.493	.53	4,020	1,760
.624	.47	3,620	2,225
.755	.42	3,280	2,695
.886	.35	2,700	3,150
1.018	.30	2,320	3,625

Table 2 (Cont.)

Run 6-5

ΔP = 9.30
Q/L = 166,000
$(Q/L)^{2/3}$ = 3,021

Dist. Z ft.	Read mv	Intensity Btu/hr.ft^2	$Z(Q/L)^{2/3}$
.217	.73	5,740	720
.296	.66	5,170	980
.361	.61	4,760	1,195
.427	.59	4,600	1,410
.493	.57	4,440	1,630
.624	.48	3,680	2,065
.755	.43	3,320	2,500
.886	.36	2,780	2,940
1.018	.31	2,400	3,360

Run 6-7

ΔP = 13.30
Q/L = 198,750
$(Q/L)^{2/3}$ = 3,407

Dist. Z ft.	Read mv	Intensity Btu/hr.ft^2	$Z(Q/L)^{2/3}$
.217	.75	5,900	638
.296	.67	5,270	870
.361	.64	5,000	1,060
.427	.60	4,680	1,250
.493	.58	4,510	1,445
.624	.49	3,770	1,830
.755	.46	3,540	2,220
.886	.40	3.090	2,600
1.018	.34	2,620	2,985

Table 3

Intensity of Radiation for a

Different Slot Width and Two Different Heat Liberation Rates

Slot Width = 1"

Run 9-2

ΔP = 7.40
Q/L = 148,500 Btu/hr-ft

Dist. ft.	Read mv	Intensity $Btu/hr\text{-}ft^2$
.176	.75	5,900
.255	.66	5,160
.320	.63	4,920
.386	.585	4,560
.452	.50	3,840
.583	.47	3,620
.714	.395	3,040
.845	.36	2,780
.977	.31	2,400

Run 9-3

ΔP = 3.42
Q/L = 101.000 Btu/hr-ft

Dist. ft.	Read mv	Intensity $Btu/hr\text{-}ft^2$
.176	.63	4,920
.255	.53	4,100
.320	.50	3,840
.386	.46	3,540
.452	.41	3,160
.583	.37	2,860
.714	.29	2,240
.845	.25	1,940

Table 4

Intensity of Radiation for Different Fuels and

for Single Slot Width and Heat Liberation Rate

Slot Width = 2"

Run 6-4 (Average)

Pure City Gas

Dist. Z, ft	Intensity Btu/hr-ft^2	$\frac{10^{25} I}{(T_F^4 - T_o^4)^2}$
.217	5,750	.511
.296	5,040	.448
.427	4,370	.388
.624	3,580	.318
.755	3,110	.276
.886	2,680	.238
1.018	2,260	.201

Run 8-1

90% City Gas - 10% Nitrogen

Dist. Z. ft.	Read mv	Intensity Btu/hr-ft^2	$\frac{10^{25} I}{(T_F^4 - T_o^4)^2}$
.217	.71	5,580	.525
.296	.63	4,920	.462
.624	.455	3,510	.330
.427	.56	4,380	.412
.755	.40	3,080	.289
.886	.345	2,660*	.250
1.018	.285	2,200	.207

* Corrected for a variation in flow rates

Table 4 (Cont.)

Run 8-2

80% City Gas - 20% Nitrogen

Dist. Z, ft.	Read mv	Intensity Btu/hr-ft^2	$\frac{10^{25} I}{(T_F^4 - T_o^4)^2}$
.217	.67	5,260	.527
.296	.585	4,560	.457
.427	.53	4,100	.411
.624	.43	3,320	.333
.755	.38	2,940	.295
.886	.33	2,540	.255
1.018	.27	2,080	.209

Run 8-3

75% City Gas - 25% Nitrogen

Dist. Z, ft.	Read mv	Intensity Btu/hr-ft^2	$\frac{10^{25} I}{(T_F^4 - T_o^4)^2}$
.217	.63	4,920	.519
.296	.565	4,400	.464
.427	.49	3,760	.397
.624	.40	3,090	.326
.755	.35	2,700	.285
.886	.305	2,360	.249
1.018	.23	1,780	.188

Table 4 (Cont.)

Run 8-4

Pure Propane

Dist. Z, ft.	Read mv	Intensity Btu/hr-ft^2
.230	.70	5,480
.296	.63	4,920
.427	.515	4,020
.624	.39	3,040
.755	.33	2,560
.886	.27	2,130
1.018	.22	1,700

<u>Table 5</u>

Radiometer Calibration

Furnace mv	T °F	Room T °F	Distance inches	Read mv	Flux Btu/hr-ft^2	View factor	Flux to radiometer Btu/hr-ft^2	Flux to radiometer Btu/hr-ft^2-mv
34.25	1565	85	12	.090	28,804	.0268	772	8570
34.25	1565	85	11	.111	28,804	.0310	893	8040
34.60	1581	85	10	.139	29,726	.0370	1100	7910
34.68	1584	85	9	.171	29,901	.0450	1346	7870
34.62	1582	85	8	.226	29,784	.0565	1683	7440
34.62	1582	85	7	.276	29,784	.0725	2159	7820
34.57	1580	85	6.5	.309	29,667	.0835	2477	8010
34.57	1580	85	6	.372	29,667	.0965	2863	7690
34.52	1577	85	5.5	.432	29,493	.1125	3318	7680
34.52	1577	86	5	.493	29,492	.1330	3923	7950
34.55	1579	86	4.5	.600	29,609	.1595	4723	7870
34.52	1577	86	4	.687	29,483	.1940	5722	8320

Table 5 (Cont.)

Furnace T M_v	^{o}F	Room T ^{o}F	Distance inches	Read mv	Flux Ftu/hr-ft^2	View factor	Flux to radiometer Btu/hr-ft^2	Flux to radiometer Btu/hr-ft^2-mv
23.85	1119	87	12	.020	10,648	.0268	285	14,250
23.82	1117	86	11	.044	10,595	.0310	328	7450
23.75	1114	86	10	.048	10,514	.0370	389	8100
23.75	1114	86	9	.055	10,514	.0450	473	8,600
23.69	1111	86	8	.071	10,434	.0565	590	8,300
23.62	1108	86	7.5	.080	10,347	.0635	657	8210
23.62	1108	85	7	.090	10,347	.0725	750	8330
23.56	1105	86	6	.132	10,270	.0965	991	7500
23.56	1105	86	5.5	.152	10,270	.1125	1155	7590
23.50	1103	86	5	.175	10,220	.1330	1359	7760
23.50	1103	86	4.5	.207	10.220	.1595	1630	7870
23.43	1100	86	4	.245	10,145	.1940	1986 *	8030

*This datum point is not reliable. The closeness to the furnace and the temperature of the furnace made the distance measurement very awkward and probably erroneous.

Table 7

Flame Heights for Different Heat Liberation Rates

ΔP inches	Flow rate cfm	Q/L Btu/hr-ft.	Flame height ft.
1.46	2.08	64,900	1.16
4.72	3.78	117,900	1.645
8.51	5.10	159,100	2.025
10.80	5.74	179,100	2.33
12.76	6.21	193,750	2.58
13.60	6.45	201,250	2.63
3.57	3.28	102,300	1.44
5.70	4.15	129,500	1.81
10.90	5.78	180,300	2.17

APPENDIX

H / Nomenclature

A	Area	ft^2
C_p	Specific heat	Btu/lb-^oF
$\mathcal{D}$	Diffusivity	ft^2/hr
AF	View factor	ft^2
g	Acceleration of gravity	ft/sec^2
H	Flame height	ft
I	Intensity of Radiation	Btu/hr-ft^2
k	Thermal conductivity	Btu/hr-ft^2-^oF/ft
K	Gas absorption coefficient	ft^{-1}
L	Fuel bed thickness	ft
M_v		millivolts
P	Pressure	lb-force/ft^2
Q	Heat liberation rate	Btu/hr
T	Temperature	^oR
T_F	Flame temperature	^oR
T_a	Ignition temperature	^oR
T_o	Base temperature	^oR
U	Heat transfer coefficient	Btu/hr-ft^2-^oF
U	Local velocity	ft/sec
V	Velocity of fire spread	ft/sec

λ	Thermal conductivity	Btu/hr-ft^2-$^\circ$F
μ	Viscosity	lb/sec-ft
ϵ, ϵ_F	Emissivity	
ρ	Density	lb/ft^3

APPENDIX (Cont.)

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