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UNIVERSITY OF DELAWARE
NEWARK, DELAWARE

DEPARTMENT OF CHEMICAL ENGINEERING

March 13, 1951

Office of Naval Research
Navy Department
Washington 25, D. C.

Dear Sir:

This is to inform you that I have received permission by Dr. Parker, Director of Project Squid, to publish the enclosed report and that I have submitted the report to the North American Committee for the Discussion on Heat Transfer to be held in London, September 11 - 13, 1951.

The research work which is reported in the paper was carried out under the contract No. N8onr-74001.

Very truly yours,

Kurt Wohl

Kurt Wohl,
Professor of Chemical Engineering

Encl.
Kw/ub

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The Determination of the Temperature of Non-Luminous Flames
by Radiation in the Near Infrared. 1)

By L. Bernath, H. N. Powell, F. Welty, and K. Wohl²⁾

Introduction

MAR 20 1951.

The problem of how to measure the temperature of non-luminous flames - i.e. of flames which are free from glowing soot particles - has not found an entirely satisfying solution. Thermocouples and pneumatic probes are liable to influence the state of flow and the rate of combustion by their presence - quite apart from other limitations. The visible and ultraviolet radiation originates in intermediates of the combustion reaction and is of chemiluminescent nature so that its intensity is not a unique function of temperature. This is compatible with the fact that the intensity ratio of the rotational lines corresponds in a number of cases to a certain temperature. It remains uncertain, however, whether this is the case or not, and what the relation of this temperature is to the translational temperature. Taking further into account the experimental and theoretical difficulties of the method, it appears that the method is more suitable for exploring the combustion mechanism than for determining "the" temperature, i.e. the translational temperature, of flames.

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Most widely used is the sodium line-reversal method. The question, however, is still open whether the sodium radiation is invariably thermal in regions of intense burning (1). Moreover, the sodium has to be introduced in a manner which does not disturb the flame - which is not always feasible with technical flames - and has to be prevented from being deposited at windows whenever enclosed flames are investigated.

Flame radiation in the infrared has not in recent years been employed extensively for measuring temperatures. An evaluation of the intensity ratios of the rotational lines of the infrared spectrum has so far not been attempted since the main emitters are the triatomic molecules H_2O and CO_2 which possess an extremely complex band structure. The measurement of emission and emissivity in a narrow infrared wave length range is a standard scientific method for obtaining flame temperatures which is still in use (2). The method requires a substantial absorptivity of flame gases as exists mainly in the range of long wave lengths where measuring instruments responding to the thermal effect of radiation have to be used. It appears advantageous to use instead the more sensitive lead sulfide photoconductive cell. This, however, restricts the spectral range to wave lengths below about 3μ where the CO_2 band at 2.7μ is just strong

enough to apply the method with a reasonable degree of accuracy although overlapping with H_2O bands is disadvantageous in some respects.

A. The Method.

The authors have taken advantage of the low light absorptivity in the nearest infrared and have developed a two-wave length method in which the temperature is obtained from the ratio of the intensities of two peaks of the water band system in the near infrared after the ratio of emissivities at these two wave lengths has been established as a function of temperature as will be explained below. The method appears applicable to any combustion process in which water vapor is produced. In order to be able to ascertain temperatures in narrow well defined flame regions, a two-dimensional (inverted) flame has been made the object of study, and the aperture of the spectrophotometer has been narrowed down such that light is received from a flame zone of small cross-section which has a nearly uniform temperature throughout the depth of the flame.

B. The Apparatus.

A cross-section through the burner used is shown in Fig. 1A. The burner has a depth of 5.1 cm and has quartz plates on the front and back side. The side walls are cooled. The primary burning zone, shown in Fig. 1A, appears truly flat to the eye. The burner can be

tilted so that the burning surface becomes parallel to the slit of the spectroscope. The flame zone under observation has a height of 3 mm, and an average width of 0.3 mm.

The spectrophotometer operates with a LiF prism and a "Cetron" lead sulfide photoconductive cell*. The signals, after amplification and reduction of noise, are recorded on a Brown Elektronik strip chart recorder. The slit width is 0.13 mm, corresponding to a resolution of 0.01μ in the range of interest. Absolute intensities of flame radiation at any wave length are obtained by comparing them with the radiation of a calibrated tungsten-in-quartz ribbon lamp (standard lamp) at the same wave length. The apparatus can be used to traverse through the spectrum for a given point of the flame cross-section as well as through the flame cross-section for a given wave length.

C. Evaluation of Data and Results.

1) Thermodynamic Check. It is possible to check the thermodynamic consistency of the temperatures obtained with the help of the radiation intensity at a third wave length, even before performing the actual computation of the temperatures. A sample of a spectral traverse for a butane-air flame is given in Fig. 2. It contains at the same time the radiation curve from the standard

* Continental Electric Company of Geneva, Illinois

lamp which is indented at a number of places due to absorption of radiation by the water vapor content of the air in the light path. It appears that at the peaks of the flame radiation curve designated by $\lambda_1 = 1.346\mu$, and $\lambda_3 = 1.819\mu$ very little light absorption by water vapor at room temperature occurs, so that the corresponding correction terms are below 2%. Wave length $\lambda_6 = 2.505\mu$ is practically free from absorption at room temperature. These wave lengths therefore have been chosen as suitable for the measurement of flame temperatures.

As the absorptivity at all wave lengths used is below 3%, it can be expressed by the product ϵcd where ϵ is the molar extinction coefficient at the wave length λ , c the water vapor concentration, and d the depth of the flame. The ratio of thermal flame radiation at the two wave lengths λ_1 and λ_6 can then be written

$$\frac{E_6}{E_1} = \frac{\epsilon_6 \lambda_1^5 (e^{c_2/\lambda_1 T} - 1)}{\epsilon_1 \lambda_6^5 (e^{c_2/\lambda_6 T} - 1)} \quad (1)$$

where E_1 and E_6 mean brightness at wavelength λ_1 and λ_6 , respectively. Within the temperature range of interest the equation can be written with sufficient accuracy

$$\log \frac{E_6}{E_1} = \log \frac{\epsilon_6}{\epsilon_1} + a_{16} - \frac{b_{16}}{T} \quad (2)$$

where a_{16} and b_{16} are known. $\frac{\epsilon_6}{\epsilon_1}$ now is only a weak function of temperature and it may be assumed that it can be described within the temperature range of interest by the theoretically plausible equation

$$\log \frac{\epsilon_6}{\epsilon_1} = \alpha_{16} - \frac{\beta_{16}}{T} \quad (3)$$

where α_{16} and β_{16} are constant coefficients which so far are unknown. Equations (2) and (3) give

$$\log \frac{E_6}{E_1} = (a_{16} + \alpha_{16}) - \frac{(b_{16} + \beta_{16})}{T} \quad (4)$$

By writing the corresponding equation for $\log \frac{E_6}{E_3}$, and by eliminating T from these two equations, there is obtained the following linear relation between $\log \frac{E_6}{E_1}$ and $\log \frac{E_6}{E_3}$:

$$\log \frac{E_6}{E_1} = a_{16} + \alpha_{16} - \frac{(b_{16} + \beta_{16})(a_{36} + \alpha_{36})}{b_{36} + \beta_{36}} + \frac{(b_{16} + \beta_{16})}{(b_{36} + \beta_{36})} \log \frac{E_6}{E_3} \quad (5)$$

Fig. 3 shows that such a linear relationship holds indeed between 1600 and 2200° K. (see below). Some of the data which are represented in this figure are given in Table I.*

* A complete list of data and a more detailed description of the apparatus will be published elsewhere.

TABLE I

Examples of Data on Infrared Radiation
and Temperatures of Butane-Air FlamesE = spectral brightness in (watts)(cm.⁻²)(micron⁻¹)(solid angle⁻¹).E₁ at $\lambda = 1.346$ micronsE₃ at $\lambda = 1.819$ micronsE₆ at $\lambda = 2.505$ microns

Burner Type	1) % Butane	E ₁	E ₃	E ₆	log $\frac{E_6}{E_1}$	log $\frac{E_6}{E_3}$	Temp. from Infra-red, °K.	Temp. by Sodium Line Reversal, °K.
B	2.55	0.0357	0.0401	0.1558	0.640	0.589	2030	2042
B	"	.0349	.0389	.1532	.643	.595	2020	
B	"	.0360	.0406	.1560	.637	.585	2035	
A	"	.0397	.0451	.1766	.636	.580	2040	2103
B	2.85	.0437	.0475	.1748	.602	.566	2110	
B	"	.0431	.0467	.1748	.608	.573	2090	
B	"	.0439	.0473	.1762	.603	.571	2105	2128
B	3.04	.0493	.0529	.1920	.591	.560	2135	
B	"	.0495	.0532	.1912	.588	.556	2145	
B	"	.0498	.0535	.1920	.586	.555	2150	1928
A	"	.0549	.0584	.2045	.571	.545	2185	
A	3.33	.0531	.0581	.2130	.604	.565	2110	
A	3.76	.0501	.0544	.2025	.607	.571	2100	1990
A	4.28	.0375	.0434	.1738	.664	.593	1960	
B	4.76	.0337	.0387	.1587	.673	.613	1935	
B	"	.0327	.0386	.1592	.688	.616	1940	1875
B	"	.0338	.0385	.1612	.679	.622	1875	
A	"	.0287	.0350	.1509	.720	.636	1875	
B	see 3)	.0120	.0186	.1000	.921	.731	1595	

- 1) Burner Type A: See Fig. 1A. The burner duct shown in Fig. 1A, through which the fuel-air mixture is supplied, was 5.5 mm. wide.
Burner Type B: See Fig. 1B.

- 2) The stoichiometric C₄H₁₀-air mixture contains 3.13 % C₄H₁₀.
3) Luminous diffusion flame, produced by introducing parallel streams of a rich fuel mixture and air through a modified Type B burner.

The linearity observed confirms that the infrared radiation of the water vapor is thermal at all conditions, and it proves at the same time that the form of equation (3) is capable of describing the temperature dependence of the ratio of the extinction coefficients with sufficient accuracy over the temperature range of Fig. 3. It is true that in principle equations (1) and (2) might be erroneous in such a fashion that the validity of equation (5) is the result of compensation of errors. This, however, is most unlikely in view of the fact that the two pertinent variables, temperature and composition of combustion gases could be varied independently without causing any systematic deviations.

It may be mentioned that one of the butane-air flames measured was a diffusion flame which was clearly, though not very strongly, luminous. This means that the visible radiation emitted by the glowing soot particles

present, was well visible to the eye in competition with the green-blue light emitted by the flame gases. It was shown in special experiments, however, that the radiation emitted by the soot particles of the same flame in the infrared was entirely negligible as compared with the water vapor radiation. This makes the method presented here applicable to flames of weak and medium luminosity.

2) Establishment of the Temperature Scale. After the consistency of results has been established, it remains to determine the coefficients α_{16} and β_{16} of equation (3) so that equation (4) can be used for the measurement of temperatures. The corresponding equations for the wave lengths λ_6 and λ_3 may be used instead. Only one pair of wave lengths is required; the other one serves merely as a check. In order to find the values of the two coefficients in the equation (3) or (4) the temperature has to be measured by an independent method for at least two points. For

this purpose the sodium line-reversal method was chosen, and it was applied to four flame points for which the infrared radiation had also been measured (see Table I).

In order to apply the sodium line-reversal method, the burner had to be modified; for the sodium salt has a tendency to form a deposit on the windows, and any absorbing layer between the standard lamp and the flame would invalidate the method. Thus, a slit was cut into the back quartz plate. In order to obtain a stable flame with this configuration, the burner duct seen in Fig. 1A was replaced by a one-dimensional Meker grid, and a closed box with a quartz window was placed outside the slit as is seen in Fig. 1B. The data obtained with this burner did not show any systematic deviation from the average line of Fig. 3. The sodium line-reversal temperature is estimated to be accurate within $\pm 10^\circ$.

The results are shown in Fig. 4 in such a way that the observed values of $\log E_6/E_1$ and $\log E_6/E_3$ are plotted as a function of $10^4/T$, T being the sodium line-reversal temperature. At the same time the Planckian function $\log E_6^0/E_1^0$ is plotted which represents the ratio of black body radiation at λ_6 and λ_1 as given by equation (1) or (2) if E_6/E_1 is made equal to 1. Similarly, $\log E_6^0/E_3^0$ is obtained and plotted. The differences between the

two straight lines in Fig. 4 thus equal $\log E_6/E_1$ and $\log E_6/E_3$, respectively. The equations obtained for these quantities are

$$\log \frac{E_6}{E_1} = 0.910 \quad (6)$$

$$\log \frac{E_6}{E_3} = 0.663 + \frac{281}{T} \quad (7)$$

The corresponding equations for the ratios of radiation intensities are

$$\log \frac{E_6}{E_1} = -0.345 + \frac{2000}{T} \quad (8)$$

$$\log \frac{E_6}{E_3} = 0.0326 + \frac{1125}{T} \quad (9)$$

These equations yield a temperature for every point of the average line of Fig. 3. The temperatures are indicated in the figure in steps of one hundred degrees.

The real flame points now at which the three radiation intensities have been measured, show a certain deviation from the line of Fig. 3 due to random error. In other words, the ratio E_6/E_1 yields a somewhat different temperature than the ratio E_6/E_3 . Averaging has been performed under the supposition that the errors in E_1 and E_3 are larger than the error in E_6 because

radiation at λ_1 and λ_3 is considerably weaker than that at λ_6 . These considerations are accounted for by choosing as an average the point on the straight line in Fig. 3 which is closest to the point in question. If the errors were attributed solely to E_1 and E_3 , the average would be obtained as the point of intersection of the straight line of Fig. 3 and a 45° - line from the point in question. The difference equals a few degrees and is below 10° C in any case. The uncertainty introduced by this procedure can be reduced below any significant amount through repeating the measurement since the points are randomly distributed among the line of Fig. 3.

The absolute accuracy of the temperatures obtained is estimated as $\pm 20^\circ$ C. The random errors are much smaller as can be seen from the following Fig. 5. A comparison of the experimental temperatures with temperatures calculated thermodynamically for the case of complete adiabatic combustion is not conclusive since heat losses are to be expected in the burner used, and since no systematic search was made for the maximum local temperature. It can be stated, however, that none of the experimental temperatures exceeded the adiabatic flame temperature while in one case (3.33% butane) the temper-

ature at a certain flame point was as much as 86° below the adiabatic temperature.

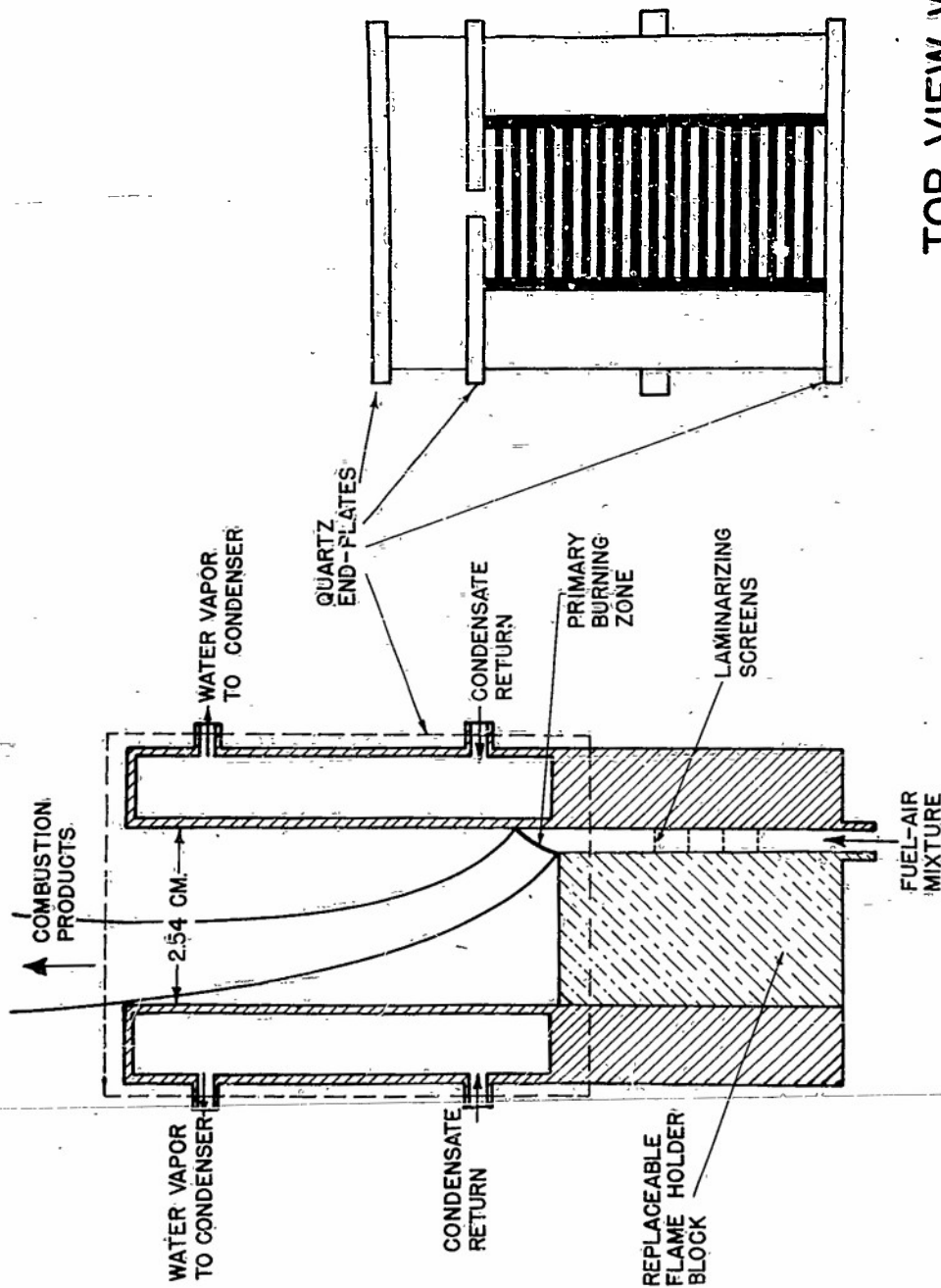
3) Application of the Method. Temperatures have been measured closely behind the burning zones of several lean and rich butane-air flames as a function of distance from the burning zone (the latter being defined as the surface of maximum visible light intensity). Two examples are presented in Fig. 5. It was found that the ratios of light intensities E_6/E_1 and E_6/E_3 follow closely the line in Fig. 3. For the rich flame shown, the distribution is entirely random, the mean error being especially small. For the lean flame shown, there seems to be a slight preference for one side of the line. On the whole, the evidence is strongly in favor of the thermal nature of the infrared radiation. It is noteworthy that this is the case up to a distance of 0.2 mm from the burning zone where combustion is still actively proceeding and, as a consequence, chemiluminescent radiation is emitted in the visible and ultraviolet part of the spectrum. The curve could not be reliably extended through the burning zone because, with the present arrangement, schlieren effects distorted the result. It is seen from Fig. 5 that the temperature rise is more gradual for the lean flame

than for the rich one. This was also observed with Meker flames and corresponds to the experience on the stability of lean and rich flames (3).

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- 2.) The Determination of Flame Temperatures by Infrared Radiation, S. Silverman, Third Symposium on Combustion and Flame and Explosion Phenomena, Williams and Wilkins, Co., Baltimore, Maryland, 1949, p. 498-500.
- 3.) The Stability of Open Flames, K. Wohl, N. M. Kapp, C. Gazley, ibidem, p. 3 - 21.



TOP VIEW WITH
 FLAME HOLDER BLOCK
 REPLACED BY GRID

FIG. 1B

CROSS-SECTION PERPENDICULAR
 TO OPTICAL PATH

FIG. 1A

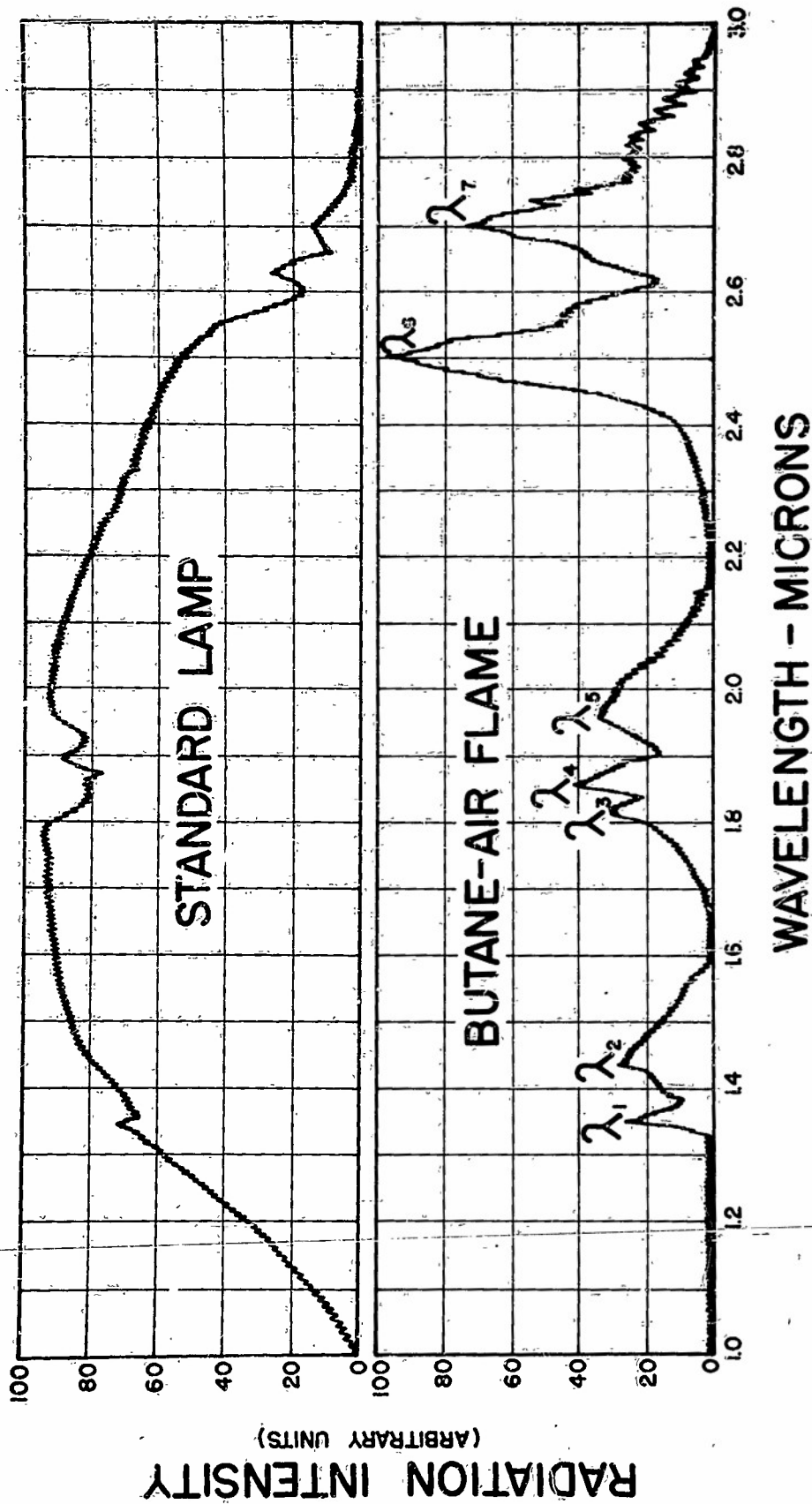


Figure 2

Infrared Emission Spectra of a Butane-Air Flame and of a Standard Tungsten Lamp at 1300° K.

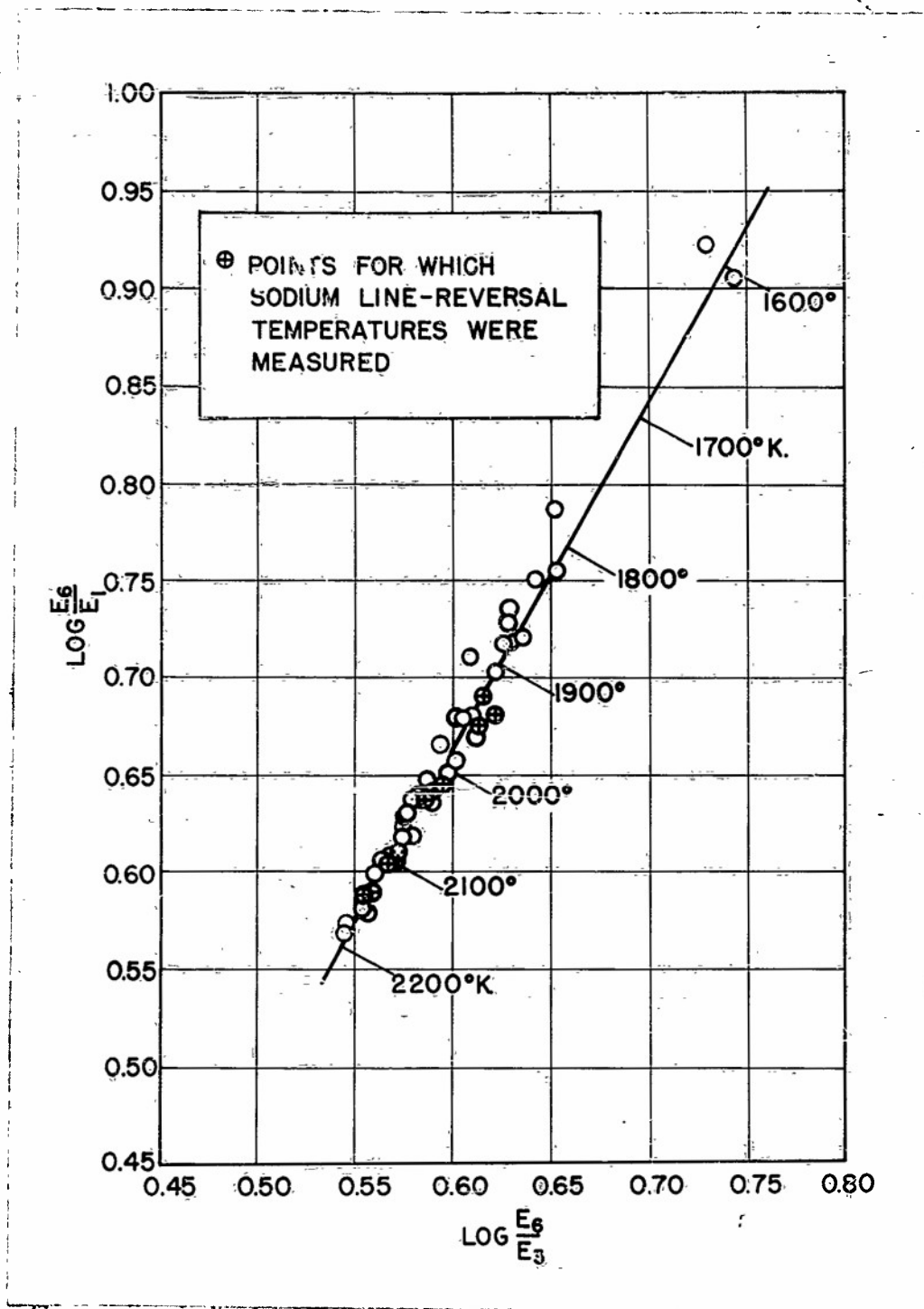


Figure 3

Thermodynamic Check of Flame Radiation Data.

E_1 = spectral brightness at $\lambda_1 = 1.346\mu$

E_3 = spectral brightness at $\lambda_3 = 1.819\mu$

E_6 = spectral brightness at $\lambda_6 = 2.505\mu$

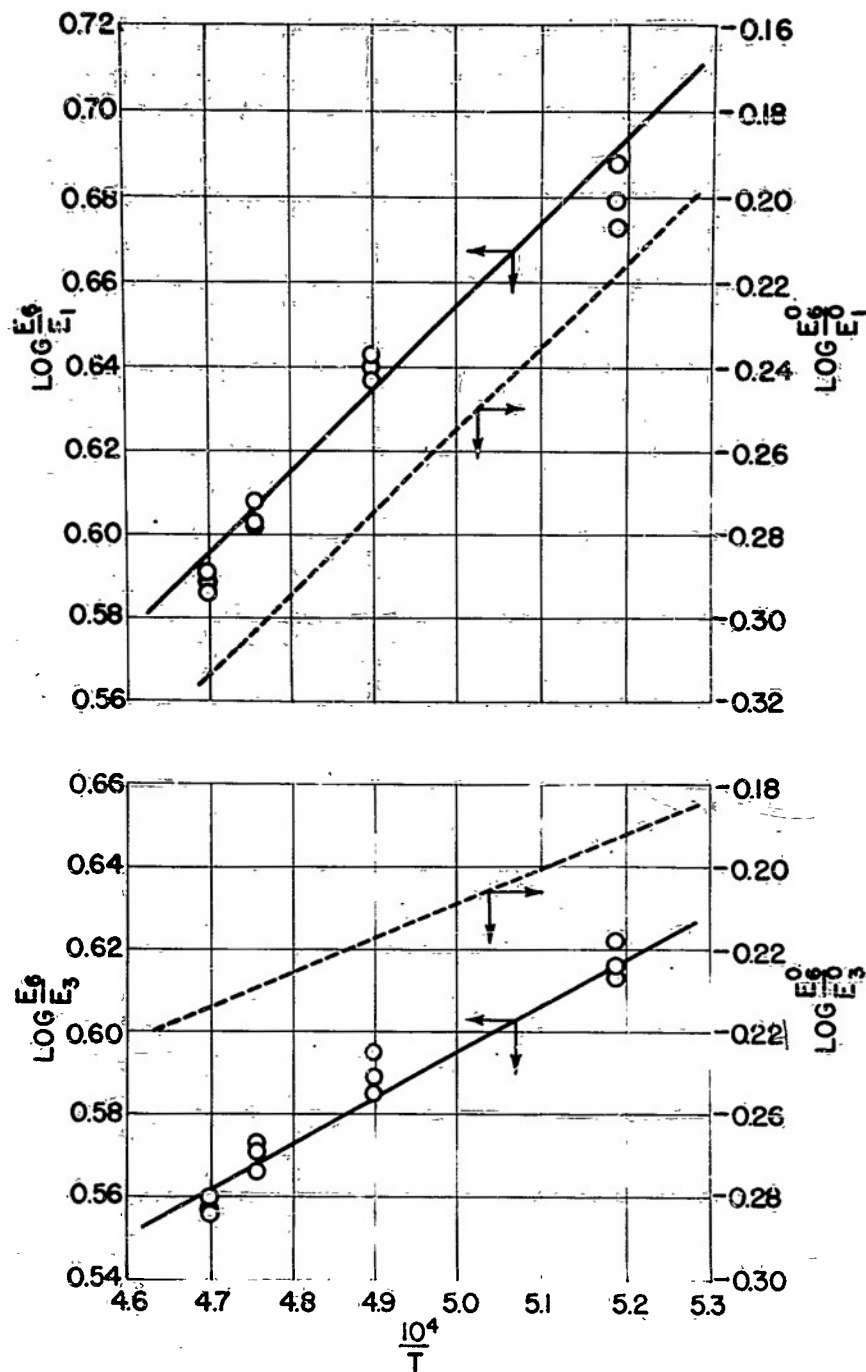


Figure 4

Establishment of Temperature Scale

E_1 , E_3 , and E_6 = spectral brightness of flame radiation at
 $\lambda_1 = 1.346\mu$, $\lambda_3 = 1.819\mu$, and $\lambda_6 = 2.505$, respectively.

E_1^0 , E_3^0 , and E_6^0 = spectral brightness of black body at the
 above wave lengths, respectively.

T = temperature in $^{\circ}\text{K}$ determined by the sodium line-reversal method

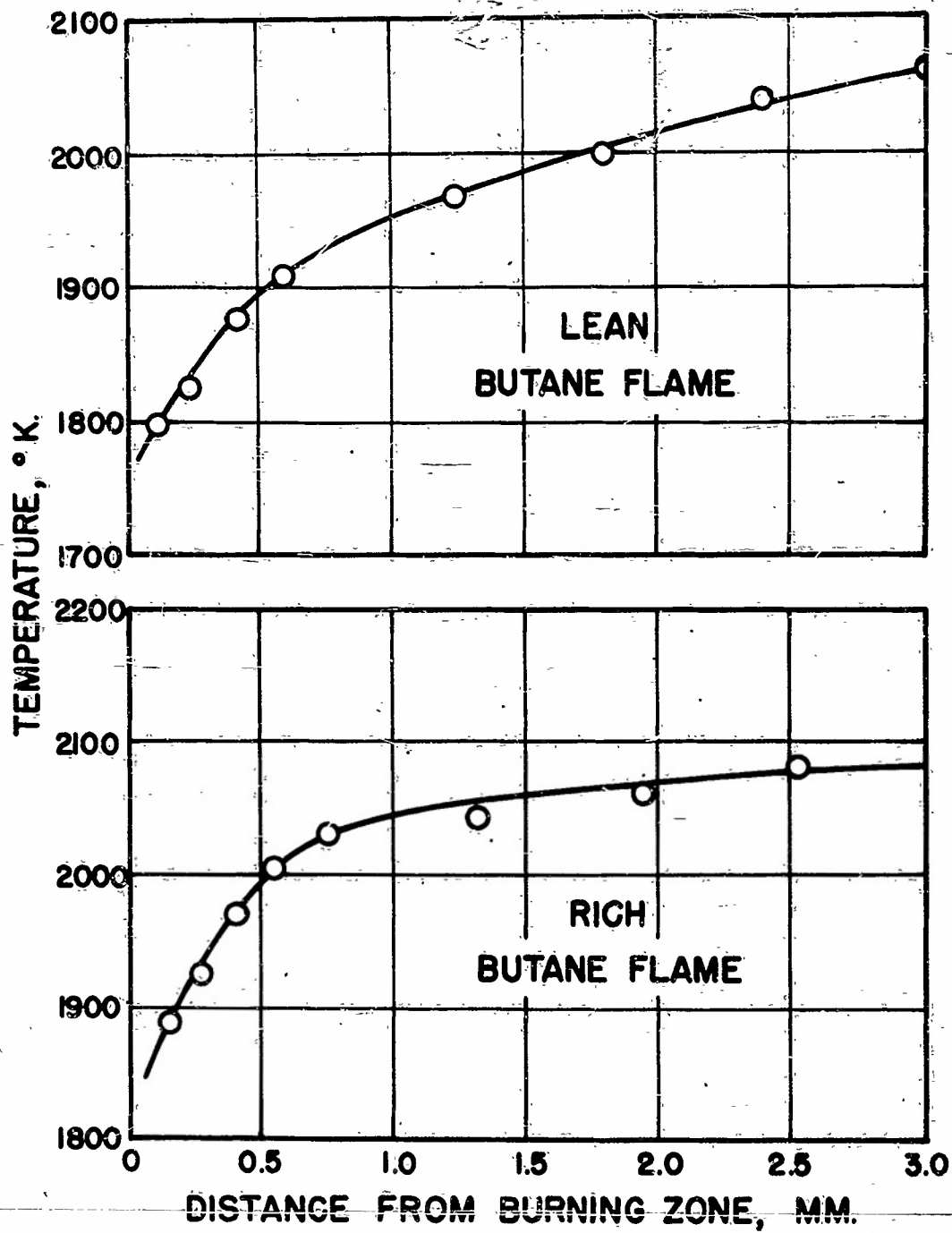


Figure 5

Local Temperatures of a Lean and a Rich Butane-Air Flame as a Function of Distance Behind the Primary Burning Zone.

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