DETERMINATION OF TEMPERATURE
IN A LOW PRESSURE FLAME

Thesis by

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ABSTRACT

The extended dimensions of a flame zone which result from reducing the ambient pressure below 10 mm. Hg provide possibility for detailed investigation of flame chemistry and thermodynamics. The present investigation constitutes the first part of a detailed survey of the temperature distribution in an oxy-acetylene flame and describes the instrumentation and development of the modified Schmidt Technique for measuring flame temperature and the measurement of the maximum temperature in the flame.

The results indicate the maximum flame temperature to be within plus or minus 30°C. of the equilibrium flame temperature at 4.3 mm. Hg. The technique developed, while laborious, may be used to determine flame temperature with a good degree of accuracy.

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I. INTRODUCTION

The behavior of a low pressure flame offers an opportunity for detailed study of combustion processes and flame structure. Physical enlarging and drawing out of a flame caused by the low pressure permit investigations with relatively great resolving power of temperature profiles, reaction zone heat flow, equilibria, flame stability including behavior near flame holders, specie excitation, and related phenomena. Although there may be variation in the actual combustion mechanism due to pressure, it is considered that this experimental approach may delineate steps in the solution of general combustion problems. Besides the implementation of fundamental combustion knowledge, these studies give promise of furnishing significant observations useful in the design of new or improved propulsion systems.

A major factor in conducting these investigations lay in the design and construction of combustion chamber apparatus of suitable characteristics. Burner diameter for instance must be increased proportionately as pressure is lowered; other components of the apparatus must then be matched.

H. Klaukens and H. G. Wolfhard (Cf. Refs. 1 and 2) made direct measurements in the reaction zone of a low pressure Bunsen flame by thermocouple and Schlieren techniques. Subsequently A. G. Gaydon and H. G. Wolfhard (Cf. Refs. 3 to 5) using interferometers and spectroscopes made optical studies of the behavior of an acetylene flame noting temperature and the behavior of various bands.

M. Gilbert (Cf. Ref. 6) designed and installed an improved combustion chamber. He then measured the temperature profile of a low pressure oxy-acetylene flame by utilizing several sets of thermocouples.

The results of thermocouple measurements in References 1, 2, and 6 were contingent, insofar as true gas temperature profiles were desired, upon estimates of various parameters such as thermal conductivity of the gas film and emissivity-temperature relationship of thermocouple wires, particularly the former. Sufficient doubt of the applicability of literature values led to the belief that a measurement of these parameters was necessary.

The method applied to obtain the results reported in this paper is based on the heat balance equations for an electrically heated wire in the flame. The method may be termed a modified "Schmidt Technique" (Cf. Ref. 7) except that it is not possible to measure flame temperature by an experimental null point. Rather it is necessary to extrapolate to this null point. Consideration of the use of such a method grew out of discussion with Dr. H. S. Tsien. This modified Schmidt Technique appears to have many limitations with regard to extensive use in the flames investigated but it has the advantage that where applicable it determines both the thermal conductivity of the gas film and the true gas temperature. The only auxiliary measurements necessary are those of emissivity-temperature characteristics of the wires used.

In carrying out the low pressure oxy-acetylene flame temperature measurement of this investigation use was made of the improved low pressure facilities (Cf. Ref. 6) of the Jet Propulsion Laboratory, California Institute of Technology. Financial sponsors of the project were the Ordnance Corps, United States Army and the Power Plants Laboratory, Wright-Patterson Air Force Base, Air Materiel Command, United States Air Force.

The wire employed to fit the Schmidt Technique was platinum and use was made of its well-defined resistivity-temperature relationship. Varying amounts of alternating current were run through the wire and the heat balance noted. The emissivities of the platinum wire specimens used were determined in an evacuated bell jar. The work was checked by repeating with platinum wires of different size and purity.

II. THE LOW PRESSURE BURNER

The combustion chamber used is essentially a large cylindrical shell, continuously evacuated. Combustion mixtures are introduced through a rectangular duct at the bottom. Tests have shown the velocity profile of this mixture flow to be laminar. When ignited under proper conditions the flame seats itself just above the duct lip (Fig. 1) with no wall interference resulting. The easily opened doors mounted on opposite sides of the chamber permit visual observation through their installed windows. All accesses and attachments to the chamber utilize mobile and stationary neoprene O-rings that have proved their effectiveness as excellent seals for the low pressures involved.

A large capacity evacuating system is installed to keep the chamber at sufficiently low pressure; it is connected to the chamber's top by a six inch main. Incorporated in the system is an acoustical filter to prevent pressure surges of the pump from resulting in flame vibration. System pressure is controlled by bleed air admitted at the pump end into a large tank from which there is no dilution by back diffusion into the exhaust gas atmosphere surrounding the flame.

Commercial bottle supply gases are used on the supply side of the combustion chamber. They undergo two stages of pressure reduction such that the pressure ratio across the installed flow control needle valves is greater than critical. Hence the upstream conditions are independent of the downstream perturbations.

Ignition is effected by the following generally invariant technique: While an accelerated oxygen flow is maintained into the combustion chamber, a high pressure jet of partially burned propane gas is admitted into an inverted cone, a fitting mounted about half way up the center of the chamber. Fuel is then introduced and ignites at the inverted cone level. By carefully reducing the oxygen flow to testing conditions the oxy-acetylene flame is caused to lower from the cone and seat just above the duct lip.

Only a general discussion covering salient features of the low pressure burner configuration is included in this paper. Extensive discussion of the apparatus is given by M. Gilbert (Cf. Ref. 6).

III. MEASUREMENT THEORY AND TECHNIQUE

To accurately measure the temperature of the flame produced by the low pressure chamber described in Part II various techniques were tried.

First wire thermocouples of several types were inserted into the flame and their output voltages measured. Wire temperature was then calculated from the literature temperature-voltage tables. Heat balance of an element of length dx of this thermocouple wire is given by

$$\pi dx \Big[hd(T_g - T_w) + \sigma \epsilon_w d(\epsilon'_g T'^4_g - \alpha'_g T^4_w) - \sigma \epsilon_w d(T^4_w - T^4_s) - \frac{Kd^2}{4} \frac{\partial^2 T_w}{\partial x^2} + q \Big] = 0 \qquad (1)$$

where

h = heat-transfer coefficient for forced convection (Btu/hr ft^2 °R)

d = wire diameter (ft)

T_g = gas temperature to be determined (°R)

T_w = observed thermocouple temperature (°R)

σ = radiation constant (0.173×10^{-8} Btu/hr ft^2 °R^4)

ϵ_w = emissivity of thermocouple surface, assumed graybody

ϵ'_g, α'_g = effective gas emissivity and absorbtivity, respectively, the latter corresponding to T_w and the former to T'_g

T'_g = effective average gas temperature for radiation (°R)

T_s = temperature of surroundings, assumed black (°R)

K = wire conductivity (Btu/hr ft °R)

q = extraneous thermal effects per unit time per unit length

In evaluating this equation the following were noted:

1. A preliminary experiment of measuring flame radiation made with a sensitive radiometer against a black body indicated that total flame radiation to its cold surroundings was less than ten per cent of the energy of release of combustion. In all but one extremely rich acetylene flame it was less than two per cent. Even then only a small portion of it may be ascribed to the luminous gas; hence gas emissivity is small, gas absorptivity negligible, and both may be neglected.
2. T_s was less than $T_w/4$ and therefore in the fourth power could be neglected.
3. Apparatus design placed the wire in an isothermal region of the flame; hence the excess of heat conducted through the element boundaries vanishes and $\frac{\partial 2T_w}{\partial x^2}$ may be neglected.
4. Extraneous thermal effects could be neglected.

The justification for neglecting the above terms is discussed in further detail in Reference 6.

Thus equation (1) when considered over a finite length reduced to

$$\pi \ell \left[hd(T_g - T_w) - \sigma \epsilon_w d T_w^4 \right] = 0 \qquad (2)$$

Dividing by $\pi \ell d$

$$h(T_g - T_w) - \sigma \epsilon_w T_w^4 = 0 \qquad (3)$$

To utilize this equation, values of wire emissivity were selected from the literature and values of the heat transfer coefficient were estimated. This left gas temperature as the only unknown; hence a solution was reached.

A great deal of temperature measurement was attempted, (Cf. Refs. 1, 2, and 6). Basically the experimental data, while accurate, was open to some question for two reasons: First, the emissivities of the wires were of uncertain constancy, particularly for flame conditions in the case of oxidizable wires (chromel and alumel are examples of such wires). Second, and of major importance here, was the use of an estimate of the value of the heat transfer coefficient h. The assumptions in defining the value of h for a mixture of flame gases and their dissociation products could be in considerable error, resulting in a corresponding error in the calculated value of flame temperature.

It was then decided to measure temperature by electrically heating a length of platinum wire in an isothermal region of the flame and noting its electrical resistance and heat balance. This gave promise because the temperature-resistivity characteristics of platinum are well-defined and a reasonable measurement of wire emissivity could be made separately.

Equations (1), (2), and (3) above, modified for electrical heating were applicable to platinum. Resistivity here was measured by a Kelvin Bridge. The size of the isothermal region of the flame (Fig. 1) permitted utilizing a considerable length of the platinum wire, thus aiding the accuracy of the measurement. This method, it will be shown, overcomes the basic disadvantages of the thermocouple.

Heat addition modified equation (2) in its unintegrated form, viz:

$$\pi\, dx \left[hd(T_g - T_w) - \sigma \epsilon_w d T_w^4 \right] + Q = 0 \qquad (4)$$

where Q is the heat added by the electrical power. Considering a finite length and dividing by $\pi \ell d$

$$h(T_g - T_w) - \sigma \epsilon_w T_w^4 + \frac{Q}{\pi \ell\, d} = 0 \qquad (5)$$

In evaluating Q it was necessary to take into account the linear expansion of the wire (Fig. 2). This expansion increased the length and reduced the power thus making the last term

$$\frac{I^2 R}{\pi f^2 \ell d}$$

where

f = ratio of the heated length to length at standard conditions

I = wire current

R = resistance of the length of wire between potential leads

To match this term with the remainder of the equation its units were altered as follows:

$$\frac{I^2R \text{ watts}}{\pi f^2 \ell d \text{ in}^2} \times \frac{1 \text{ Btu/min}}{17.58 \text{ watts}} \times \frac{60 \text{ min}}{1 \text{ hr}} \times \frac{144 \text{ in}^2}{1 \text{ ft}^2} = \frac{156.44\, I^2R}{f^2 \ell d} \; \frac{\text{Btu}}{\text{hr ft}^2}$$

Hence

$$h(T_g - T_w) - \sigma \epsilon_w T_w^4 + \frac{156.44\, I^2 R}{f^2 d\, \ell} = 0 \qquad (6)$$

T_w was measured from the calibrated resistivity of the platinum wire. The unknowns were thus reduced to T_g, h, and ϵ_w.

To determine ϵ_w the platinum wire was heated in an evacuated bell jar to be later described. Equation (6) with the first term equal to zero applied to this case since the jar was evacuated and there was no heat loss to gas. It was thus possible to solve for emissivity

$$\epsilon_w = \frac{156.44\ I^2R}{f^2 d \ell \sigma T_w^4} \tag{7}$$

With emissivity determined, equation (6) was evaluated as follows:

Let $\sigma\epsilon_w T_w^4 = \bar{E}$

and $\dfrac{156.44\ I^2R}{f^2 d \ell} = \bar{P}$

then $h(T_g - T_w) = \bar{E} - \bar{P}$

Plot $\bar{E} - \bar{P}$ versus T_w

It was then obvious that

$$T_g = T_w \text{ when } \bar{E} - \bar{P} = 0$$

or the intersection of the curve with the abscissa gave the true gas temperature. The slope of the curve equals the heat coefficient h if h is practically constant over the temperature of extrapolation.

By this time the number of operations and chances of error had grown immensely. It was decided then to verify the results by repeating the procedure on wire specimens of a different size. Specimens furnished for use in this investigation included a wire of less than highest purity. Although it was not known whether or not significant changes could be detected, this specimen was included in the study.

A comparison of results then lay in the matching of abscissa intercepts in the $\bar{E} - \bar{P}$ vs T_w plot.

In addition, in each test, the values of the thermal conductivity of the gas film k_f (Btu/hr ft °R) should be about equal. The value of k_f (Cf. Ref. 8) may be given by

$$k_f = \frac{dh}{\left[0.32 + 0.43\,(Re)^{0.52}\right]} \tag{8}$$

Hence a check was

$$\frac{kf_1}{kf_2} = \frac{h_1 d_1\left[0.32 + 0.43\,(Re_2)^{0.52}\right]}{h_2 d_2\left[0.32 + 0.43\,(Re_1)^{0.52}\right]} \tag{9}$$

The value of equation (9) should be about unity.

IV. MEASUREMENT APPARATUS

Temperature measurement components are treated in this section. Most of the elements are shown in their electrical configuration in Figure 3; more detailed sketches were prepared to illustrate points of particular interest.

Control Panel - To better correlate and control the apparatus elements during testing,a control panel was fabricated. The following elements yet to be discussed were incorporated:

1. Variable resistors of the inverter output circuit
2. Kelvin Bridge decades
3. Galvanometer switches
4. Standard resistor switches
5. The current measuring circuit
6. Kelvin Bridge reversing unit

Rectifier - This device takes the standard 230 volt, 60 cycle, 3 phase alternating current from the laboratory supply lines and changes it to 28 volt direct current. It has a variable output and this output is adjusted as indicated below after each change of the variable resistors in the inverter alternating current output circuit.

Batteries - Four 6 volt batteries in series are connected in parallel with the rectifier output. They serve a unique purpose. The laboratory electrical supply undergoes small fluctuations in value. For ordinary purposes these are of no consequence but for testing they would give unsteady data. Hence in testing, the rectifier is set at each datumpoint so that the batteries only slightly discharge. This assists in smoothing out the current.

Inverter - This changes the direct current to 115 volt 400 cycle alternating current. Its output to the transformer is controlled by four variable resistors installed in the control panel for direct use. It was found necessary in operation to cool these resistors by means of a fan. The voltage not dissipated in the resistors is lowered in a 4:1 stepdown transformer for use in heating the platinum wire.

Kelvin Bridge - A standard Kelvin Bridge is used to measure the various resistivities of the platinum wire. Five decades are used with individual resistance changes in each having the values of 1, 10, 100, 1000, and 10000 ohms respectively. The bridge measures the ratio of the platinum wire resistance to that of the standard resistor. The galvanometer used in connection with the bridge has two sensitivities and is equipped with two separate opening switches to prevent inadvertant damage. Direct current voltage for balancing the bridge is secured from a single 6 volt battery and is superimposed on the alternating current. This battery's current is limited by a series resistance and a parallel resistance so that the direct current is less than one ampere. In spite of all precautions it was found early in the experimentation that a slight difference of bridge reading occurred when the wiring to the bridge battery was reversed. This was, of course, due to very small emfs in the bridge, later shown to lie mostly in the standard resistor. In one case they added to the voltage of their side of the circuit and in the other case they subtracted from it. In most cases the variation was limited to the fourth significant figure and utilizing the average of the readings taken both ways was justified. A double pole double throw switch permits quick reversal of the leads and all other measurements were checked constant while the bridge readings were being taken.

Standard Resistor - This resistor was constructed from a length of Advance (Manganin) wire wound onto an insulated core. It is surrounded by an open-ended iron cylinder of considerable thickness with an air space in between. The core stood upright and air at 100 psi gage was fed into the bottom to keep the equilibrium temperature cool. The total resistance is 0.5128 ohms. Taps (not shown in Fig. 3) go off the standard at 0.1952 ohms and at 0.03872 ohms for sundry uses with resulting different sensitivities. A by-pass switch can essentially remove the standard from the current load during all night outgassing processes (to be later described) and put it back into the circuit for making measurements. At all points where Advance wire is joined to copper the junctions are immersed in oil to minimize thermocouple effects.

To calibrate the standard a 1.0002 ohm Rubicon resistor is used. The potential circuit to the platinum specimens is broken at X--X (Fig. 3) and leads to the one ohm standard inserted there. A switching device incorporated into the bridge reverses the internal bridge arms. This permits the standard resistor to be used as the unknown for matching it against the 1.0002 ohm laboratory standard.

Current Measuring Device - Here a constant output of a vacuum thermocouple is maintained by varying the resistance of a helipot. That it indicates current is shown by the following calibration technique: Varying direct current voltages are placed on $\overline{CD}$ in Figure 3.

To accurately determine this voltage a voltage divider circuit is utilized at $\overline{AB}$ measuring the drop across the 100.13 ohm resistor by a Leeds and Northrup potentiometer. This value multiplied by the ratio of the total resistance of this circuit (25100.13) to 100.13 ohms gives the voltage across $\overline{AB}$. All current but the minute measuring current passes through the standard resistor. Platinum wire resistance is shorted out at Y—Y. Hence the current is defined since the voltage and the standard resistance are known. The measuring current which is a constant minute portion of the main current passes through a helipot, resistors, and a vacuum thermocouple. The helipot is roughly set by adjusting so that the current in this branch of the circuit measures about 23 μa. Then the ammeter is cut out of the circuit and the helipot slightly adjusted as necessary to give exactly 2.2 mv., measured by a Leeds and Northrup potentiometer as a fiduciary calibration voltage. This then gives a duo-dial setting for each current. Therefore, in running the investigations, merely the duo-dial reading is recorded.

The calibration curve for the current measuring circuit is shown in Figure 4 and is a straight line because the resistance of the helipot is a straight line function of the dial setting. When the upper limit of the range is reached (due to all helipot resistance being out) a series resistor is then introduced (Fig. 3), shifting the calibration a constant amount and thus covering a higher portion of the test range. The helipot has a 0.1 per cent linearity making only one division of the one thousand of the duo-dial scale significant, although it can be read to one-half a division. Hence a much larger scale curve than Figure 4 was used as the working calibration chart in conducting the investigation. The critical nature of the current in the equations necessitated it and the reproducibility of the calibration data justified it.

Platinum Wire and Mountings - The following specimens of platinum wire were used in these investigations:

Number	Length	Diameter (nominal)	Grade (Cf. Ref. 9)	0°C Resistivity
I	8"	0.045"	Rerefined III	9.92 $\mu\Omega$-cm
II	10"	0.045"	I	9.86 $\mu\Omega$-cm
III	10"	0.020"	I	9.86 $\mu\Omega$-cm

Each was mounted in the bell jar for emissivity measurements and in the chamber for temperature measurements. When in the chamber an average length of 1.5 inches was taken between potential leads on the specimen to utilize the isothermal region of the flame and attain the better accuracy accompanying increased length. Potential leads were 5 mil platinum wire of laboratory purity.

It was absolutely necessary in mounting to put no tension on the wire. When heated, platinum has low strength and would draw out to a lower diameter. On the other hand, a firm contact had to be made on the wire so that up to thirty amperes of current could be conducted through the junction on each side. This created another problem. The firm contact caused buckling of the wire when it was heated. This led to the trial of a number of configurations. Most of these were rejected as having one or more drawbacks. The design finally settled upon was the spread U-shape as shown in Figure 1. The elbows here were in the section of the flame just inside the duct lip. This has several advantages. Conduction to and from the measured section between the potential leads was negligible. There was give in the elbows to permit expansion in heating with no buckling. There remained enough strength in the wire to keep it from sagging, thus retaining the measured section in an isothermal region.

The fork-shaped mountings for the wire were insulated from each other in all the structural sections, thus confining the heating current to the platinum test specimen and the measuring current to the potential leads. Mounting was an easy matter by simply setting the wire into the grooves in the end fittings of the forked conductors and locking them with screws. Potential leads were tweezer-welded and led via (yet insulated from) a structural shaft, thence through a ceramic-metal tube that was O-ring pressure sealed, out of the combustion chamber. Where attached outside the combustion chamber to copper, leads were immersed in oil to minimize thermocouple effects. The heating leads were similarly lead out an insulated pressure sealed tube. The entire assembly was made movable from the outside of the chamber by a simple linkage (Fig. 1), one motion of in-out translation and one of rotational motion about an axis parallel to the long dimension of the duct. In this way the wire could be placed at any position desired above the duct. To accurately map the position a cathetometer was used sighting the wire through the rear windows of the combustion chamber.

<u>Bell Jar</u> - The wire here was mounted in a fork assembly similar to that for the combustion chamber but vertical and not movable (Fig. 5).

Potential leads were fastened over lengths of the specimen up to three inches. The mount itself was fastened to the circular platform set in the opening of the top end of the inverted bell jar. Potential leads and heating leads were secured in the platform and led out of it by suitable fittings. All of these fittings as well as the assembly itself were sealed on the outside by de Khotinsky cement and beeswax. As from the chamber, suitable wiring led to the electrical devices used. Outside, fittings and wax were protected against heat by a cooling fan.

An evacuation tube led from the bell jar to the evacuation pump and diffuser pump used here to lower the pressure down to 10^{-5} mm. Hg abs. at temperatures in the lower range. Pressures were slightly higher in the higher temperature level. A mercury switch automatically cut out the diffuser pump when the pressure went over 100 microns and thus prevented damage. Pressure in the system was measured by means of a McLeod gage.

In all of the connections of dissimilar metals here, the junctions were immersed in an oil bath to minimize the thermocouple effects.

<u>Emissivity Calibration</u> - To prepare for emissivity measurements it was necessary to outgas the bell jar for long periods. Some heat was provided by running alternating current through the platinum wire specimen. Additional heat was furnished for this purpose by an external electrical heating wire wound with many turns around the outside of the bell jar. All the while the outgassing process was being carried on, the standard resistor was shorted out; this obviated the necessity for compressed cooling air over such long periods.

Data taken for the determination of emissivity characteristics included pressure, duo-dial reading (hence current), and the Kelvin Bridge readings. Data were reduced utilizing equation (7). Then a semi-log plot was made of emissivity versus pressure for each temperature, with pressure plotted on the logarithm scale. Pressure limits were 1×10^{-5} to 11×10^{-3} mm. Hg absolute. A lower asymptotic limit was determined for each temperature. With this data Figure 6 was constructed showing emissivity as a function of temperature.

Although there was some emissivity variation in the lower temperature range shown, this was unimportant here since the lowest chamber reading was 1321°C. In the range used the emissivity of the rerefined commercial grade wire was higher than that of the purer wire by six to twelve per cent. This may have resulted from the type of die or the impurities causing drawing to expose a surface of larger relative area. Undoubtedly the impurities, whatever they were, individually gave higher emissivity and affected the results.

The slight variation noted between the two wires of laboratory purity showed the effect of size, the smaller wire having the higher emissivity.

<u>Switching of Chamber-Bell Jar Wiring</u> - Around the platinum wire in Figure 3 is shown a dashed circle. This physically represents the combustion chamber or the emissivity bell jar. Each occupied the same position in the circuit. To physically change them it was necessary only to break the circuit at X--X for the potential leads, and at Y--Y for the heater leads, and insert the opposite elements. A double pole, double throw switch enabled the heating circuits to be shifted rapidly.

A pronged plug contact was easily switched to change the potential leads back and forth.

Platinum Wire Calibration - Although the well-defined relation between temperature and resistivity in a platinum wire was noted it was necessary in this case to carefully investigate the relationship in order to attain accuracy of any degree. Accordingly reference 9 showed the purest grade I platinum wire for laboratories to have a 0°C. resistivity of $9.83\,\mu\Omega$-cm and a $(R_{100} - R_0)/100\,R_0$ of 0.00392/°C. Specimens II and III had 0°C. resistivities of $9.86\,\mu\Omega$-cm each. This was close enough to use a modified literature equation for the relationship, viz:

$$\rho_t = 9.86\,(1 + 3.9788 \times 10^{-3}\,t - 5.88 \times 10^{-7}\,t^2)\,\mu\Omega\text{-cm}$$

In the case of the rerefined grade III 0.045" wire the 0°C. resistivity was higher and this demanded a special calibration. Accordingly resistivity was checked at carefully set temperatures of melting ice, room temperature, and boiling water. Then the wire was immersed in an oil bath and the resistivity measured for various temperatures up to 200°C. Following that, the assembly was placed in a powdered alumina bath held in a furnace. The alumina settled the tendency for the temperature to wander, a tendency that was very pronounced in cases where any air currents were allowed to come in contact with the wire at elevated temperatures. By this means resistivities were measured up to 650°C. Temperatures in this range were measured by two chromel-alumel thermocouples and by one platinum-rhodium thermocouple. From this data a second degree equation relating resistivity and temperature was calculated. All points found in the calibration were discovered to lie directly on the curve of this equation, viz:

$$\rho_t = \left[9.918 + 0.039188\ t - 5.3156 \times 10^{-6}\ t^2\right] \mu\Omega\text{-cm}$$

Accordingly extrapolation of this equation was justified to include the test range. It was noted that the slight deviations of grade III wire from the literature values for pure wires were in the correct direction, i.e., increased resistivity in correct proportions with slightly increased wire impurities.

The calibration curves are shown in Figure 7. Because of the critical nature of the temperature measurement in the equations , a curve of greater resolution than the graph shown was necessary in actual computations. Accordingly tables were constructed from the applicable equations giving resistivities for five degrée temperature intervals. The precise resistivity-temperature relationship made use of such tables justified.

A special technique was necessary in working with the 0.020" wire. Unlike the 0.045" wires whose ambient resistance remained constant from day to day, the 0.020" wire sustained a very, very small, yet definite, permanent elongation and resulting resistance increase each time an investigation run was made. To understand its effect recall that

$$R = \rho \frac{\ell}{A} \sim \frac{\ell}{d^2}$$

The equation of mass conservation for the wire gives

$$\ell d^2 = \text{constant}$$

Hence

$$\Delta\left[\frac{\ell}{d^2}\right] = \Delta\left[\frac{1}{d^4}\right] = \Delta\left[\ell^2\right]$$

It follows that when the length ℓ is increased by (say) one-half per cent, then d^2 decreases by one-half per cent (or d decreases by one-fourth per cent) and R goes up one per cent. Very small dimension changes of this amount cannot be readily detected during the day-to-day progress of the investigation except by the ambient resistance technique which is sensitive to these changes. This gives a method for one correction to the run data. In this investigation the dimensions of the 0.020" wire were first taken outside the chamber with optical assistance. Then the wire was installed for tests and the ambient resistance checked before and after each run. By this means it was possible to correct the resistivity and consequently the temperature data.

V. RESULTS AND DISCUSSION

Each platinum wire specimen was placed in the combustion chamber and the oxy-acetylene flame ignited. Chamber pressure during the test was 4.3 mm. Hg absolute; oxygen-acetylene mole ratio was 6.18 or 40 per cent of stoichiometric on the lean side. Reynolds numbers were 0.66 for the 0.045" wires and 0.29 for the 0.020" wire. With the platinum wire held 20.2 mm. above the duct lip varying amounts of current were run through the wire; duo-dial (current) and bridge (resistivity) readings were taken. This data was reduced with the aid of equation (6). The quantity $\bar{E} - \bar{P}$ was plotted in Figure 8 versus wire temperature.

The results were extrapolated as shown to the point of no radiation heat exchange or null point. This gave the gas temperature and the slope of each line gave the heat transfer coefficient. As noted in the theory the straight line extrapolation hinges on h varying insignificantly with T_w. Over the range of the actual experimental data this condition is fulfilled. Consequently it is assumed that further extension to the entire temperature range would probably result in only slight evidence of curvature, signifying variation of h with T_w. This observed fact is curious in that the value of h depends primarily upon the film conductivity, k_f. For a gas or gas mixture k_f would tend to increase with temperature. However in the case of a narrow film with one boundary at a fixed temperature T_g and the other at a varying but lower temperature T_w it is not unplausible that T_g is so predominant that k_f shows little change. At any rate we may conclude that, probably, the lack of significant concave downward curvature in the experimental ranges means little variation over the total range and the straight line extrapolation point will be high by an unimportant amount. The experimental errors are certainly greater than any effect of variation of h with T_w.

Both 0.045" specimens gave very close to the same results. Each had a slight increase of slope at the upper left end. Two reasons are furnished for this quite reproducible phenomenon of the larger wires. First, for these wires in the low temperature portion, the relatively short span can cause a conduction error. This error makes the wire emissivity look larger than actual. Second, the pressure-emissivity calibration data in the low temperature range for the larger wires did not reach to the lowest pressure points achieved for the other wire in the bell jar. The slight extrapolation to the lowest asymptotic emissivity level was taken conservatively and thus the emissivity here was very slightly high. The net result is that one expects final data in the lower portion of the wire temperature to be high if anything. Though this region is less important than the higher temperature region, it is worthwhile to note that the possible correction in this range will act to make the data more consistently a straight line than shown. These considerations provide justification for treating the data as in Figure 8.

Data on the 0.020" wire gave a flame temperature consistent with the other two within the limits of experimental accuracy. Note the short range of heating possible for the 0.020" wire. The low temperature point indicated the heat balance with no current flowing and was fairly close to the melting point of platinum. Hence only a small amount of current could be safely added. Greater resolving power could be attained if a metal of higher melting point and comparable good resistivity-temperature relationship could be used.

From equation (9) the slopes of the data in Figure 8 were used to calculate the film coefficient k_f. The values of k_f agreed within ten per cent and were 0.072 Btu/hr ft °F plus or minus five per cent. This value appears low based on the expectation of thermal contribution from atomic species in the equilibrium flame mixture.

Many runs were made in this investigation. Data plotted in Figure 8 is representative of these runs and is very reproducible. Note in the foregoing figure that the average of the flame temperatures obtained was 2223°C. The difference of this result from the calculated equilibrium flame temperature of 2208°C. is of the order of the experimental error, a value arrived at by the following considerations:

Measurement	Flame Temp. Error Caused by One Per Cent Measurement Error	Maximum Measurement Error This Investigation	Maximum Flame Temp. Error This Investigation
1. Emissivity	15 °C.	1 per cent	15 °C.
2. Current	30 °C	0.5 per cent	15 °C
3. Resistivity	120 °C	0.2 per cent	24 °C

The probable error is then $(15^2 + 15^2 + 24^2)^{\frac{1}{2}}$ or about 32°C.

The curves of Figure 6 representing the asymptotic limit with pressure of the emissivity-temperature relation make it clear why literature emissivity values could not be used. These latter values vary by as much as twenty-five per cent and would, if used, completely negate the results. Not only would this be true in the absolute value but the literature emissivity-temperature variation was sufficiently different from that found to render the finding of a flame temperature or film coefficient well nigh impossible.

Results obtained in this investigation were for a point in the flame of peak temperature. Care must be exercised to insure that measurements are not attempted in catalytic regions. The results in these cases would be dubious since attempts to traverse the flame in the high temperature gradient region indicated definite existence of surface effects on the platinum wire.

VI. CONCLUSIONS AND RECOMMENDATIONS

In this investigation it was necessary to make an auxiliary measurement of emissivity for each specimen used.

The results apparently showed a higher resolving power than obtained before by thermocouple techniques for measurement of temperature in the range tested. The temperature of the oxy-acetylene flame was determined to be 2223°C. plus or minus 30°C probable error.

Further problems must be overcome before this modified Schmidt Technique may be adaptable to regions of high temperature gradient or catalysis. It is recommended that further investigation of this type be made using wire suitable to the gradient region of the flame. Rhodium wire, although presenting a difficult calibration problem, permits heating to a temperature above 1900°C. Hence the extrapolation would be shorter. The question of its surface behavior remains although there are indications it may be suitable in this connection also. If Iridium wire of the proper size could be fabricated for potential leads and could be calibrated, it would permit heating beyond the null point of the Schmidt Method and give a more conclusive result.

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TABLE I

NOMENCLATURE

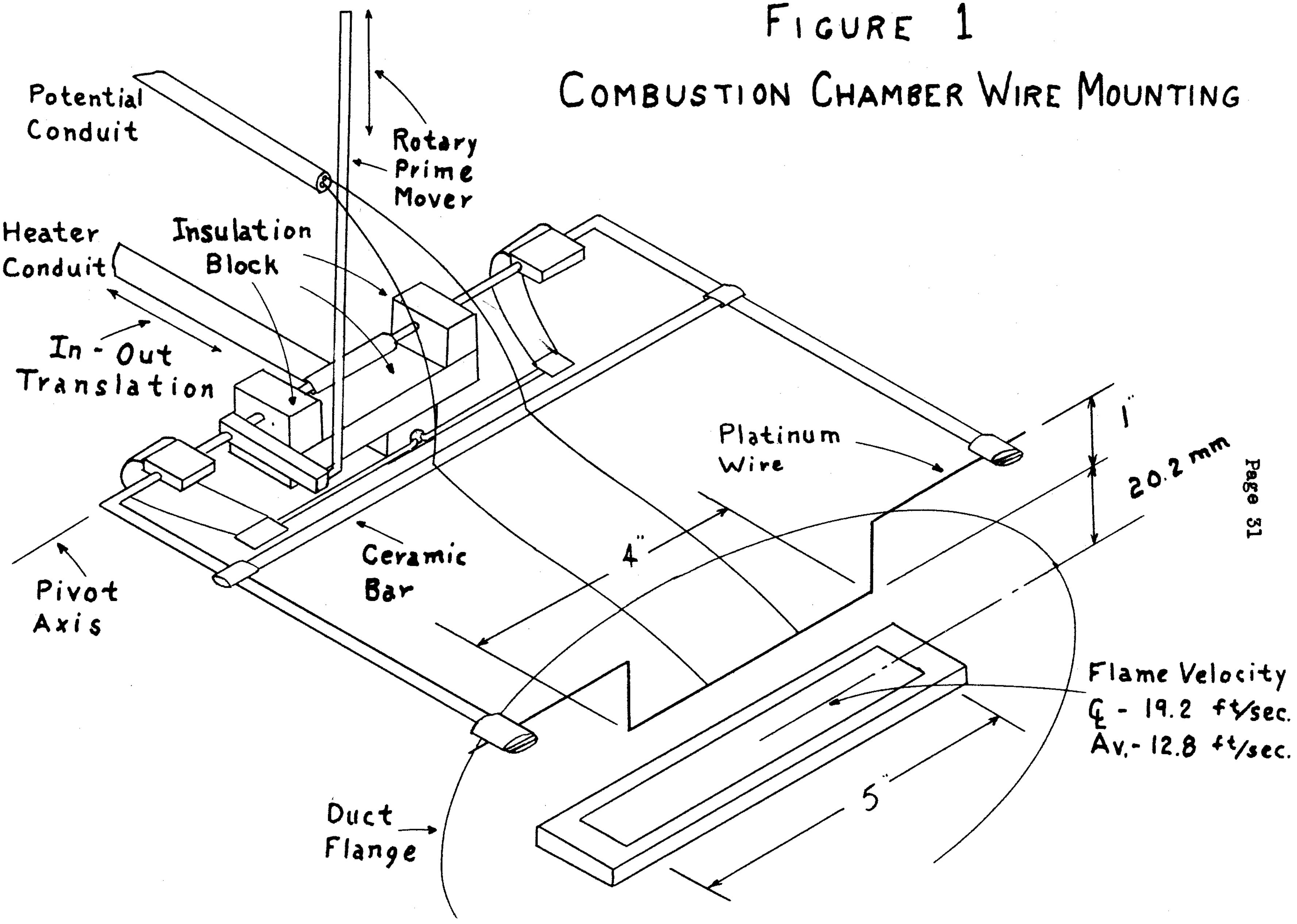
A	area
d	diameter
E	emissivity term (see equation 6)
f	ratio of heated length to length at standard conditions
h	heat transfer coefficient
I	current
k_f	thermal conductivity of gas film
K	wire conductivity
ℓ	length
P	power term (see equation 6)
q	extraneous thermal effects
Q	electrical heat addition
R	resistance
Re	Reynolds number
T, t	temperature
T_g	gas temperature
T'_g	effective average gas temperature for radiation
T_s	temperature of surrounding surface
T_w	thermocouple or wire temperature
x	unit of length
dx	elemental unit of length

TABLE I (Continued)

α_g'	effective gas absorptivity
Δ	a small change
ϵ_g'	effective gas emissivity
ϵ_w	emissivity of wire
μ	fraction 10^{-6}
ρ	resistivity
ρ_t	resistivity at temperature t
σ	radiation constant
Ω	ohm-unit of resistance

FIGURE 1

COMBUSTION CHAMBER WIRE MOUNTING



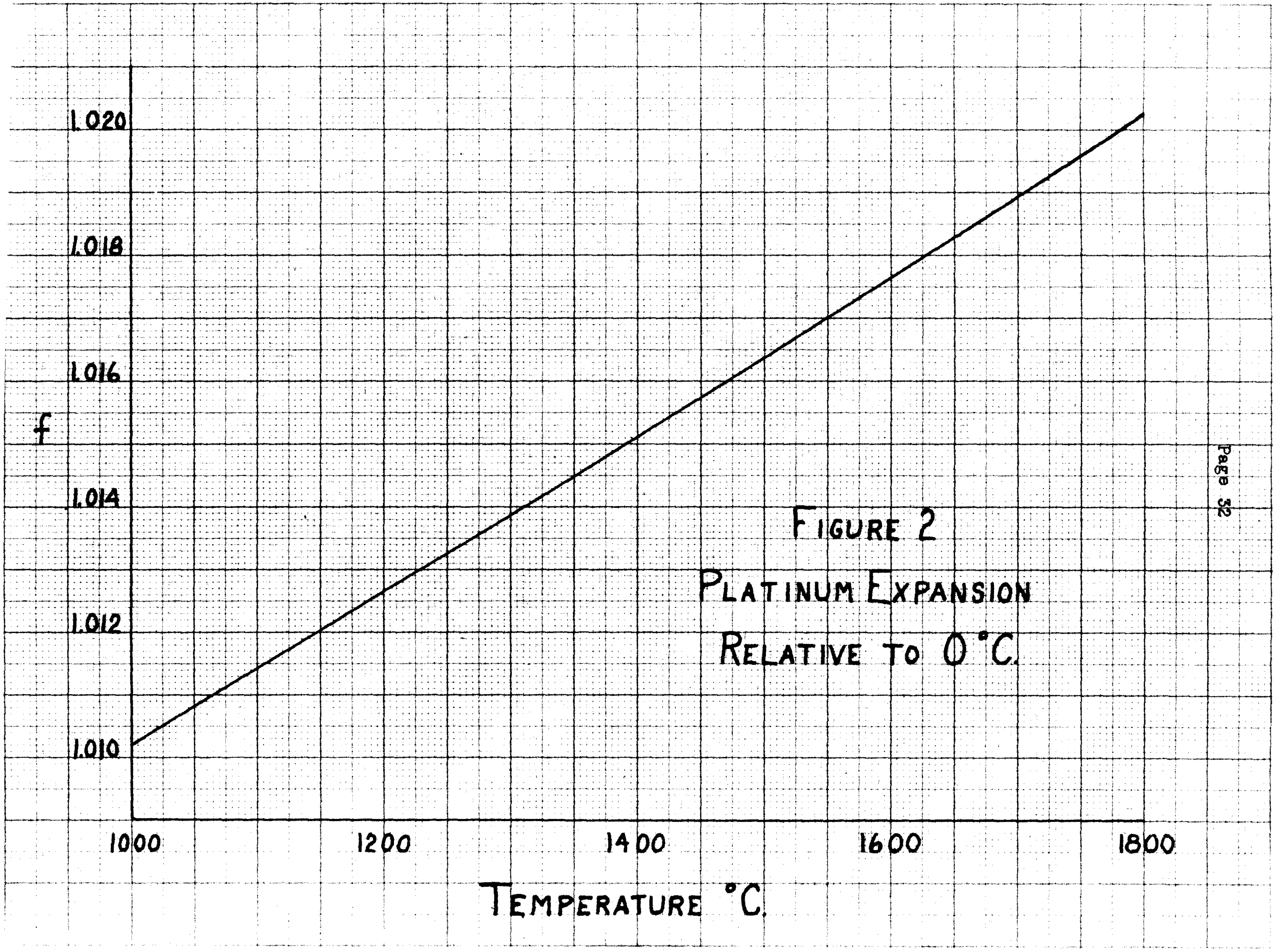
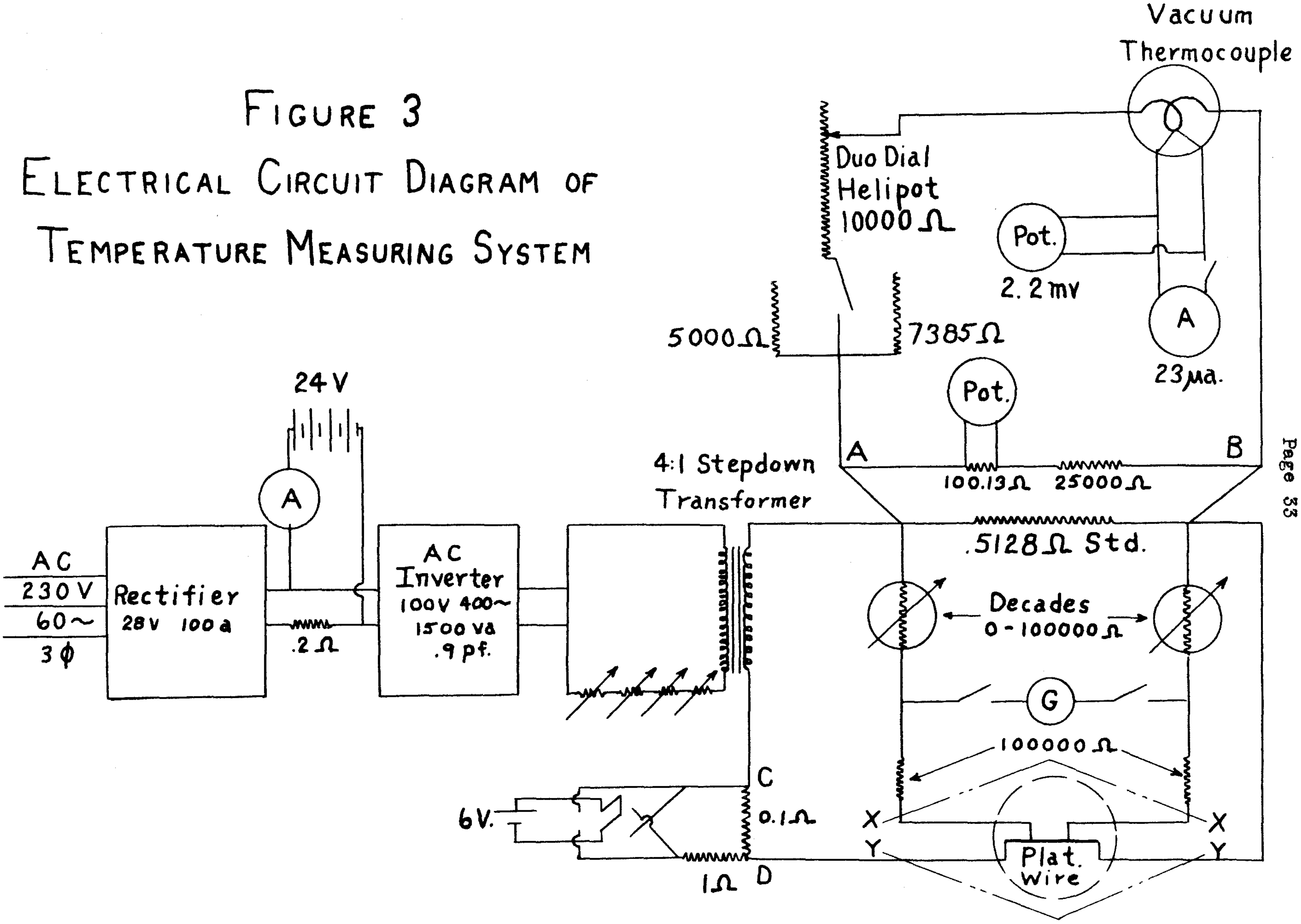


Figure 2
Platinum Expansion
Relative to 0°C.

FIGURE 3

ELECTRICAL CIRCUIT DIAGRAM OF TEMPERATURE MEASURING SYSTEM



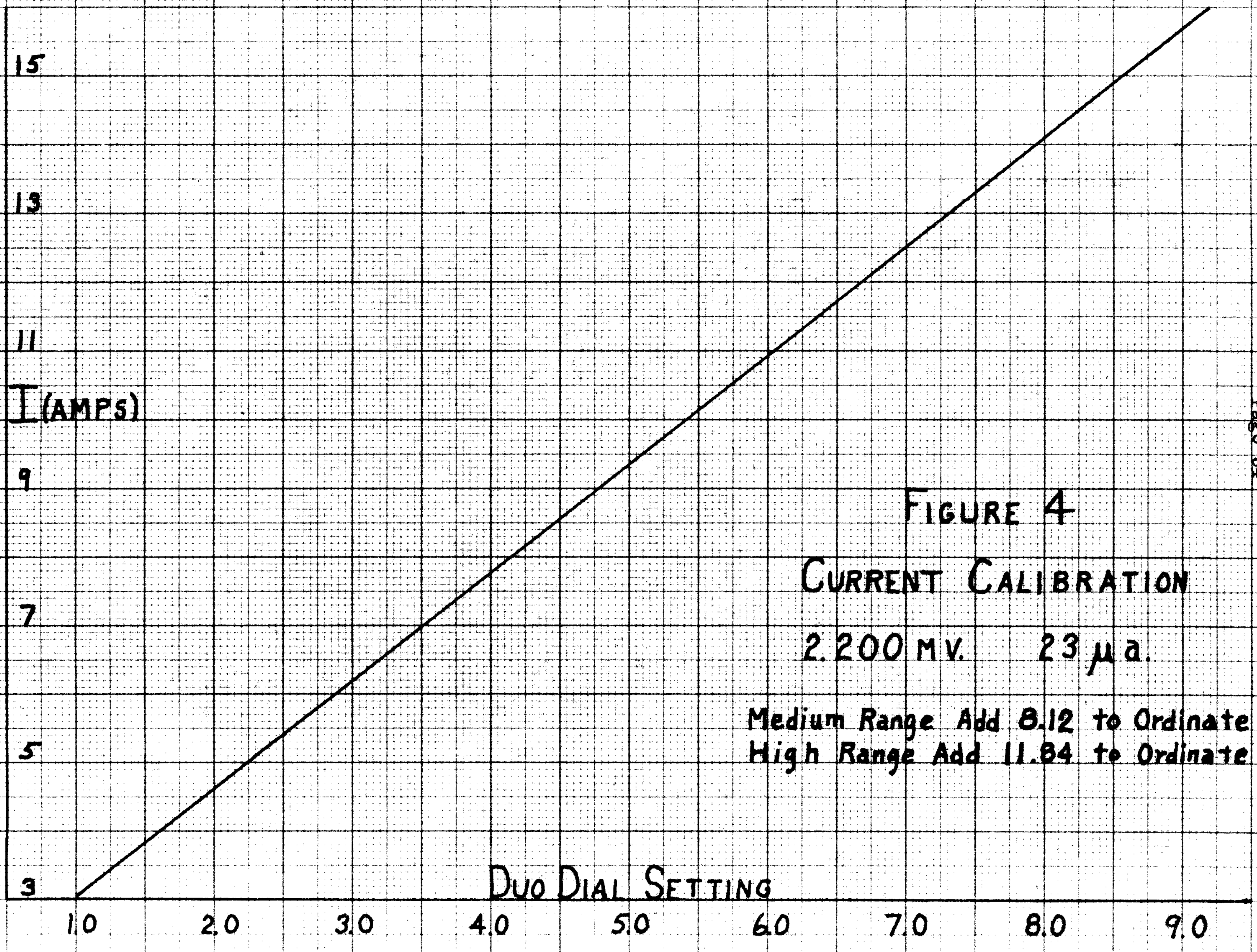


FIGURE 4

CURRENT CALIBRATION

2.200 MV. 23 μa.

Medium Range Add 8.12 to Ordinate
High Range Add 11.84 to Ordinate

FIGURE 5

EMISSIVITY BELL JAR CONFIGURATION

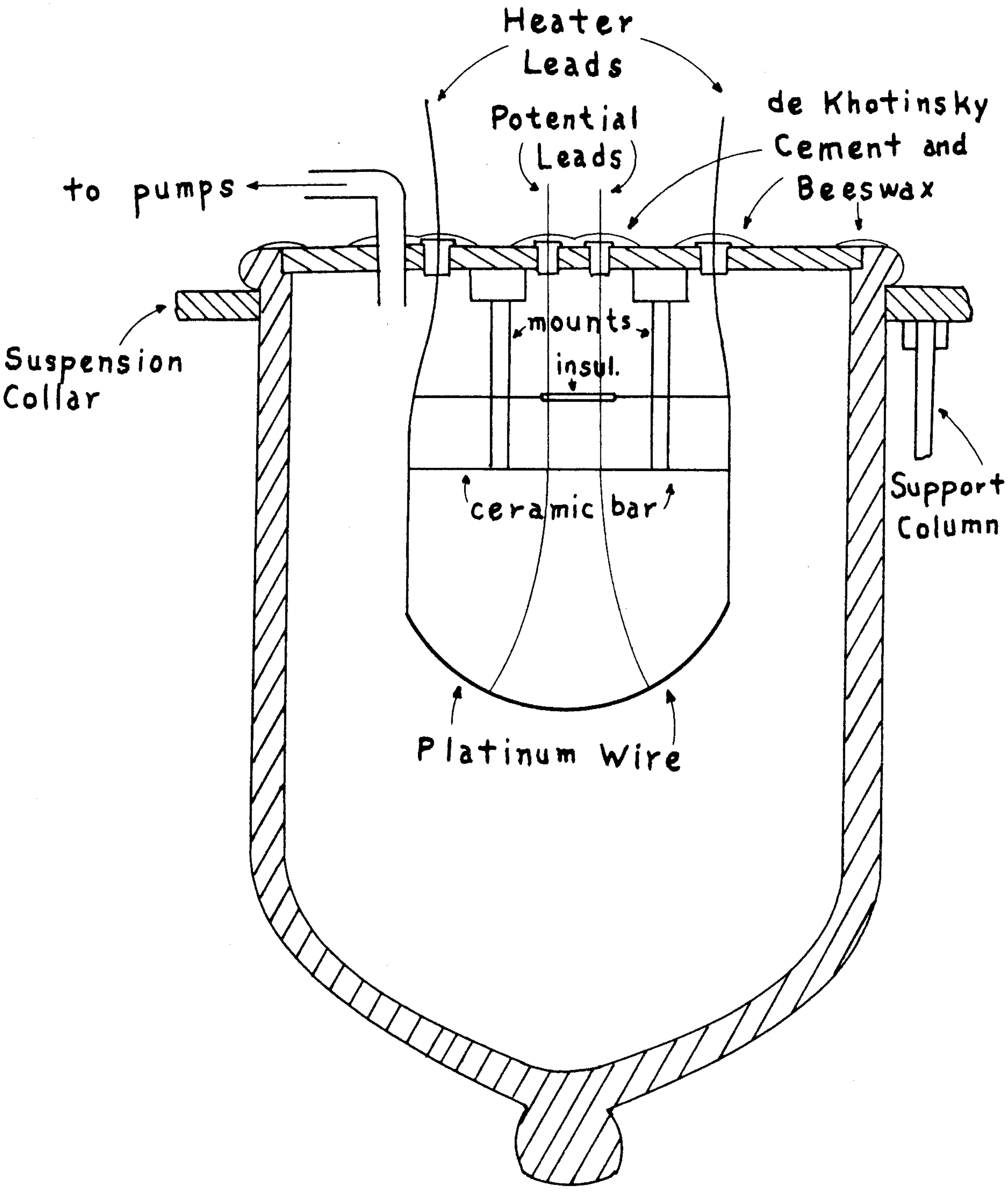
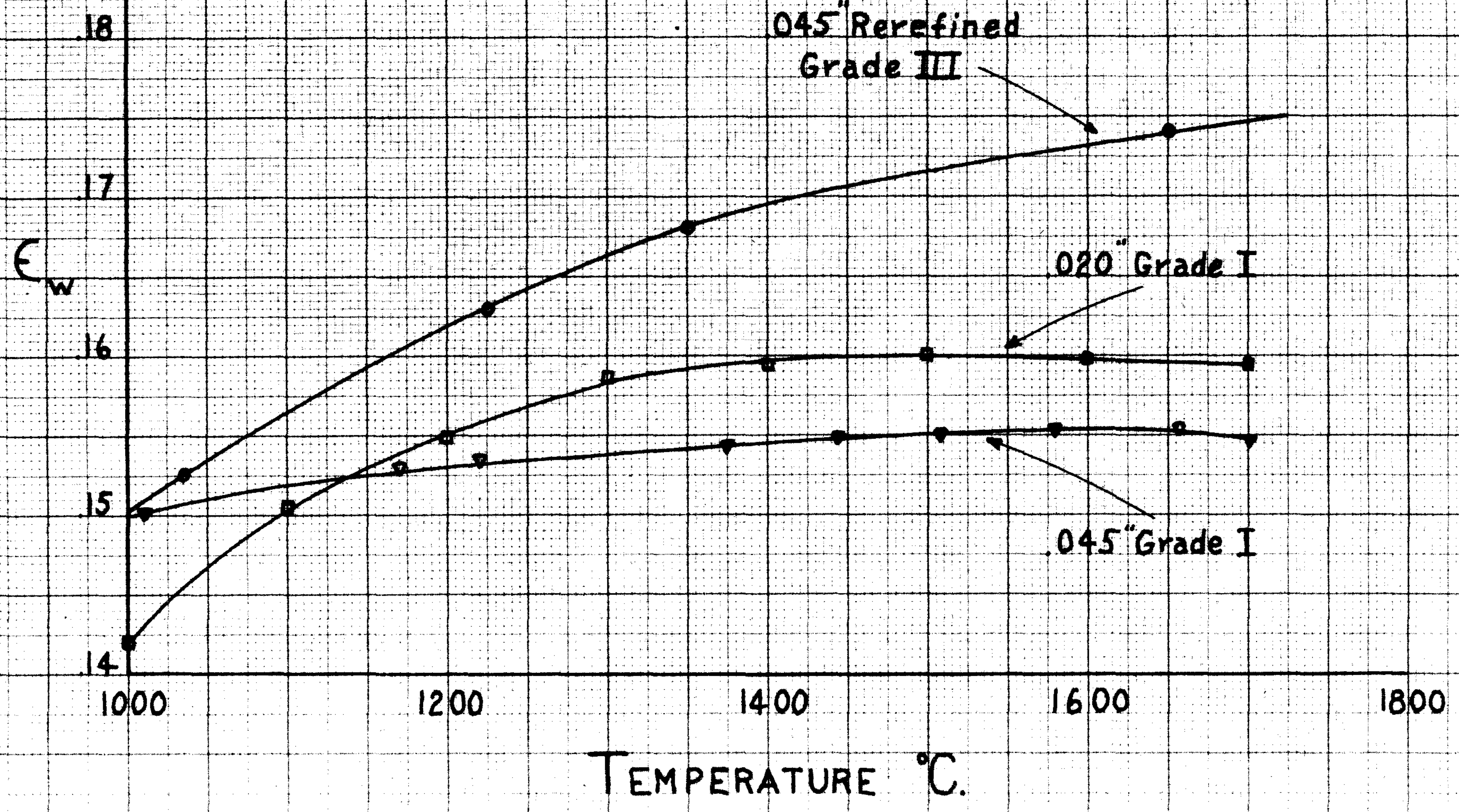


FIGURE 6

EMISSIVITY CHARACTERISTICS

PLATINUM WIRE SPECIMENS



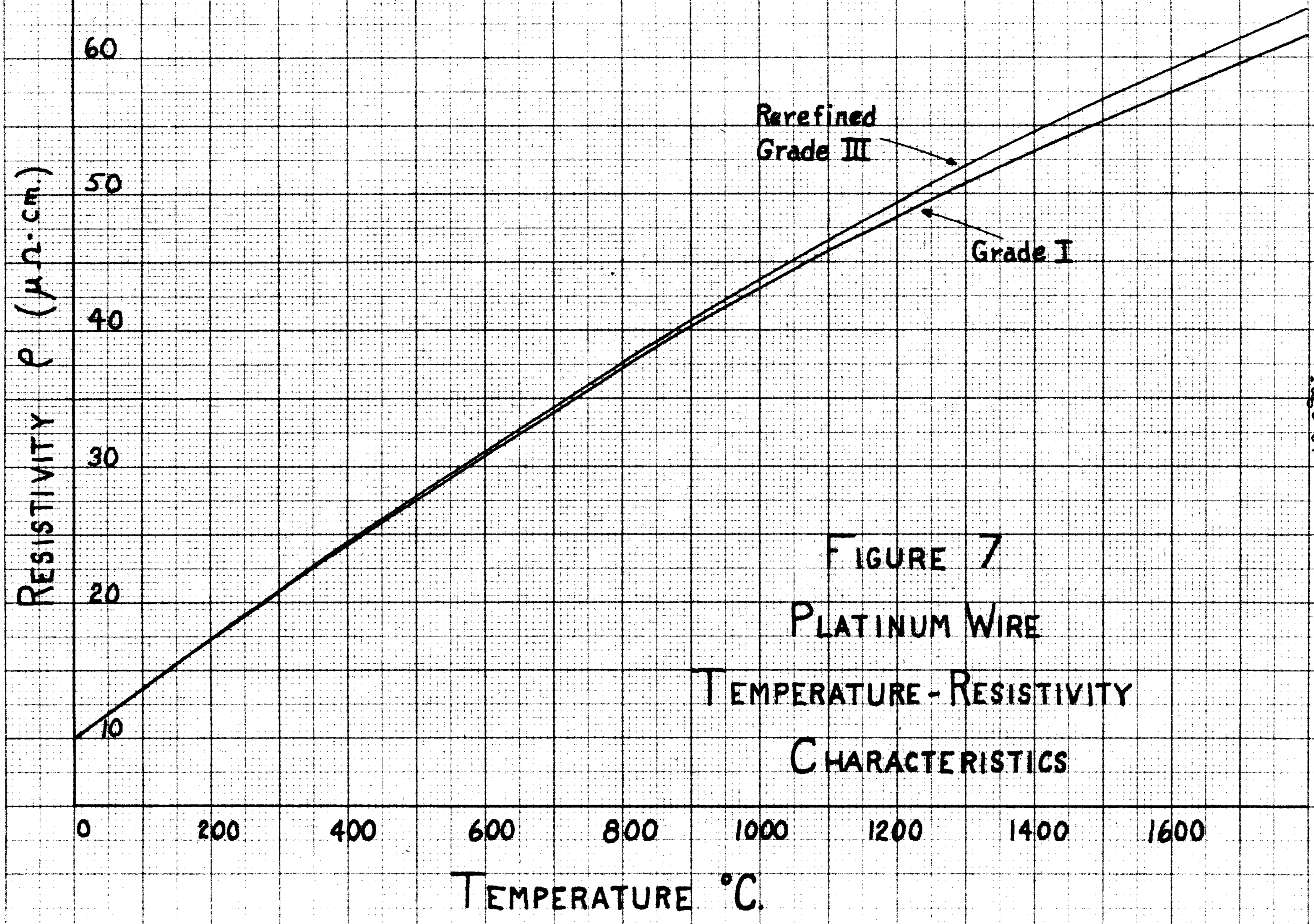


FIGURE 7
PLATINUM WIRE
TEMPERATURE - RESISTIVITY
CHARACTERISTICS

FIGURE 8

PLATINUM WIRE

TEMPERATURE VARIATION WITH ELECTRICAL HEATING