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Influence of transient radiation properties upon heating rates

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INFLUENCE OF TRANSIENT RADIATION

PROPERTIES UPON HEATING RATES

by

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Master of Science

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1965

CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

18 May 1965
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Date

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Professor in Charge

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Head of the Department

ii

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

v

ABSTRACT

When an object is heated by infrared radiation an expression relating temperature and time can be derived using the Stefan-Boltzmann relationship. Such an expression must include a quantity which measures the radiation properties of the object. The parameter generally used is "emittance" and it is usually assumed to be constant over the temperature range of interest.

In fact, it is unlikely that the radiation properties are constant over the temperature range of interest. To accurately predict heating rates, it is necessary to know how these transient properties vary as a function of temperature.

This paper shows that the radiation properties of copper change drastically with temperature and they are influenced by environment, heating rate and initial surface condition. An approach is developed which takes into account the transient radiation properties when calculating heating rates. Failure to take this variation into account can cause errors as large as 175%.

1

INTRODUCTION

The radiation properties of materials have an important influence in many applications. Emittance is of most concern when heat loss from an object is considered, as when measuring the temperature of a body using a radiation pyrometer (1), and when calculating heat losses from the work during induction heating (2). Absorptance is the property describing the ability of a material to absorb impinging radiant energy. A high value of absorptance would be desirable for the tubes in a boiler for example.

When focused infrared energy is used to heat an object, both absorptance and emittance of the object are important factors. Equations relating time and temperature of the target include a parameter describing these radiation properties. The effect which the parameter has on the heating curves is illustrated in Figure 3 showing three specimens heated under identical conditions but having different initial surface finishes. The radiation properties of a specimen vary with temperature and extent of oxidation and this must be taken into consideration for accurate calculation of heating rates.

There is some data showing how the emittance of a material with a specified surface finish will vary with temperature (3,4,5). However, heating with focused infrared is usually a high speed operation involving a rapid temperature change and in many cases a surface change due to oxidation. Because of the high heating rate, the surface at a particular temperature cannot be assumed to be the same as a surface oxidized at that temperature for a long period of time as often reported in the literature.

2

The book by Trinks and Mawhinney (6) develops the use of heat transfer equations to calculate heating rates. The very useful equations, charts, and curves described in this text represent what is probably the most generally used approach to the problem of calculating heating rates. However, they are based on the work piece behaving like a gray body with constant emittance and specific heat over a temperature range. These assumptions will introduce errors.

It is the purpose of this paper to show that although the radiation properties of copper change greatly when heated in air, an equation can be used to predict heating rates in a focused infrared system.

THEORY

In general, when any two surfaces exchange energy by virtue of their temperature difference the processes of convection, conduction and radiation are involved. As the temperature difference increases, radiant transfer becomes the predominant mode.

The use of high temperature enclosures to heat an object is a familiar operation relying primarily on heat transfer by diffuse radiation. Recently, the use of focused infrared energy has been developed to an advanced state (7). This system consists of a quartz iodine lamp for an energy source and an ellipsoidal reflector to concentrate the energy on the target as shown schematically in Figure 1.

For the following analysis, define the total emittance as the ratio of the power a body will emit at a given temperature to the power a black body of the same size will emit at the same temperature. Total absorptance is the ratio of the power a body will absorb to the incident power. A gray body has a spectral absorptance which is independent of the wavelength of the incident radiation. A non-gray body has a spectral absorptance which is dependent on the wavelength of the incident radiation and therefore the total absorptance is dependent on the quality of the incident radiation. The spectral absorptance of polished copper increases sharply at wavelengths less than 6000Å and therefore cannot be considered a gray body.

When radiant heat is focused on a specimen an analysis can be developed using the following symbols.

A = Surface area of the specimen in cm^2

T = Temperature of the specimen in $°K$

P = Net power absorbed by specimen in cal/sec.

t = Time elapsed in seconds

c = Specific heat at constant pressure in cal/mole-deg.

n = Weight of specimen in moles

a = Total absorptance of the specimen

e = Total emittance of the specimen

K = Power striking specimen in cal/sec.

σ = Stefan-Boltzmann Constant =

$$13.62 \times 10^{-13} \text{ cal/cm}^2\text{-sec-}^\circ K^4$$

The temperature rise of the specimen is the net energy absorbed divided by the specific heat and the weight.

$$dT = \frac{Pdt}{cn} \tag{1}$$

The net power absorbed is the energy absorbed less the energy radiated by the specimen according to the Stefan-Boltzmann equation.

$$P = a K - e A \sigma T^4 \tag{2}$$

For a gray body, the total absorptance is equal to the total emittance.

$$a = e \tag{3}$$

Combining equations (1), (2) and (3) and solving for "e" we have:

$$e = \frac{cn}{K - A\sigma T^4} \quad \frac{dT}{dt} \tag{4}$$

As already described, however, copper like most materials is not a gray body and the value of "e" from equation (4) will be a function of "e" and "a" but somewhat different from either. To avoid confusion, a new term called the radiation factor "f" will be defined:

$$f = \frac{cn}{K - A_\sigma T^4} \frac{dT}{dt} \tag{5}$$

If a specimen is heated and the temperature versus time curve recorded, then all quantities on the right side of equation (5) are known. dT/dt is the slope of the temperature versus time curve and c is the specific heat of copper as reported in (8):

$$c = 5.41 + 1.5 \times 10^{-3} T \quad \text{(cal./mole-deg.)}$$

The power impinging on the specimen is determined by multiplying the power input to the lamp by the efficiencies of the lamp, reflector, quartz tube, and size of the specimen compared to the size of the focused spot. The overall efficiency for the system used in this investigation was found to be 43% for a 3/8 inch diameter specimen and 50% for a 1/2 inch diameter specimen. Thus, equation (5) provides the means for determining to what extent the radiation factor changes as a function of temperature.

The next step in this analysis is to solve equation (5) for dt.

$$dt = \frac{cn \, dT}{f(K - A_\sigma T^4)} \tag{6}$$

Integrating equation (6) provides an expression for the time to reach a temperature T from $298^\circ K$. Also, assuming for the moment that c and "f" are constant:

$$t = \frac{nc}{f} \int_{298}^{T} \frac{dT}{K - A_\sigma T^4} \tag{7}$$

$$t = \left(\frac{c}{f}\right) \frac{n}{2K \left[\frac{A_\sigma}{K}\right]^{\frac{1}{4}}} \left[\tan^{-1} \left(\frac{A_\sigma}{K}\right)^{\frac{1}{4}} T + \tanh^{-1} \left(\frac{A_\sigma}{K}\right)^{\frac{1}{4}} T \right]_{298}^{T} \tag{8}$$

6

It is known that c is not a constant and it will be shown that "f" varies considerably. Therefore, c/f must be an effective value dependent on the path followed by the specimen during heating. Define "F" to be the effective value of f/c and rewrite equation (8).

$$t = \left(\frac{n}{F}\right) \ \frac{1}{2K \left(\frac{A\sigma}{K}\right)^{\frac{1}{4}}} \ \left[\tan^{-1}\left(\frac{A\sigma}{K}\right)^{\frac{1}{4}} T + \tanh^{-1}\left(\frac{A\sigma}{K}\right)^{\frac{1}{4}} T \right]_{298}^{T} \qquad (9)$$

To use equation (9) to predict the time t to reach a temperature T it is necessary to know how "F" changes with T. This relationship can be established by solving equation (9) for "F":

$$F = \left(\frac{n}{t}\right) \ \frac{1}{2K \left(\frac{A\sigma}{K}\right)^{\frac{1}{4}}} \ \left[\tan^{-1}\left(\frac{A\sigma}{K}\right)^{\frac{1}{4}} T + \tanh^{-1}\left(\frac{A\sigma}{K}\right)^{\frac{1}{4}} T \right]_{298}^{T} \qquad (10)$$

The parameters from a particular test can be inserted into the equation to find "F" at corresponding values of T. From this information, a curve of "F" versus T can be plotted. This function and equation (9) can be used to predict the heating curve for different size specimens for any power input but under the same conditions of material, initial surface finish and atmosphere. Strictly speaking, the initial surface finish should be evaluated on the basis of radiation factor using a power source of the same spectral energy distribution as will be used in the heating operation. This would avoid errors caused by the surface not acting as a gray body.

There is a small change in the radiation properties of copper purely by virtue of temperature change (9). However, the largest change results from formation of oxides on the surface. The formation of oxides on copper has been intensively studied. Lustman and Mehl (10)

7

discuss the initial formation of oxides on copper. This initial oxide, or temper film, consists entirely of cuprous oxide until the thickness exceeds $400\overset{o}{A}$. During this time, the increase in thickness is proportional to the logarithm of time.

Pilling and Bedworth (11) performed their classical tests on copper at elevated temperatures and showed that the increase in thickness of the oxide film beyond temper film thickness is proportional to the square root of time. The authors propose that any metal forming an oxide having a greater volume than the metal which it replaces will have a continuous adherent oxide. This rule holds for copper and therefore the oxidation is a diffusion controlled process. On this basis, the parabolic relationship is readily developed in this reference (11) and elaborated upon in Wagner (12).

It can be mentioned in passing that there is a third relationship between the amount of oxide and time. This is a linear one which occurs when the oxide is a loose and porous scale permitting oxygen to easily reach the metal surface without the necessity for diffusion (13).

In addition to the effect of oxide thickness, there are two oxides of copper. Cuprous oxide (Cu_2O) is a transparent red and cupric oxide (CuO) is black. Above temper film thickness and in air at atmospheric pressure cupric oxide is the stable form up to $1025^{o}C$. Above $1025^{o}C$ cuprous oxide is the stable oxide. As the partial pressure of oxygen is lowered the temperature at which cuprous oxide becomes stable is also lowered. This is readily shown by free energy considerations (14). Since the two oxides have different optical properties the change from one oxide to another should have an effect

8

on the heating rate of a specimen.

MATERIAL AND PROCEDURE

Material

The specimens were made from cold drawn electrolytic tough pitch copper. Where desired the specimens were electropolished in 57 per cent orthophosphoric acid at 1.4 volts for 30 minutes. The procedure followed is that generally described by Tegart (15). It was necessary to rinse the specimen at least once during the polishing cycle to prevent pitting.

Procedure

The equipment used to conduct this investigation is shown in the schematic diagram Figure 1 and photograph Figure 2. It consisted of two 1000 watt quartz iodine lamps and associated reflectors to focus the radiant heat on the specimen inside a quartz tube. The bottom of the quartz tube was connected to a vacuum pump, and a precision needle valve at the top of the tube was used to bleed in the air required to maintain the desired pressure.

A 30 gauge chromel-alumel thermocouple was imbedded in the specimen and connected to a recording millivoltmeter to provide a plot of temperature versus time. These curves are reproduced in the Figures referred to in the discussion. Voltmeter and ammeter readings were used to determine the power input as controlled by a variac. The reflectors were water cooled to avoid overheating during prolonged cycles.

The specimen was accurately held at the focal point by a ceramic pin. This maintained its rigidity at high temperatures and minimized conduction losses.

DISCUSSION OF RESULTS FOR RADIATION FACTOR "f"

The heating curves for tests 1, 2 and 3 are shown in Figure 3. Each specimen was heated under identical conditions except for initial surface finish as noted. The effect of surface finish is most obvious between room temperature and $550^{\circ}C$.

Tests 3, 4 and 5 in Figure 4 show the effect of air pressure with all other factors including surface the same. At approximately $250^{\circ}C$ oxide films begin to affect the surface on specimen 3 and the heating rate increases rapidly. Specimen 4 heated in air pressure of only .01mm Hg. does not show this sharp increase.

The effect of air pressure on the radiation factor "f" is shown in Figure 5 for tests 3, 4 and 5. The values of "f" are calculated from equation (5). In test 3, "f" reaches a maximum and then decreases presumably because of a change from cupric to cuprous oxide. Specimens quenched from slightly above $1000^{\circ}C$ show a large proportion of red cuprous oxide. The change from black to red can take place very quickly because as stated by Pilling and Bedworth (11), the oxide is always predominantly cuprous with only a thin film of cupric on the surface.

Figure 6 shows the heating curves for three tests run at different power inputs but all other factors the same. The purpose was to determine if the length of time to reach a given temperature had any effect on the instantaneous value of "f". The transient values of "f" for these tests are shown in Figure 7 and isothermal lines are drawn in to permit comparison. It is apparent that the longer heating times (slower rates) result in higher values of "f" for a given temperature

11

particularly at the higher temperatures. The explanation for this is that the thickness of the oxide film is time dependent and "f" is a function of film thickness.

Another point of interest is the change in "f" during heating as a function of initial surface finish. Figure 8 shows the heating curves for tests 9 and 10 which are identical except for surface finish. Specimen 9 is degreased only and specimen 10 is electropolished. The radiation factor versus temperature curve for both specimens is shown in Figure 9. As expected, there is a wide difference between the two specimens at lower temperatures but above 550^OC, the values of "f" are identical. This behavior of "f" manifests itself by the 90 second heating time to 550^OC for the degreased specimen compared to 262 seconds for the electropolished specimen. The heating time from 550^OC to 1000^OC is 42 seconds for both specimens.

7

DISCUSSION OF RESULTS FOR HEATING FACTOR "F"

Equation (9) provides a means for calculating a heating curve. All of the parameters can be measured except "F" which accounts for the changes in specific heat and radiation properties upon heating. If a heating curve for a particular material, surface finish, and atmosphere is available then an "F" versus temperature curve can be evaluated from equation (10).

If it was necessary to run a test curve of time versus temperature for each condition of interest then the advantages of this approach would be limited to calculating the effect of power, weight and shape changes. Far greater advantage would be realized if the heating time for an object could be calculated without the need for an experimental heating curve.

To accomplish this goal, the "F" curves for three test specimens having different initial surface conditions are plotted in Figure 10. Other conditions of atmosphere and power input are identical as described in Figure 3.

The differences between the curves for tests 1, 2 and 3 in Figure 10 are approximately constant with respect to temperature. Therefore, it is easy to interpolate for the curve of a specimen having a different initial surface finish. As guides, the interpolated "F" curves for specimens having an initial radiation factor "f_o" of 0.270 and 0.102 are shown. The initial radiation factor "f_o" is dependent on the surface condition of the specimen at the beginning of the heating cycle which is room temperature (298° K). In these tests "f_o" is calculated from a heating curve and equation (5). To eliminate the need for experimental

13

data it would be necessary to obtain "f_o" by comparison with known surfaces or develop a method for determining "f_o" from a knowledge of surface roughness and degree of oxidation. When "f_o" is known for a specimen to be heated in air at one atmosphere pressure the values of "F" are readily obtained from Figure 10, and an accurate heating curve can be calculated.

If the specimen is to be heated in atmospheres having an oxygen partial pressure less than that found in air at one atmosphere then a modification of the "F" curve is necessary. In Figure 11 the effect of reduced pressure on the "F" curves for an electropolished specimen is shown. The slope of the curve at 20mm Hg. air pressure is 66 per cent of the slope at 760 mm Hg. air pressure. Reducing the air pressure to .01mm Hg. reduces the slope of the "F" curve to zero. This is consistent with Pilling and Bedworth (11) who found that lowering the oxygen pressure has little effect on the oxidation rate until very low pressures are obtained.

As an example of using this information, let us calculate the heating curve for specimen 13 having "f_o" equal to 0.140 when heated in air at 20mm Hg. pressure. The specimen is 3/8" diameter and 1 3/32" long. The power input is 1000 watts. The first step is to determine the proper "F" curve. This is done by interpolation of the curves in Figure 10 and then the slope of the interpolated curve is reduced by 0.34 to account for the reduced pressure. Using equation (9) the heating curve is calculated and compared to the test curve in Figure 12. Close agreement is apparent.

As a second illustration the heating curve for a specimen heated at much reduced power is calculated in a similar manner. Specimen 11 has an "f_o" equal to 0.18 and a power input of 371 watts. The calculated heating curve and the actual curve are compared in Figure 13. Note that the actual heating rate is somewhat faster at higher temperatures. This is caused by the higher radiation factors resulting from the slower heating rate as discussed in relation to Figure 7.

As a last check on the validity of the equation, the heating curve is calculated for a larger specimen and a higher power input. Specimen 12 is 1/2 inch diameter and 1 3/32 inches long. The power input is 1300 watts. The calculated and actual heating curves are shown in Figure 13.

Thus the heating times are accurately calculated based on a knowledge of initial surface condition, atmosphere, power input, area and weight.

When the value of "F" is obtained by interpolation of Figure 10, the small change in slope is accounted for. If the slope is considered the same for all values of "f_o" a small error will be introduced, but it is possible to write a general equation for heating copper:

$$t = \frac{n}{.171 f_o + 2.02k(T-600)10^{-5}} \left[\frac{1}{2K\left(\frac{A\sigma}{K}\right)^{\frac{1}{4}}} \right] \left[\tan^{-1}\left(\frac{A\sigma}{K}\right)^{\frac{1}{4}} T + \tanh^{-1}\left(\frac{A\sigma}{K}\right)^{\frac{1}{4}} T \right]_{298}^{T}$$

where f_o = Initial radiation factor

k = Correction to account for environments other than air at 1 atmosphere pressure.

15

Air Pressure	k
760mm Hg.	1
20mm Hg.	.66
.01mm Hg.	0

Also k = 0 for T less than 600° K

GENERAL DISCUSSION

Basically there is no reason why the procedure used for copper could not be applied to other metals. However, if the metal undergoes a transformation on heating then the heat of transformation will reduce the slope of the time versus temperature curve. It is apparent from equation (5) that this would artificially lower the calculated value of the radiation factor.

The lower conductivity of some metals will distort the values of "f" and "F" because the equations were developed on the basis of uniform temperature throughout the specimen. In the 3/8 inch diameter copper specimens used in this investigation, the maximum temperature difference was 12°C at 900°C. Increased size of specimen will also increase the non-uniformity of temperature and therefore larger sizes should be heated at a slower rate if the conclusions based on uniform temperature are to remain reasonably valid. The reason that a non-uniform temperature will distort the radiation factor is that the radiation factor is evaluated on the basis of the net power absorbed by the specimen. This is the product of weight, specific heat and temperature change.

This investigation was based on radiant heating; except in a vacuum there can be convection heating or cooling. These convection effects will be reflected in the values of "f" and "F". This may not be undesirable for "F" because the purpose of this factor is to predict heating times under a specified set of conditions. However, if the value of "f" as a purely radiation factor is desired then convection effects will make it less accurate. In these tests the quartz tube compensated somewhat for the convection cooling by heating up during

17

the test. As a result of these opposing factors, it was calculated that the error in "K" is zero at room temperature, 2.5 per cent low at 640°C and 5 per cent high at 1000°C.

Curves of "f" versus temperature may be useful for calculating heat losses in induction heating. The emittance of the part being heated has a large effect on radiation heat losses. Although these losses may be negligible for rapid surface heating, they become significant for through heating when heating times become longer. Simpson (2) states that accurate heat loss calculations are difficult because of the change in emittance of the work piece. Information given by the "f" versus temperature curves should be useful in improving the accuracy of the heat loss calculations. The curves in Figure 5 suggest that a copper work piece heated in air at 20 mm Hg. would have heat losses approximately one half those that occur in atmospheric pressure.

CONCLUSIONS

These tests show clearly that the radiation properties of copper change appreciably with temperature when heating in air. These properties are a function of initial surface condition, environment and to some extent heating rate. This information is useful in situations where the transient nature of the radiation properties greatly affects the results as in temperature measurement and in calculation of radiant heat losses.

The equation for calculation of heating rates in focused infrared systems which takes into account the transient nature of the radiation properties is shown to be valid. The usefulness of the equation is based on being able to predict the manner in which the radiation properties will vary during heating. This information was developed for copper and presented in Figure 10. Failure to take into account the variation of radiation properties as a function of temperature can result in errors in calculated heating times as large as 175 per cent as shown by the "F" curve for specimen 3.

The heating characteristics of copper can be summarized to a close approximation by a single equation as follows:

$$t = \frac{n}{.171f_o + 2.02k(T-600)10^{-5}} \left[\frac{1}{2K \left(\frac{A\sigma}{K} \right)^{\frac{1}{4}}} \right] \left[\tan^{-1} \left(\frac{A\sigma}{K} \right)^{\frac{1}{4}} T + \tanh^{-1} \left(\frac{A\sigma}{K} \right)^{\frac{1}{4}} T \right]_{298}^{T}$$
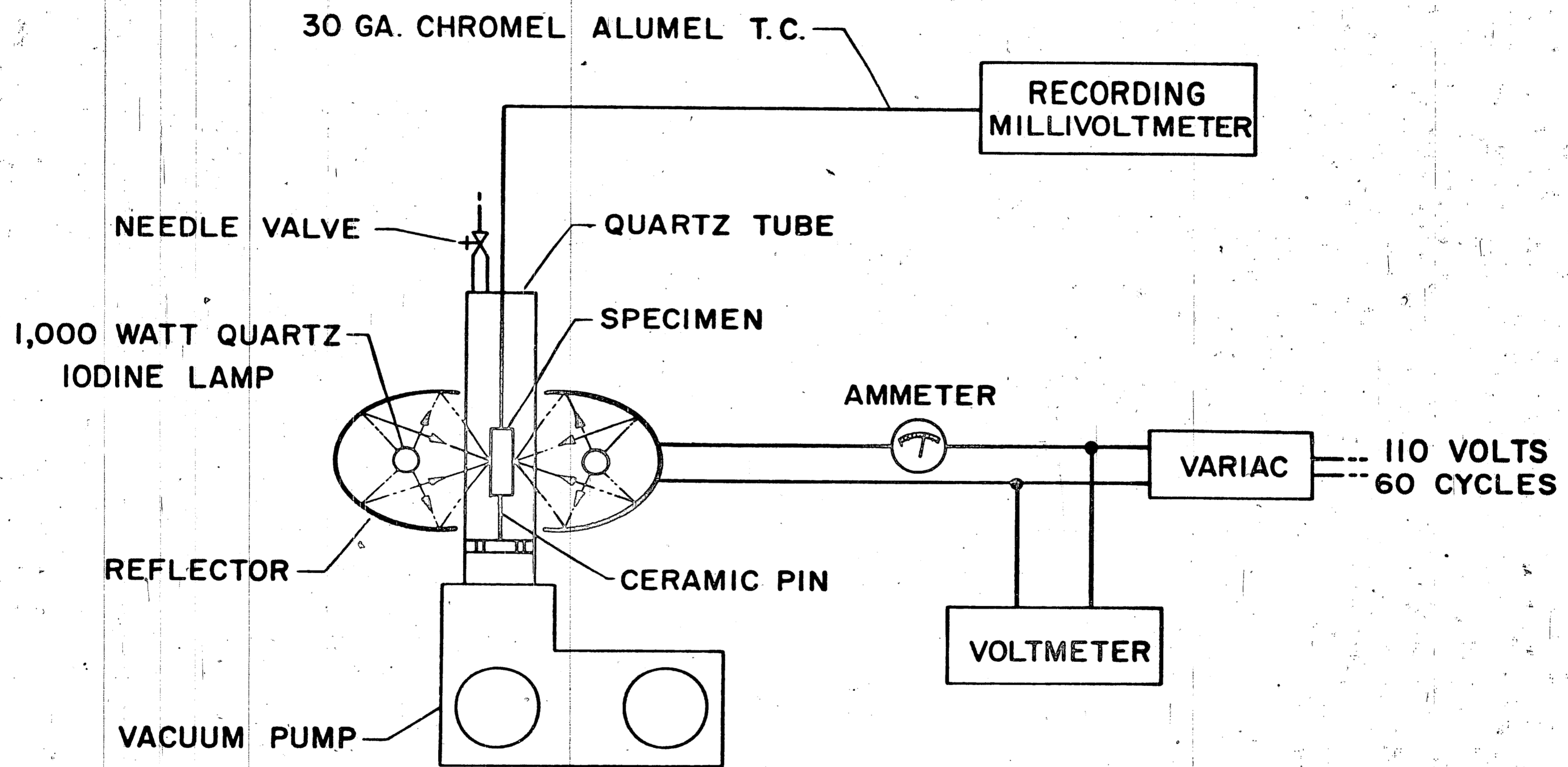
Where f_o = Initial radiation factor

k = Correction to account for environments other than air at 1 atmosphere pressure

$k = 0$ for T less than $600^{\circ}K$

SUGGESTIONS FOR FUTURE WORK

1. The "F" curves for copper were found to be very regular and therefore easy to interpolate. Other metals should be investigated to determine if the information on the variation of radiation properties could be put in an equally useful form.

2. Focused infrared heating closely approaches a purely radiant method of heating. Other methods such as furnace heating usually include convection effects. Work could be done to determine how useful the approach would be for heating calculations in a furnace.

3. When a heating curve is calculated by the method outlined, it is necessary to estimate the initial radiation properties of the surface. A guide for this purpose could be made by correlating the radiation properties with a wide range of surface finishes.

4. Referring to Figure 9, there appears to be a very rapid increase in the radiation factor between $300^{o}C$ and $400^{o}C$. This is most pronounced on the degreased sample. Work to determine the cause of this would probably center on the formation of oxides in the temper film stage.

30 GA. CHROMEL ALUMEL T.C.

RECORDING
MILLIVOLTMETER

NEEDLE VALVE — QUARTZ TUBE

1,000 WATT QUARTZ
IODINE LAMP

SPECIMEN

AMMETER

VARIAC

110 VOLTS
60 CYCLES

REFLECTOR

CERAMIC PIN

VOLTMETER

VACUUM PUMP

SCHEMATIC ARRANGEMENT OF APPARATUS
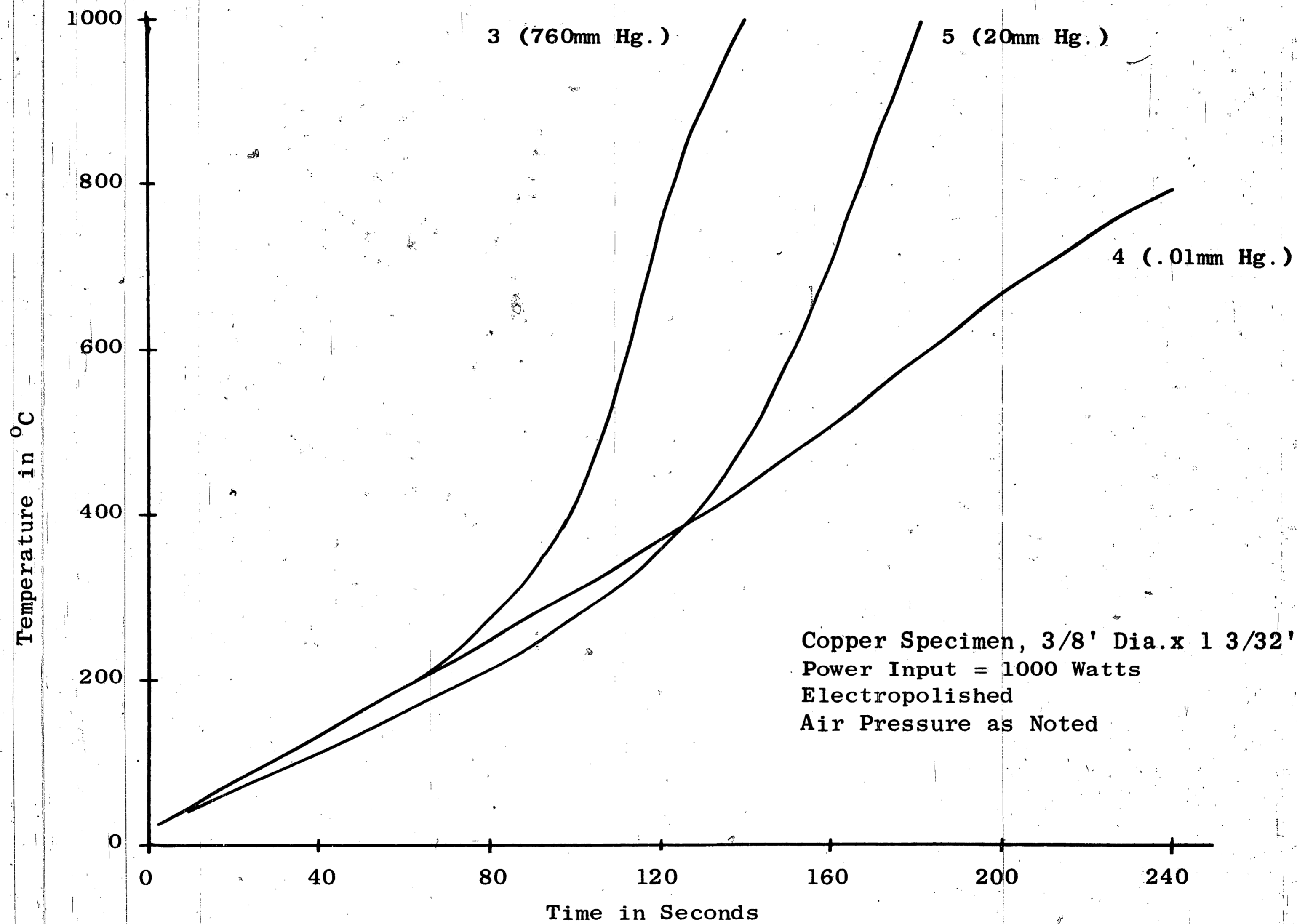
FIGURE 1

21
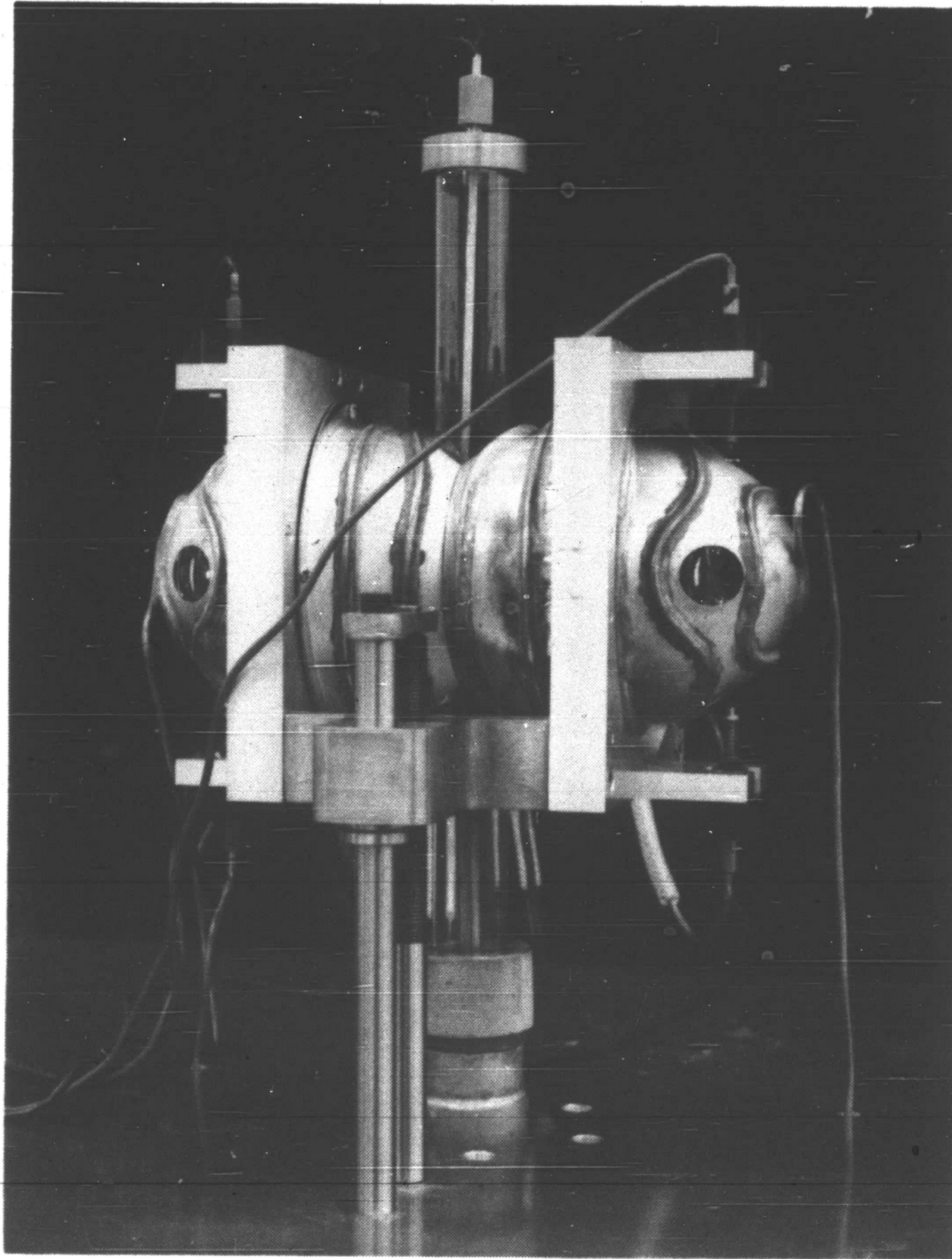
FIGURE 2   PHOTOGRAPH OF APPARATUS
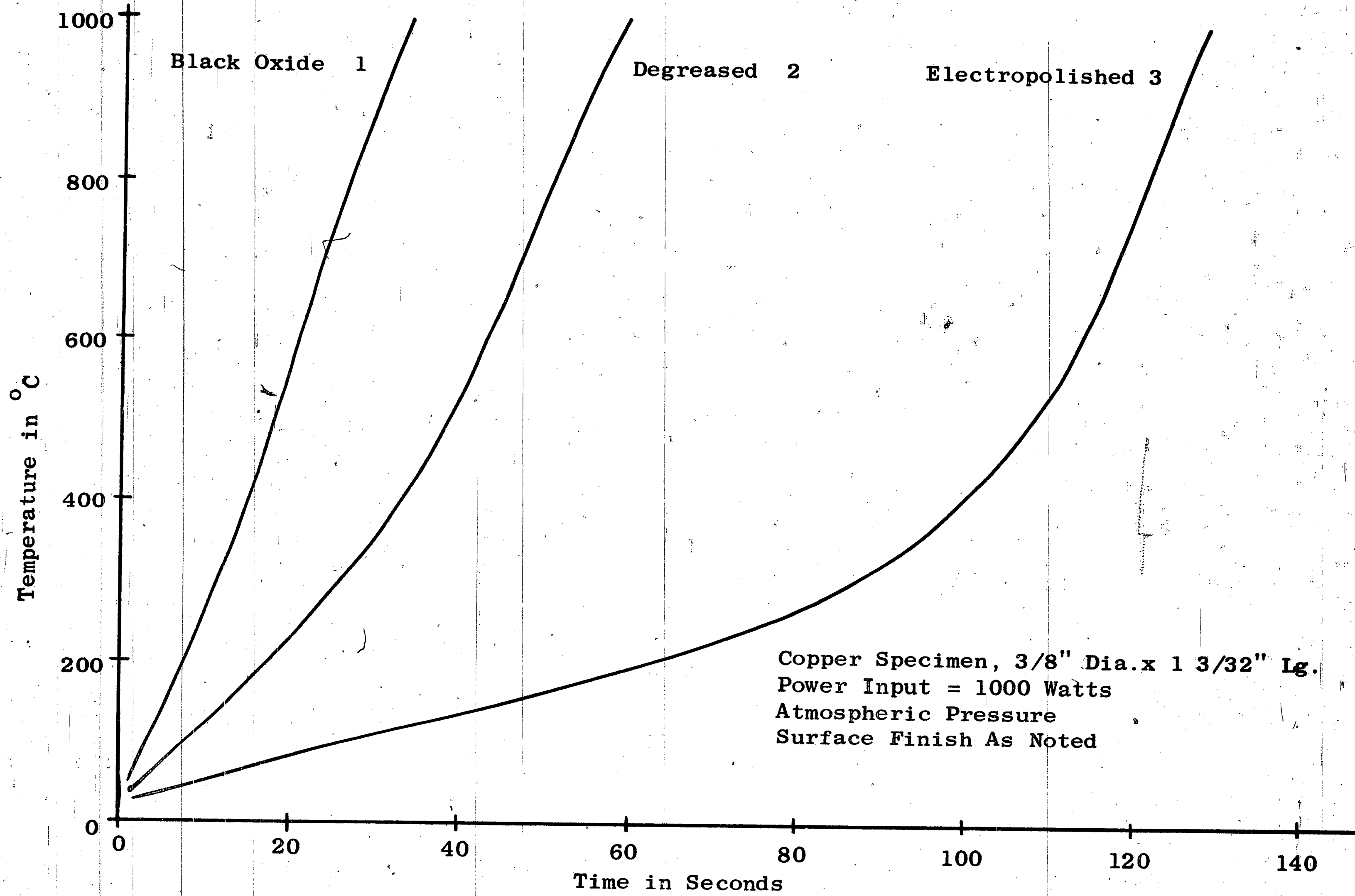
FIGURE 3   EFFECT OF SURFACE FINISH ON HEATING CURVES

FIGURE 4 EFFECT OF AIR PRESSURE ON HEATING CURVES

Copper Specimen, 3/8" Dia. X 1 3/32" Lg.
Power Input = 1000 Watts
Air Pressure As Noted
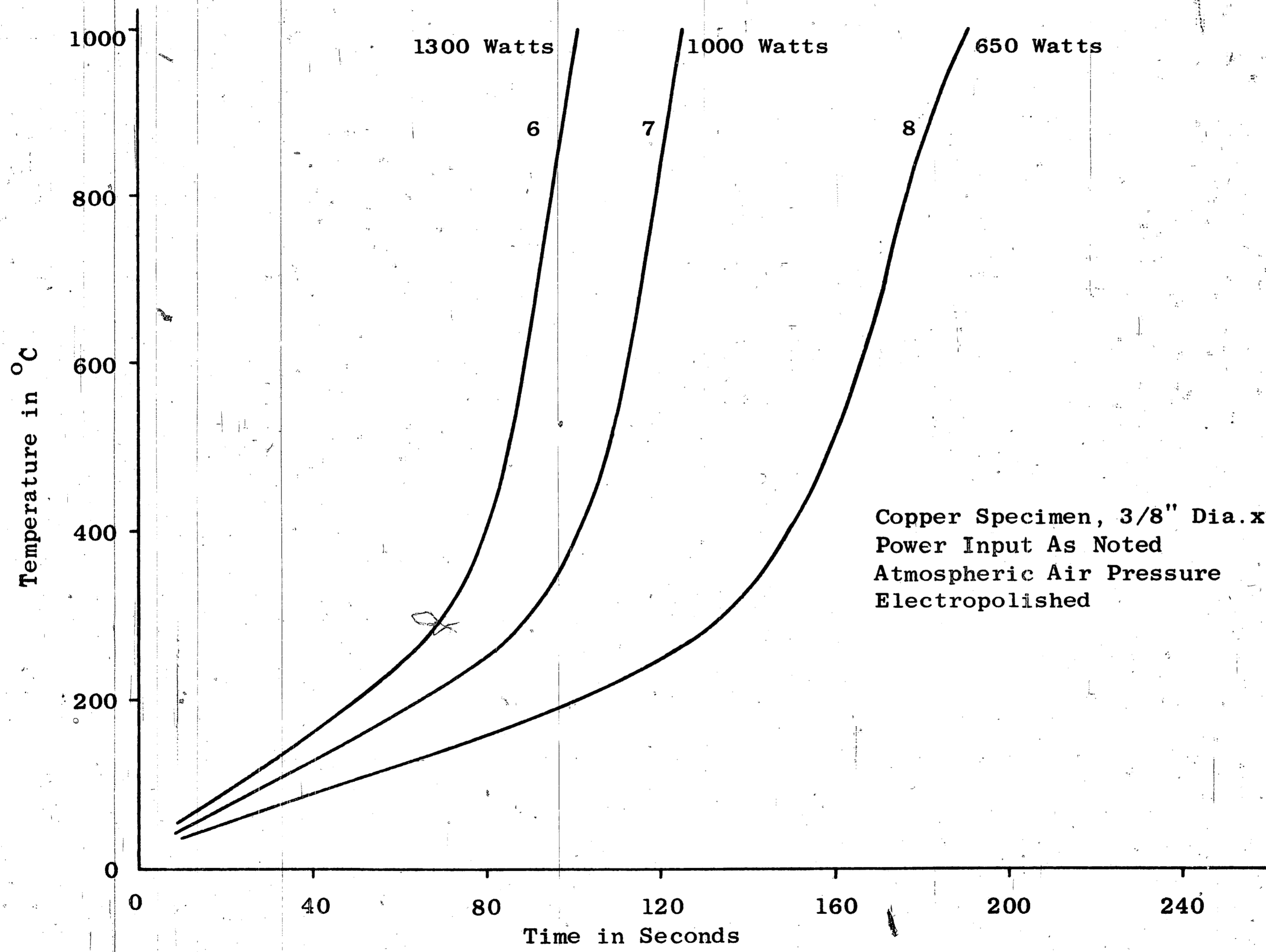Electropolished
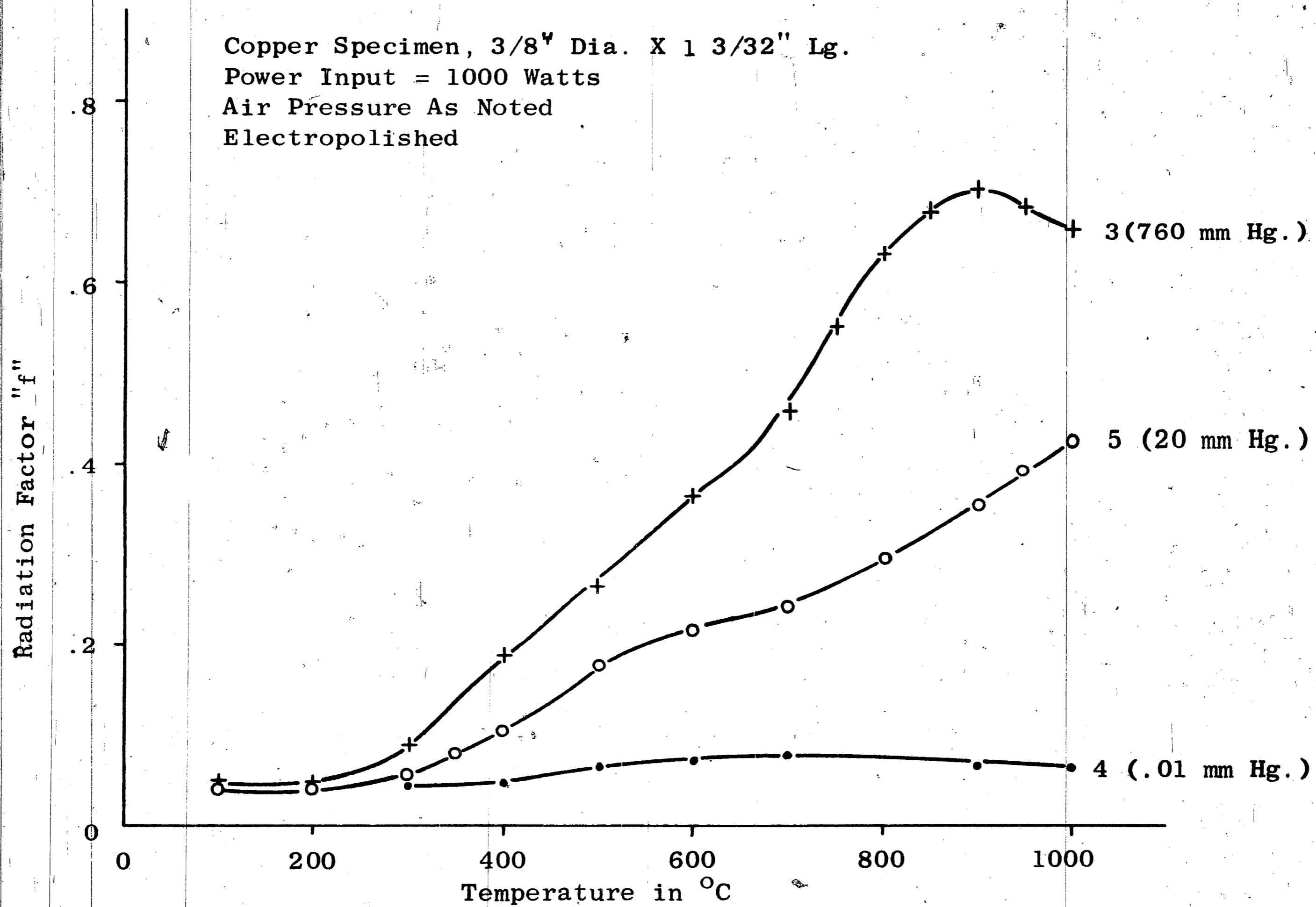
FIGURE 5 EFFECT OF AIR PRESSURE ON RADIATION FACTOR

FIGURE 6   EFFECT OF POWER ON HEATING CURVES

Copper Specimen, 3/8" Dia.x 1 3/32" Lg.
Power Input As Noted
Atmospheric Air Pressure
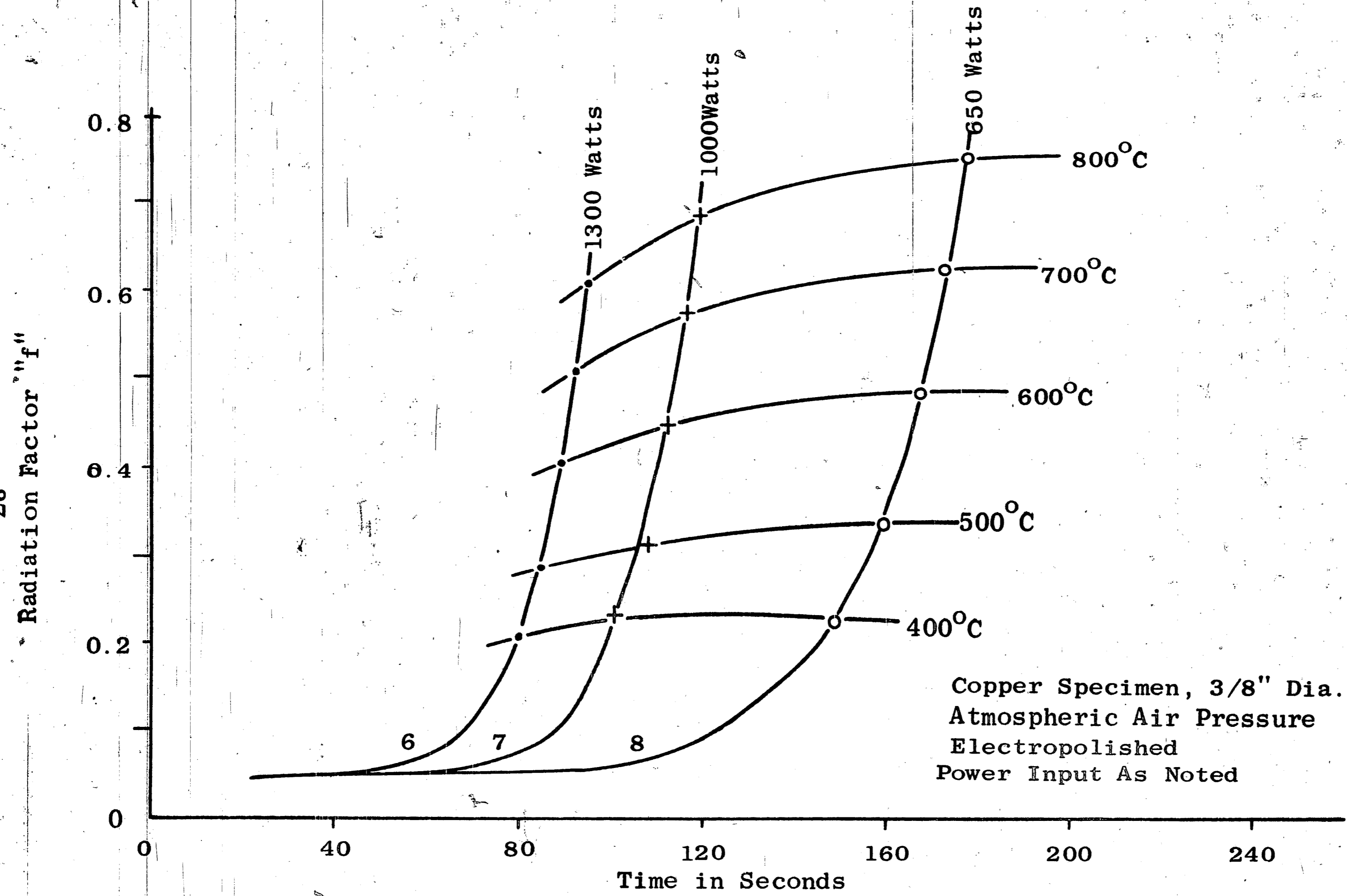Electropolished

26

FIGURE 7   EFFECT OF POWER ON RADIATION FACTOR
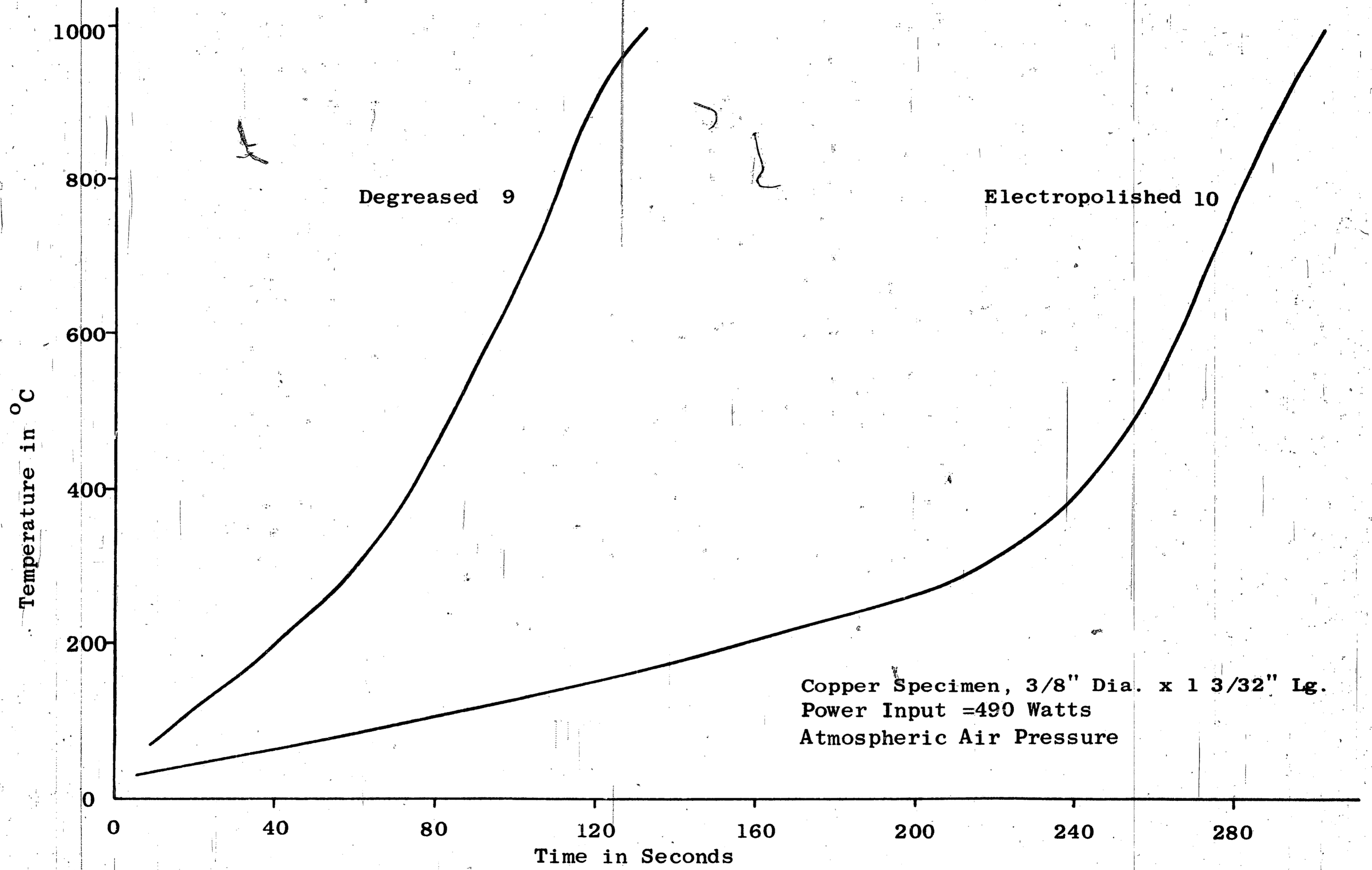
FIGURE 8   EFFECT OF SURFACE FINISH ON TEST CURVES

Degreased 9

Electropolished 10

Temperature in °C

1000

800

600

400

200

0

0   40   80   120   160   200   240   280

Time in Seconds

Copper Specimen, 3/8" Dia. x 1 3/32" Lg.
Power Input =490 Watts
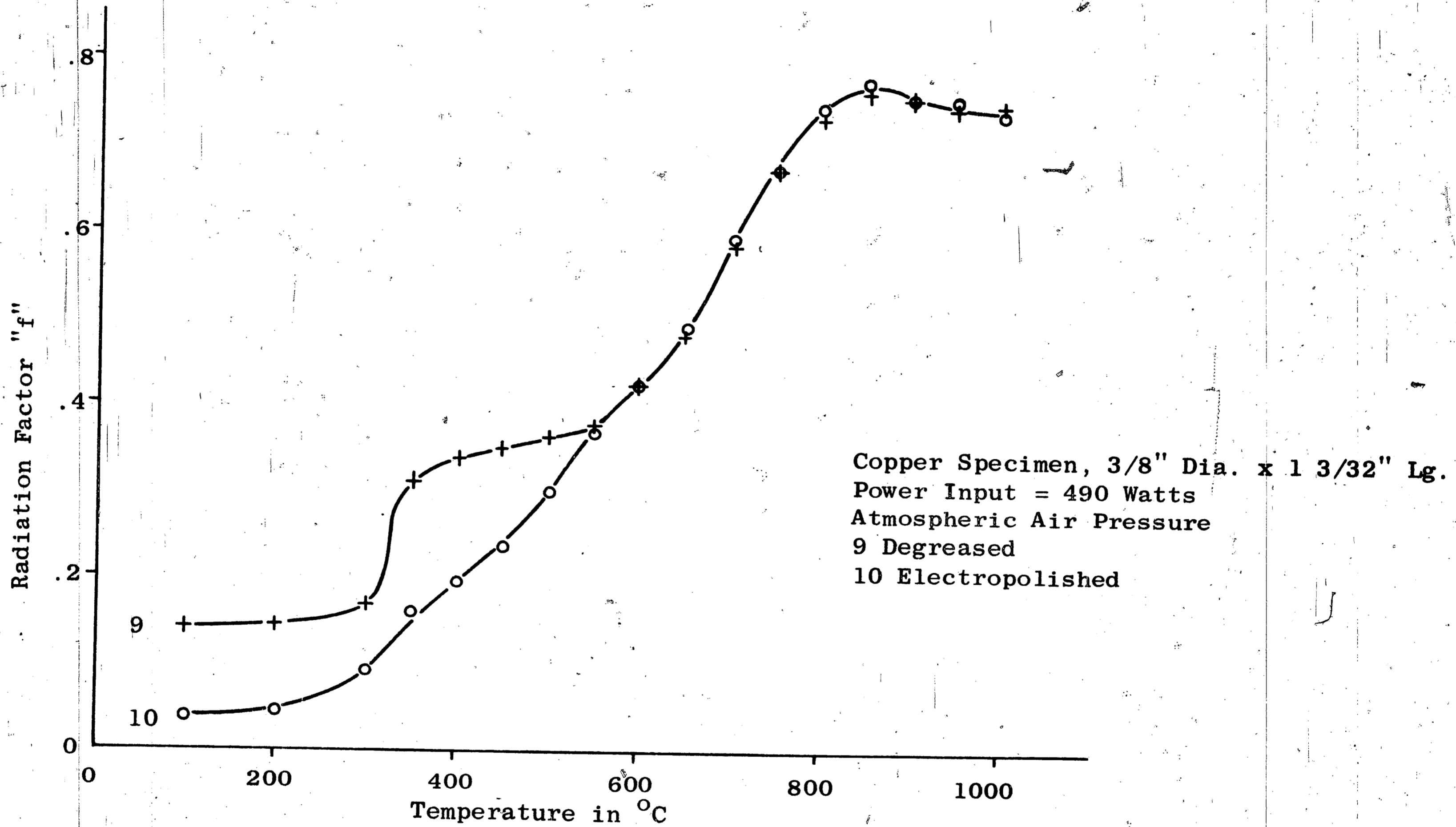Atmospheric Air Pressure

28

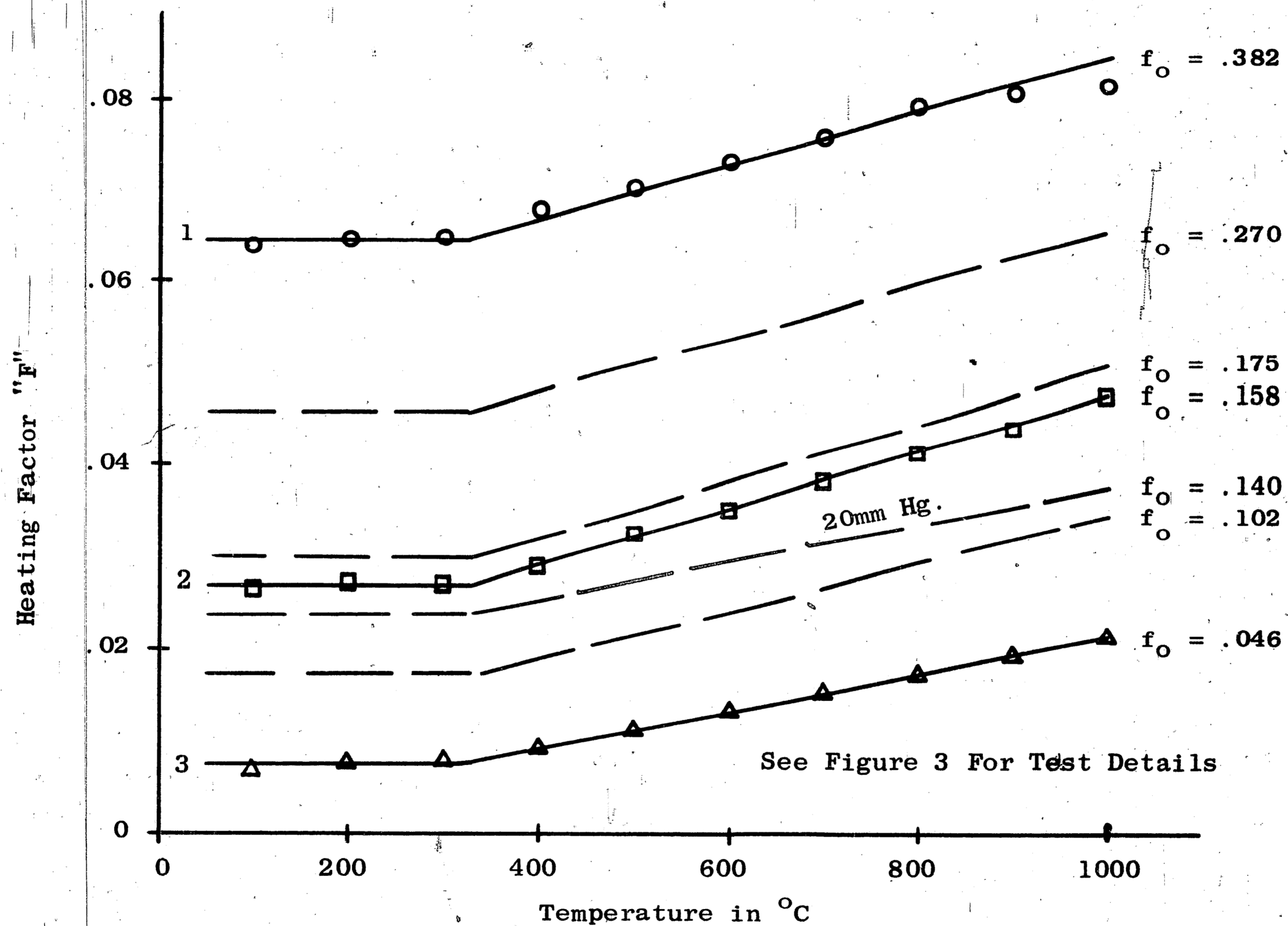FIGURE 9   EFFECT OF TEMPERATURE ON RADIATION FACTOR
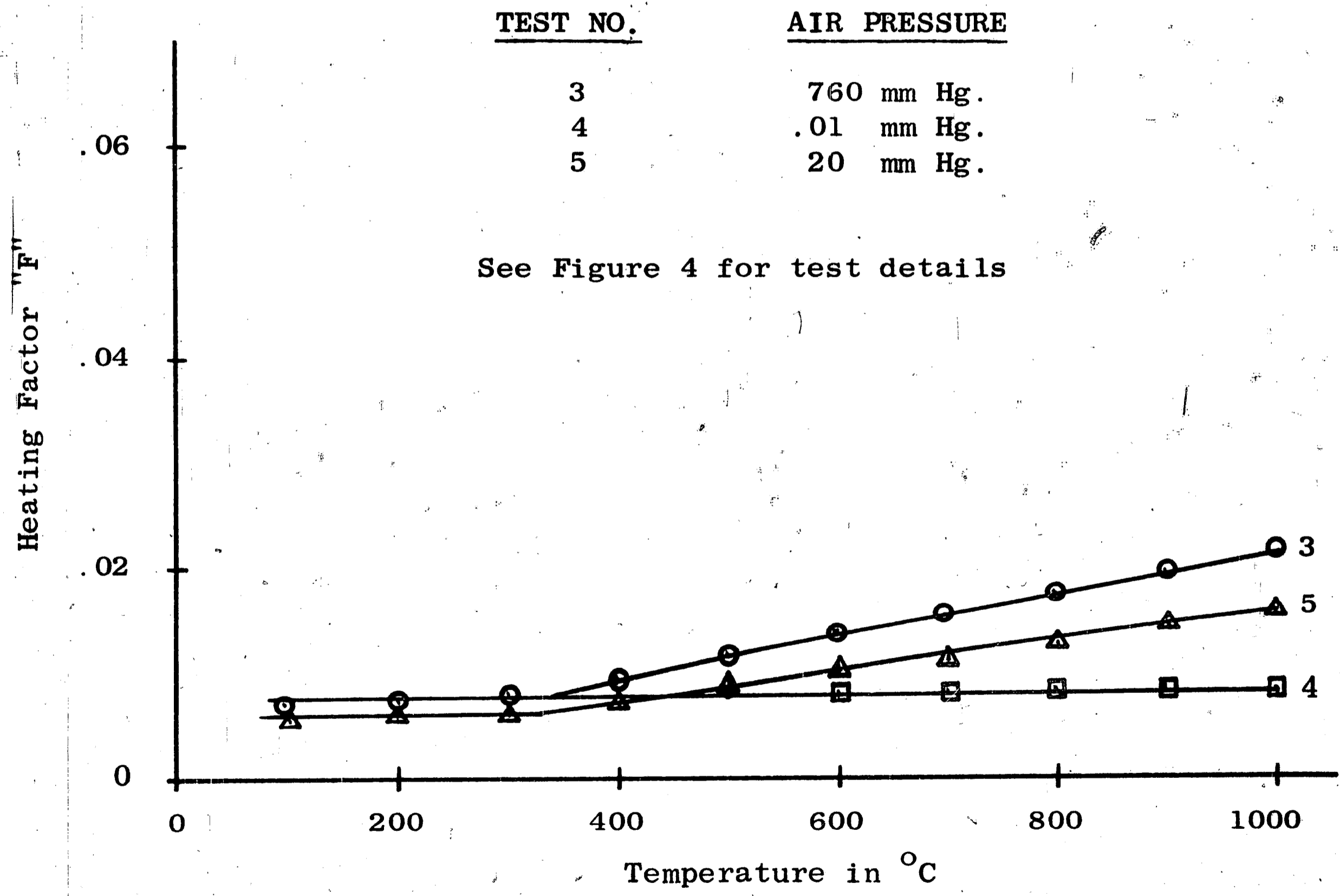
FIGURE 10   EFFECT OF SURFACE FINISH ON HEATING FACTOR

30

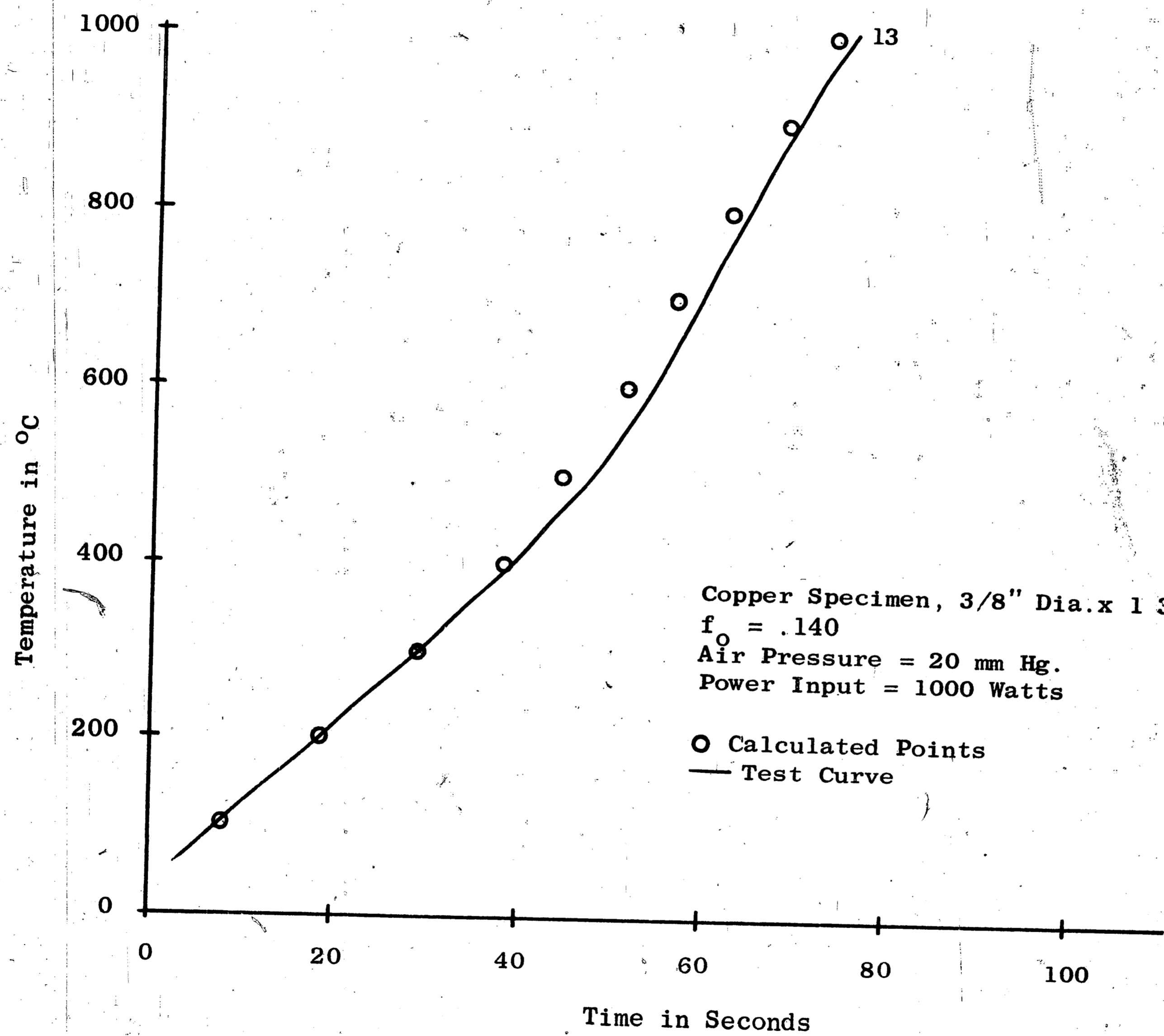FIGURE 11 EFFECT OF AIR PRESSURE ON HEATING FACTOR

FIGURE 12   COMPARISON OF TEST AND CALCULATED HEATING CURVES

Copper Specimen, 3/8" Dia. x 1 3/32" Lg.
f_0 = .140
Air Pressure = 20 mm Hg.
Power Input = 1000 Watts

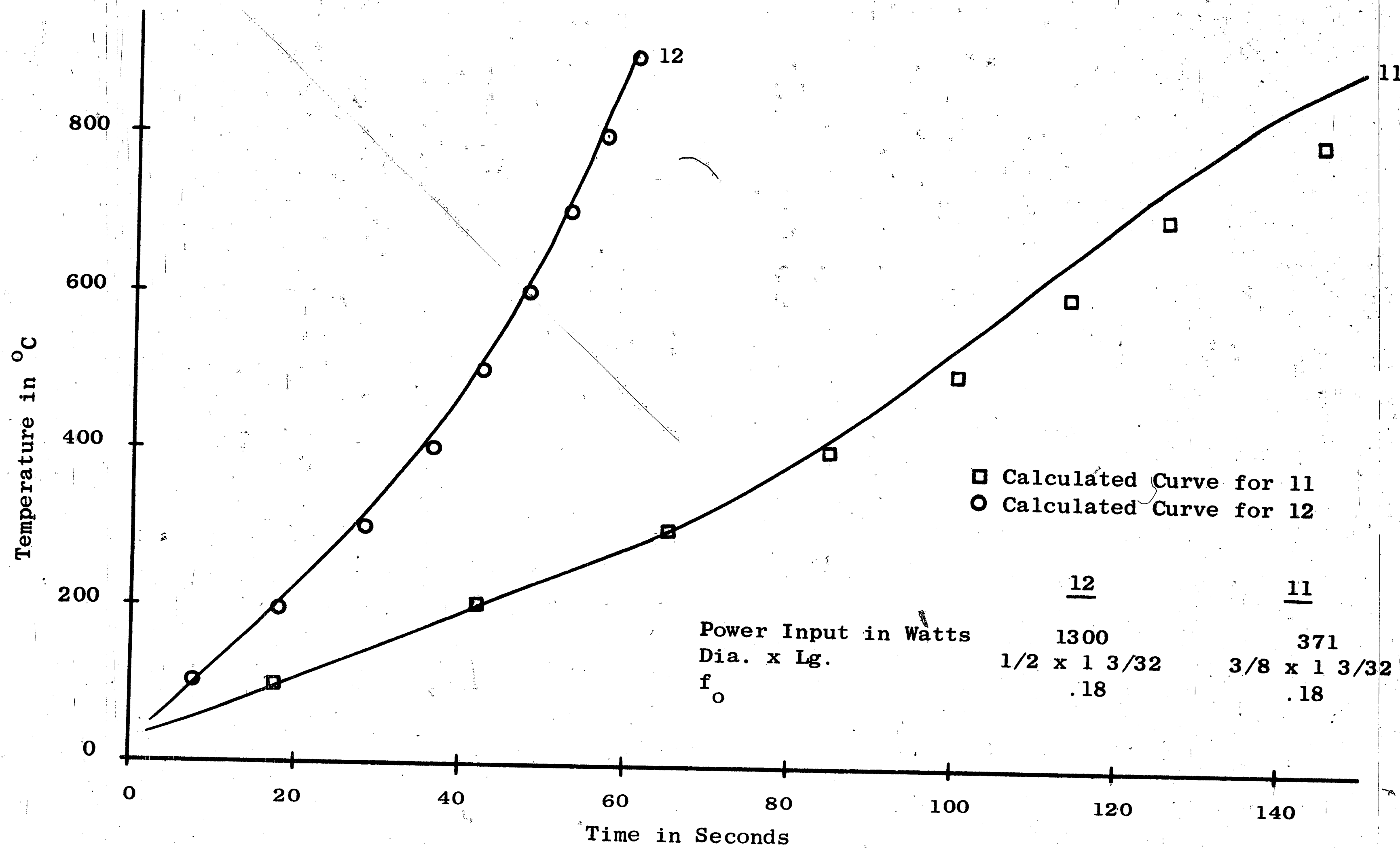O Calculated Points
— Test Curve

32

FIGURE 13   COMPARISON OF TEST AND CALCULATED HEATING CURVES

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