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Use of Thin-Skinned Calorimeters for High Heat Flux Arc Jet Measurements

JULY 1967

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Los Angeles, California

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USE OF THIN-SKINNED CALORIMETERS FOR HIGH
HEAT ARC JET MEASUREMENTS

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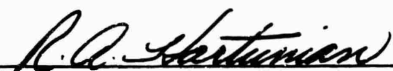
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FOREWORD

This report is published by the Aerospace Corporation, El Segundo, California, under Air Force Contract No. F 04695-67-C-0158 and documents research carried out from January 1967 through March 1967. On 31 July this report was submitted to Lt Curtiss R. Lee, SMFRE, for review and approval.

Approved



R. A. Hartunian, Director
Aerodynamics and Propulsion
Research Laboratory

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.



Curtiss R. Lee, Lt, USAF
Project Officer

ABSTRACT

Fast-response, thin-skinned calorimeters provide a simple, rapid means of obtaining heat flux profiles of arc jet flows. A probe-sweeping technique is used to permit repeated radial profile measurements of heat flux during a single test run. It is shown that this technique is well suited for use in high heat flux environments when simplicity of calorimeter construction and data analysis is required. Such fast-response calorimeters also have application for catalytic surface measurements in nonequilibrium flows where time-dependent surface contamination is experienced. Experimental heat flux data from thin-skinned calorimeters used in arc jet flows are presented.

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INTRODUCTION

Calibration of arc jet facilities for reentry materials testing often requires the use of high heat flux calorimeters. Many calorimeter types have been used for this purpose. Typical problems in transient calorimeter design involve response time and calorimeter lifetime, whereas steady-state types suffer from complexity and cooling limitations at high heat flux.

Use of transient designs usually involves rapid exposure of the calorimeter to the arc jet flow by rapid probe insertion, use of a cooled shutter, or rapid removal of an insulating probe cover. In cases of high heat flux where test time is limited to only a fraction of a second, it is difficult to remove a stationary calorimeter from the flow following a test in time to prevent probe overheating. This situation indicates that either the calorimeter must be of simple enough construction that a probe can be sacrificed for every measurement or a technique must be devised to prevent probe burnout.

Thin-skinned calorimeters of flat faced and hemispherical nose design are shown in Figure 1. With this type of probe construction the sensing surface is unbroken (no air gaps or ablating insulator rings as found with slug type instruments) and the thermocouple is accurately located and easily installed at the rear of the sensing disk or shell ($\delta \ll R$) that forms the thin-skinned calorimeter face. The rear surface of the sensing skin faces an insulating boundary of air or gas at a pressure compatible with skin thickness and calorimeter use in high or low pressure arc jets.

The absence of surface insulator rings can be important in studies involving chemical boundary layer and surface effects. The continuous skin design also prevents the temperature discontinuities experienced when segmented calorimeters are used. Reusable fast-response calorimeters are desired for nonequilibrium flow studies in supersonic arcs where test time is limited because of time-dependent arc contamination of the calorimeter surface.⁽¹⁾ In such studies, it may be necessary to calibrate the probe for surface catalytic properties before and after the test; thus it is important to avoid probe overheating.

This paper describes operation of the thin-skinned calorimeter as applied to high heat flux, arc jet environments. Time response of the calorimeter is investigated, and test time limitations resulting from radial conduction effects and probe overheating are discussed. The thin-skinned calorimeter is presented as a simple, inexpensive instrument which, for simplicity of operation, may be operated to burnout to obtain a heat flux measurement or may be preserved by use of a rapid sweeping motion through the arc jet.

STATIONARY PROBE OPERATION

This section describes general operation of a calorimeter when it is exposed to a step input of heat flux. The calorimeter response time is discussed, and test time limitations resulting from the following effects are investigated:

1. Thermal capacity of calorimeter housing.
2. Radial conduction caused by heat flux gradients on the probe surface.

- Possible probe overheating resulting from excessive temperature rise of the sensing surface.

During operation, the change of average skin temperature (across δ) with time is proportional to the instantaneous surface heat flux according to the equation.

$$\dot{q} = \delta \rho c_p \frac{dT}{dt} \quad (1)$$

This is the basic equation of calorimeter operation and applies if test time limitations and calorimeter response time criteria are met as outlined in this paper.

Response time for this type of calorimeter will be defined as the time required for the rear surface temperature time derivative to equal the average dT/dt of (1) within about 1%. At time greater than this, for a step input of heat flux, the thermocouple temperature time trace gives a measure of instantaneous surface heat flux. This response time can be given in terms of the dimensionless Fourier number $Fo_\delta = \alpha \tau / \delta^2$ based on calorimeter skin thickness δ . Reference 2 shows that $Fo_\delta \geq 0.50$ meets the above criteria so that response time is given by

$$\tau_R = 0.50 \left(\frac{\delta^2}{\alpha} \right) \quad (2)$$

Figure 2 shows calorimeter time response for several metals and a range of skin thickness. Note that response time is on the order of milliseconds for a thickness of 0.010 in. or less.

Figure 1 shows that in thin-skinned calorimeter design no attempt is made to thermally isolate the sensing surface from the probe housing. In most cases this will result in a near-constant temperature at the housing bond radius. It can be shown from solutions found in References 3 and 4 that the constant temperature boundary has a negligible effect on probe centerline temperature for a Fourier number less than 0.05 based on distance x . For purposes of this analysis, it will be assumed that maximum test time is always limited to a value no large than that given by this Fourier number so that

$$\tau_{m,x} = 0.05 \left(\frac{x^2}{\alpha} \right) \quad (3)$$

In Figure 3 it is seen that for calorimeters constructed of steel, an x dimension of 0.250 in. or greater allows test times of hundreds of milliseconds based on this criteria.

A calorimeter immersed in an arc jet flow may experience a heat flux gradient across the sensing surface resulting from calorimeter geometry or gradients within the flow stream. For instance, when a hemispherical shaped calorimeter is used in supersonic flow, it is known that the heat flux varies from a maximum at the centerline to near zero at the 90-degree point.⁽⁵⁾ Such a heat flux

distribution across the x -dimension gives rise to temperature gradients within the sensing surface which can lead to centerline thermocouple errors. The following analysis points out how the probe test time may be limited as a result of this effect.

Following the reasoning of Reference 6, one estimates the magnitude of this effect for the axisymmetric case by computing the ratio of heat entering the probe centerline region through convection q to heat leaving by radial conduction q_L as a function of time. Test time should be limited so that this ratio E is restricted to the order of a few percent. Consider the case of a step input of heat flux varying over the calorimeter surface according to $\dot{q} = \dot{q}_0 f(x/R)$. Neglecting radial conduction, one finds the average local temperature is

$$T = \frac{1}{\delta} \int_0^\tau \frac{\dot{q} d\tau}{\rho c_p} \approx \frac{\dot{q} \tau}{\delta \rho c_p} \quad (4)$$

A first approximation to radial conduction near the probe centerline is then

$$q_L = \delta k 2\pi x \left(\frac{dT}{dx} \right) = 2\pi \alpha \tau x \left(\frac{d\dot{q}}{dx} \right) \quad (5)$$

Incoming convection heat transfer near $x = 0$ is given by $q_\infty \approx \dot{q}_0 \pi x^2$, so by forming the ratio q_L/q_∞ one finds

$$E_L = q_L/q_\infty = \frac{2\alpha\tau}{\dot{q}_0 x} \left(\frac{d\dot{q}}{dx} \right) \quad (6)$$

For the case of a cosine heat flux distribution where $\dot{q} = \dot{q}_0 \cos(x/R)$, the magnitude of the conduction error is found to be

$$E_L = \frac{2\alpha\tau}{R^2} \quad (7)$$

Note that E_L is not a function of skin thickness or heat flux. Equation (7) is plotted in Figure 4 for several metals with $R = 0.250$ in. A two-dimensional axisymmetric computer solution for $\delta = 0.01$ and $R = 0.250$ in. was used to calculate E_L for low carbon steel. Excellent agreement was found at times up to 100 msec when compared with the one-dimensional approximation of Equation (7). A comparison of Figures 3 and 4 shows that for $R = 0.250$ the test time limitation resulting from E_L is more restrictive than $\tau_{m,x}$. It is clear from Equation (7) and Figure (4) that a low α material such as stainless steel is desirable for the calorimeter skin in order that radial heat losses may be reduced. However, Figure 2 shows that response times may be quite large for such material if a thick skin is required for other reasons.

The exact form of $\dot{q} = f(x/R)$ to use in Equation (6) for E_L estimation is usually not known. Use of several thermocouples at different x -locations will provide an experimentally determined estimate of heat flux profile across the calorimeter surface.

Equation (1) shows that for a step input of heat flux the average skin temperature continuously increases during the time of calorimeter exposure. Figure 5 shows temperature rise expected for a skin thickness of 0.01 in. and ρc typical of the metals shown in Figures 2, 3, and 4.^P Test time τ_T will be necessarily limited to a value below which the calorimeter is overheated. This point will be determined by probe and thermocouple construction and will depend upon whether or not it is necessary to preserve the instrument for future use. Actual data time for a step input of heat flux is restricted to the interval between τ_R and τ_T if the previously mentioned radial conduction effects are not dominant. Reference 7 points out that, based on response time and front surface temperature limits only, an optimum value of skin thickness is

$$\delta_{opt} = \frac{kT_{m,1}}{1.366 q} \quad (8)$$

where $T_{m,1}$ is the maximum allowable front surface temperature. This equation allows for a maximum value of the time interval between τ_R and τ_T .

Additional time response restrictions may apply, based on thermocouple construction, and they may be estimated by use of the analysis of Burnett.⁽⁸⁾ In some cases, the available thermocouple sizes and skin structural considerations may call for a δ thickness larger than that calculated by use of Equation (8).

SWEEP OPERATION

The findings of the preceding section apply most generally to a step input of heat flux such as that obtained by use of a cooled shutter, removable probe cover, or from very rapid probe insertion into the arc flow. At high heat flux values, sufficient time is often not available to permit probe removal or covering following a test; thus, overheating or burnout will occur.

This section presents the technique of sweep operation whereby the probe may be swept through a jet radially in one continuous motion, thus minimizing the dwell time and preventing probe burnout. Response time requirements for this mode of operation are discussed. It is shown under what conditions of operation a radial heat flux profile across the jet may be obtained from a single sweep measurement. Typical arc jet heat flux profiles are investigated, and corresponding calorimeter output is discussed. Test time limitations resulting from radial conduction effects are analyzed for sweep operation. Thin-skinned calorimeter data from sweeps across a supersonic arc jet are shown. A method of correcting for variations of calorimeter specific heat and thermocouple sensitivity with temperature is presented.

Figure 6 illustrates typical arc jet, radial heat flux profiles ranging from nearly flat to slightly peaked, depending upon stream enthalpy and pressure gradients. If a small calorimeter is swept across a large, nearly flat enthalpy profile

from $-r_N$ to $+r_N$, the centerline thermocouple will experience a near step input of heat flux, and operation will be as discussed in the preceding section. Figure 7 shows the typical thermocouple data expected. Total temperature rise of the skin during sweep operation will depend on the integrated heat load over the sweep period and can usually be estimated for preventing burnout. For the nearly flat profile, Figure 5 can be used directly for such estimates by replacing τ by the sweep period P . For a profile where heat flux follows a sinusoidal variation with time, $\dot{q} = \dot{q}_m \sin(\pi\tau/P)$, total heating load is equal to $(2/\pi)P\dot{q}_m$, i.e., final skin temperature is about 40% less than that for the flat profile case. The test time limitation $\tau_{m,x}$ resulting from the cool housing applies for $\tau_{m,x}$ both stationary and sweep operation.

During sweep operation, one must be assured that calorimeter response is adequate to give a true $dT/d\tau$ for most of the sweep period. Reference 9 gives frequency response analyses applicable for sinusoidal heat inputs to a conducting slab. It will be found that for many cases of a small probe sweeping through a large jet

$$\tau_R < 0.10 P \quad (9)$$

gives adequate time response. An arc jet having a peaked profile (Figure 6), presents a more strict requirement on probe time response.

If response time requirements are met for the sweeping mode of operation, the $dT/d\tau$ values (in this case, dT/dP), as would be measured from Figure 7, would be proportional to the local heat flux at any time during the sweep. The data will be accurate in the central region of the sweep but should not be relied upon near $\tau/P = 0$ or 1, where $\dot{q} \ll \dot{q}_m$. A differentiator circuit can be used to good advantage for direct readout and display of the local slopes.

Figure 8 shows calorimeter sweep data obtained from measurements made with a 0.5-in.-diameter flat-faced probe of low carbon steel with 0.010-in. skin thickness ($\tau_R < 3$ msec, $\tau_{m,x} > 150$ msec). The calorimeter was swept radially across a 3-in.-diameter supersonic arc jet. Total sweep time P was 60 msec. Position of the probe within the flow is deduced from the potentiometer trace. The potentiometer was linked directly to the probe-traversing mechanism. The two thermocouple traces of Figure 8 illustrate how heat flux profile changes with test section static pressure level. The somewhat rounded profile of Figure 8a resulted from a slightly fanned out underexpanded jet, while 8b shows a flatter profile as the jet is operated in an overexpanded mode.

Since the thin-skinned calorimeter usually will have a cool housing, the sensing disk will cool down within a few seconds following a heating sweep. This then permits repeated sweeps to be made across a jet during any given arc run. Such data can be used to evaluate slow, arc heat flux variations if run time continues for several seconds.

A plot of the ratio of calorimeter variables, specific heat and thermocouple sensitivity, as a function of output voltage, such as seen in Figure 9, is convenient for heat flux calculation. By use of such a combined constant, Equation (1) becomes

$$\dot{q} = \delta \rho K \left(\frac{dV}{d\tau} \right) \quad (10)$$

where K is evaluated at the output voltage of interest.

As with stationary probe operation, test time for sweep operation may be limited by radial temperature gradients which develop on the probe sensing surface because of probe heat flux gradients. Thus, during sweep operation, probe heat flux will be a function of x and τ . Let $\dot{q}_{m,L}$ be the probe centerline heat flux value as the instrument passes through jet centerline. Then, in general, $\dot{q}$ may be written as $\dot{q} = \dot{q}_{m,L} f(x/R, \tau/P)$. For the case of a sinusoidal arc jet profile and axisymmetric probe surface distribution in a cosine manner

$$\dot{q} = \dot{q}_{m,L} \cos \left(\frac{x}{R} \right) \sin \left(\frac{\pi \tau}{P} \right) \quad (11)$$

From Equation (4)

$$T \approx \frac{1}{\epsilon \rho c_p} \int_0^{\tau} \dot{q} d\tau \quad (12)$$

and following the procedure outlined for stationary probe analysis at near $x = 0$, one obtains

$$E_L = \frac{q_L}{q_c} \approx \frac{2}{\pi} \left(\frac{\alpha F}{R^2} \right) \frac{[\cos(\pi \tau/P) - 1]}{\sin(\pi \tau/P)} \quad (13)$$

Figure 10 shows Equation (13) plotted for a probe of 0.250-in. radius with sweep periods of 25 and 50 msec. Note that near the end of the sweep the error becomes large since q is falling rapidly, but q_c still remains because of temperature gradients built up across the calorimeter face. In the case illustrated, reliable heat flux values would not be obtained over the last 25 percent of the sweep. The one-dimensional result of Equation (13) was checked by using a two-dimensional axisymmetric computer solution for a skin thickness of 0.010 in., and good agreement was found.

HIGH HEAT FLUX OPERATION

In the previous sections, calorimeter operation was discussed and criteria for obtaining valid test data were investigated. In this section, the use of this information for typical high heat flux applications is examined.

For heat flux values of a few thousand Btu/ft²-sec or less, many combinations of probe material,

thickness, and diameter are possible. In this range of heat flux, the most likely test time limitation for small diameter probes is that due to E_L as calculated from Equations (7) and (13). Test times will range to 100 msec or more, based on ΔT of the probe-sensing surface, if temperatures are allowed to exceed 1,000°F. In this heat flux range, either stationary- or sweeping-probe operation is possible.

As heat flux approaches 10,000 Btu/ft²-sec, the possibilities of probe operation become more limited. For instance, for low carbon steel, Equation (8) gives an optimum thickness of about 0.010 in., with the maximum test time interval between τ_b and τ_f equal to less than 10 msec to probe burnout. If such short test times are realistic for arc testing, then the limitations imposed by E_L and $\tau_{m,x}$ are usually not major considerations. Use of high conductivity material will greatly increase allowable test time at high heat flux if heat flux gradients do not cause restrictions resulting from E_L (see Figure 4). A copper probe of 0.10-in. thickness would allow a test time interval of about 60 msec to burnout at a 10,000 Btu/ft²-sec level. In this high heat flux range usually only stationary probe operation with rapid injection, fast shutter, or removable cap techniques will be applicable, as the requirement $P > 10 \tau_b$ would be quite difficult to meet without probe burnout.

CONCLUSIONS

A technique has been proposed whereby a simply constructed, fast-response calorimeter, consisting of a thin metal skin with a thermocouple on the rear surface, can be used for arc jet measurements. The calorimeter may be used at a stationary radial jet location, or it may be rapidly swept across the flow stream to prevent burnout or to obtain a heat flux profile. The following criteria were investigated with respect to calorimeter test time:

1. Basic response time of calorimeter based on thermal diffusivity and skin thickness.
2. Influence of cool boundary at sensing surface bond to calorimeter housing.
3. Overheating of the calorimeter surface at a given heat flux level.
4. Heat loss from the vicinity of the sensing thermocouple resulting from radial heat flux gradients across the calorimeter surface.

It was seen that calorimeters of this type have potential application at heat flux levels to the 10,000 Btu/ft²-sec range with test times ranging from several hundred to less than 10 msec. The main advantages of the proposed calorimeter technique in arc jet use are simplicity of construction and ease of data reduction. Use of the thin-skinned calorimeter has been demonstrated for sweep operation across a supersonic arc jet.

NOMENCLATURE

c_p	Specific heat
E	Ratio q_L/q
Fo	Fourier number
K	Ratio of specific heat to thermocouple sensitivity
k	Thermal conductivity
P	Sweep time or heating period
q	Heat transfer rate, Btu/sec
$\dot{q}$	Convective heat flux, Btu/ft ² -sec
R	Calorimeter radius
r	Nozzle radius
T	Temperature
V	Output voltage
x	Distance from calorimeter centerline measured in a radial direction parallel to probe surface
α	Thermal diffusivity $k/\rho c_p$
δ	Calorimeter skin thickness
ρ	Density
τ	Time

SUBSCRIPTS

L	Centerline
L	Loss by conduction
R	Response
m	Maximum
N	nozzle
l	Front surface
T	Temperature limited

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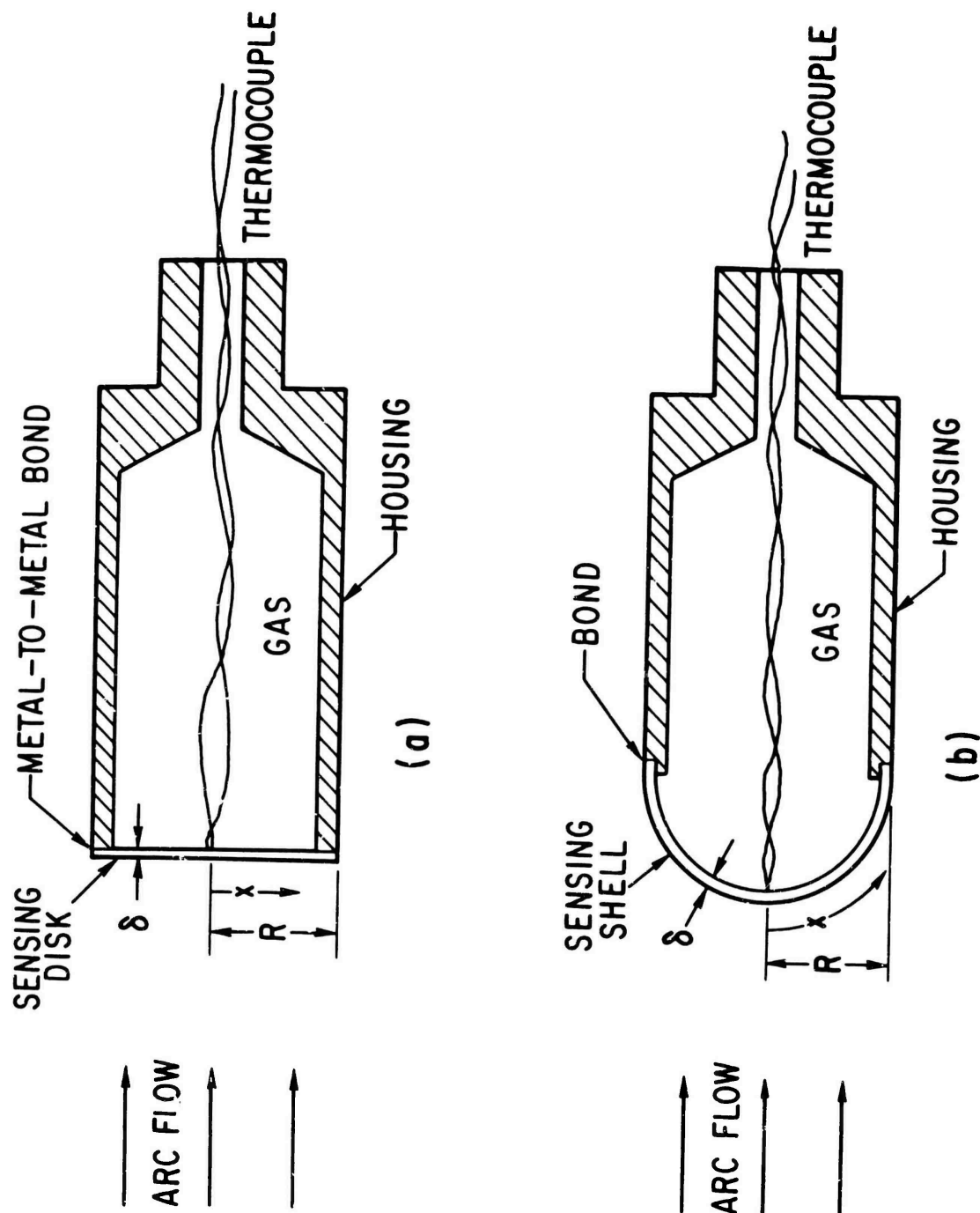


Figure 1. Calorimeter Designs: (a) Flat-faced, (b) Hemispherical.

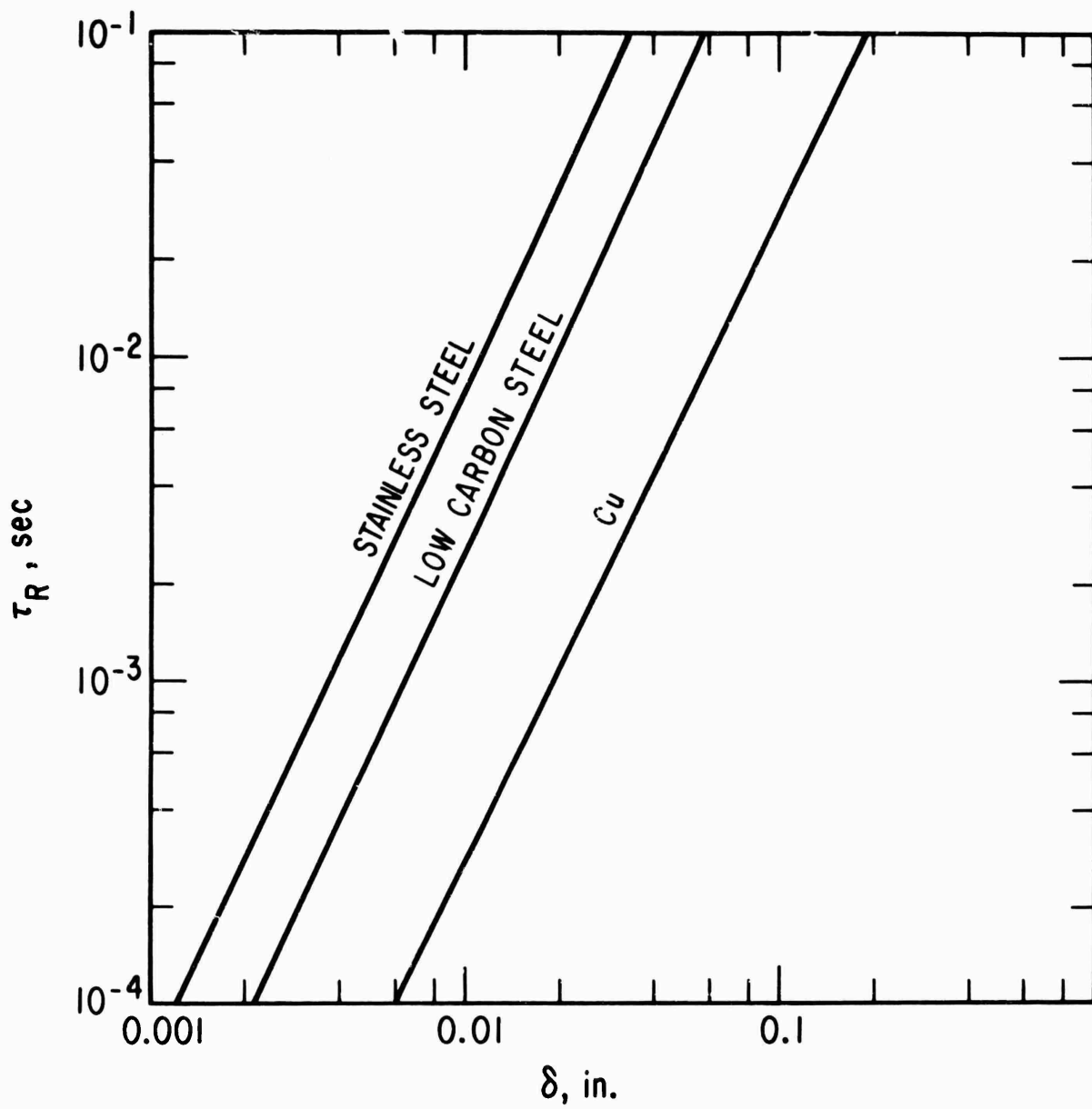


Figure 2. Response Time Based on Thickness δ

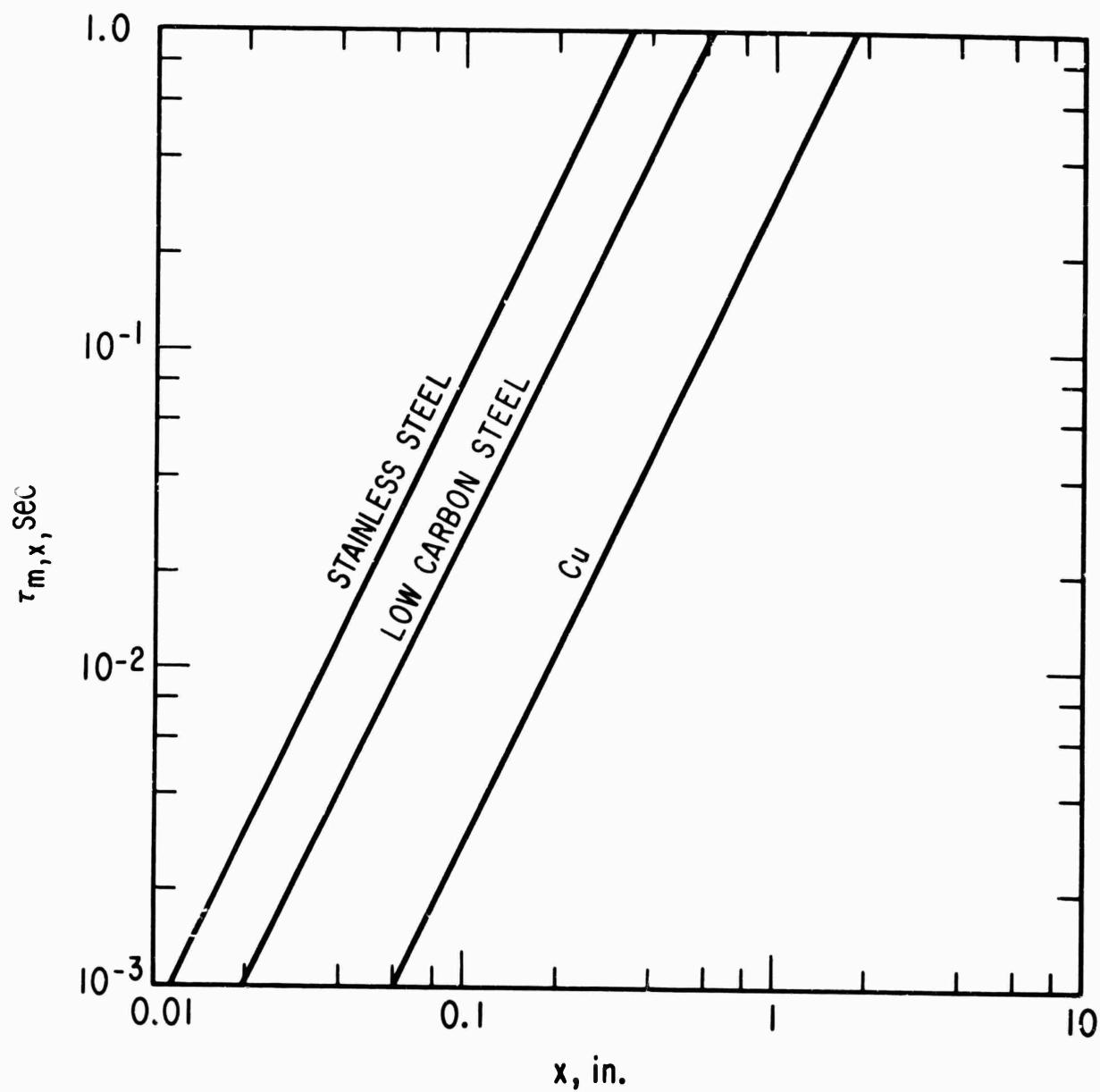


Figure 3. Maximum Test Time Based on Distance x .

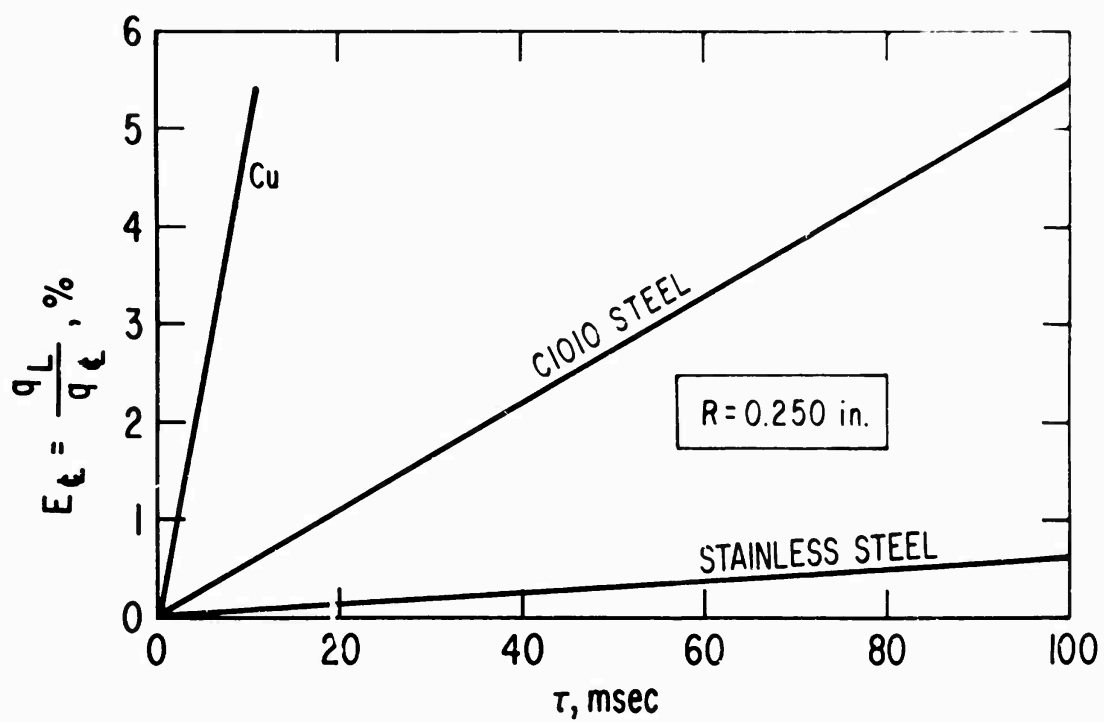


Figure 4. E_L for Step Input of Heat Flux.

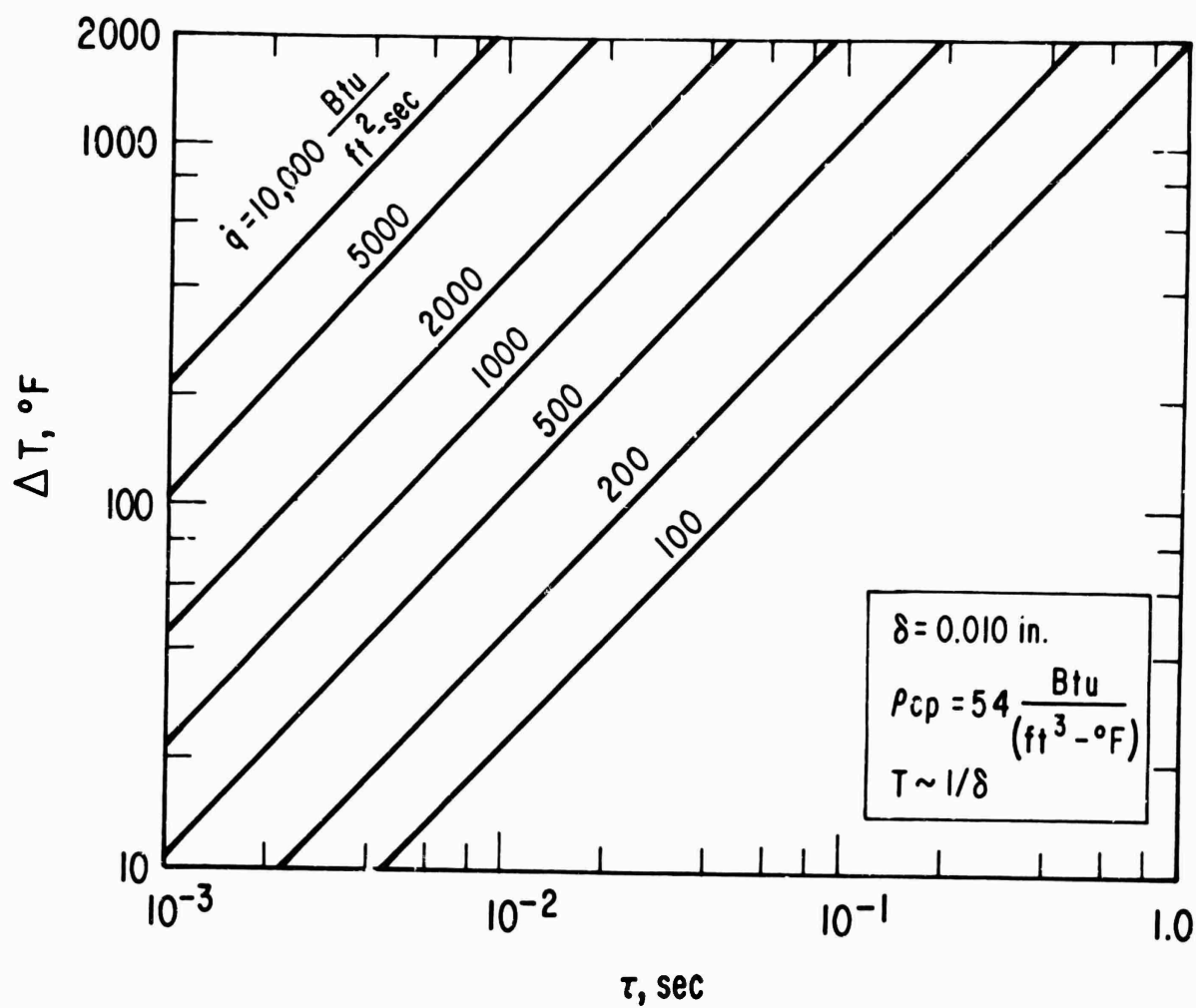


Figure 5. Surface Temperature for Various Test Conditions

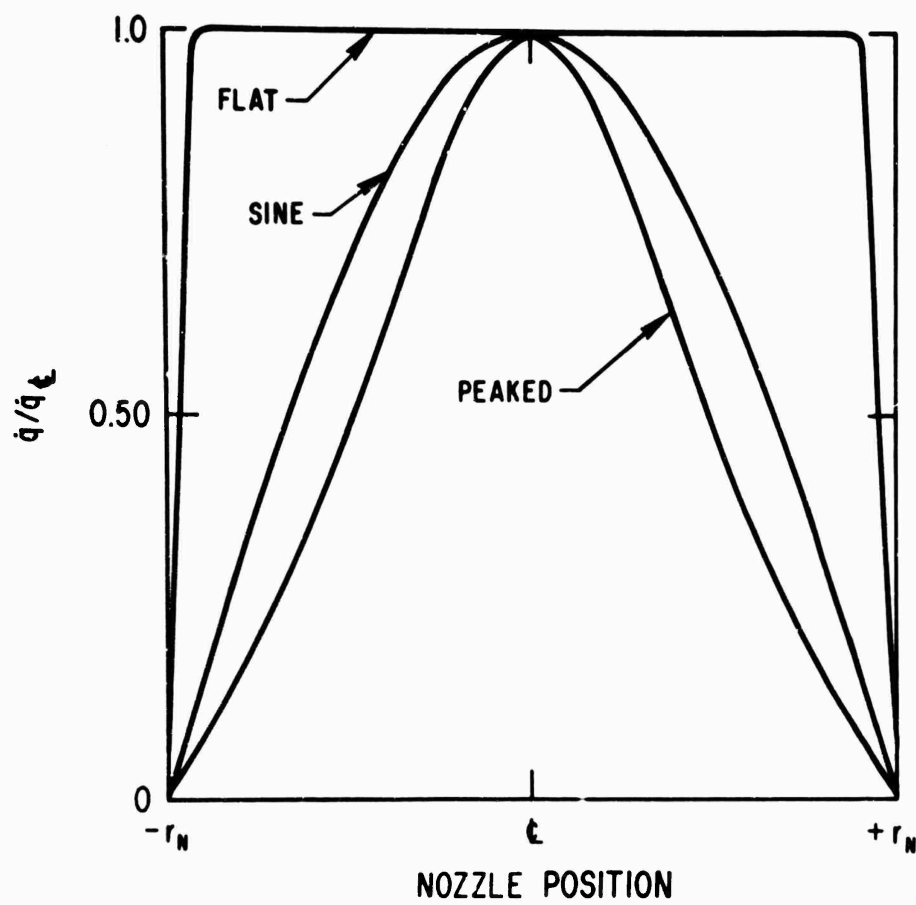


Figure 6. Typical Nozzle Heat Flux Profiles.

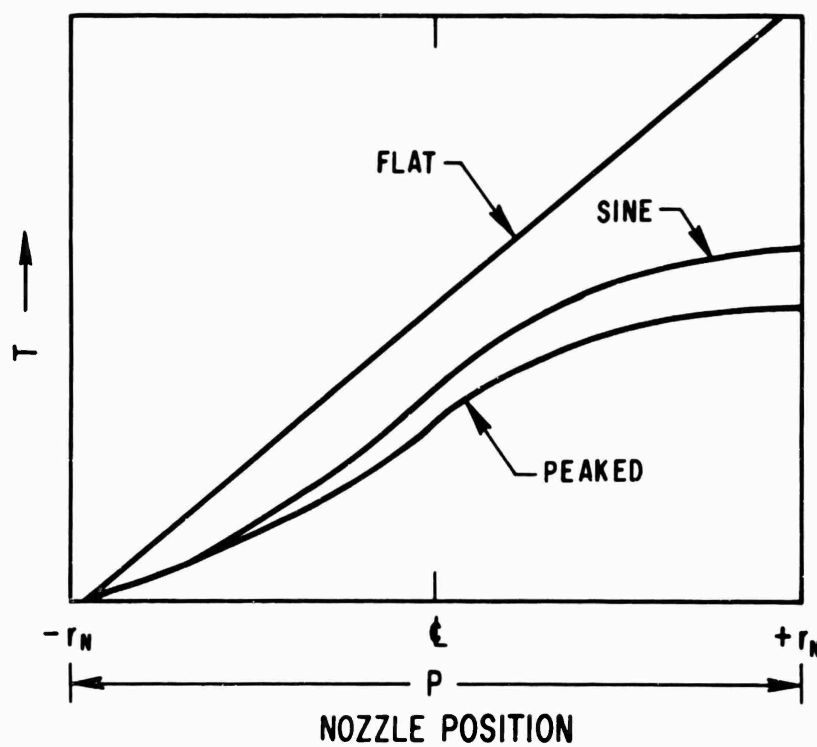


Figure 7. Typical Thermocouple Traces.

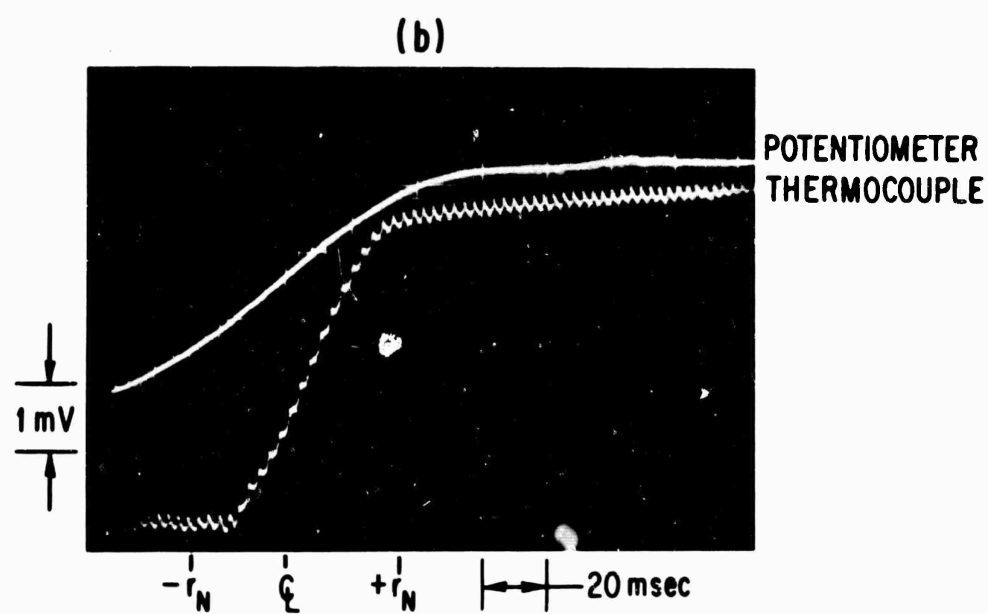
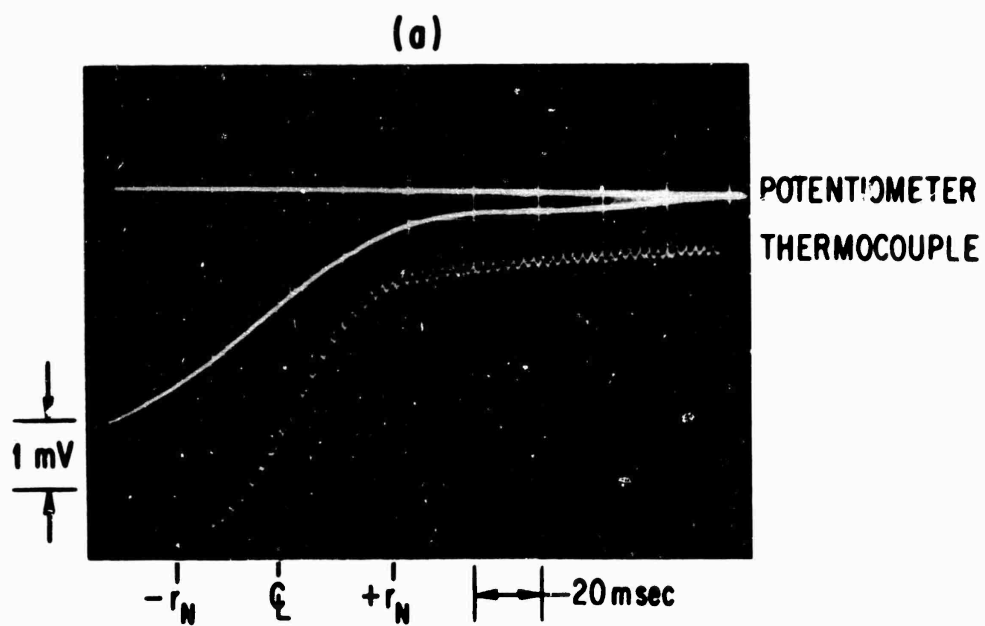


Figure 8. Calorimeter Traces: (a) from 3-in. Underexpanded Nozzle, (b) from 3-in. Overexpanded Nozzle.

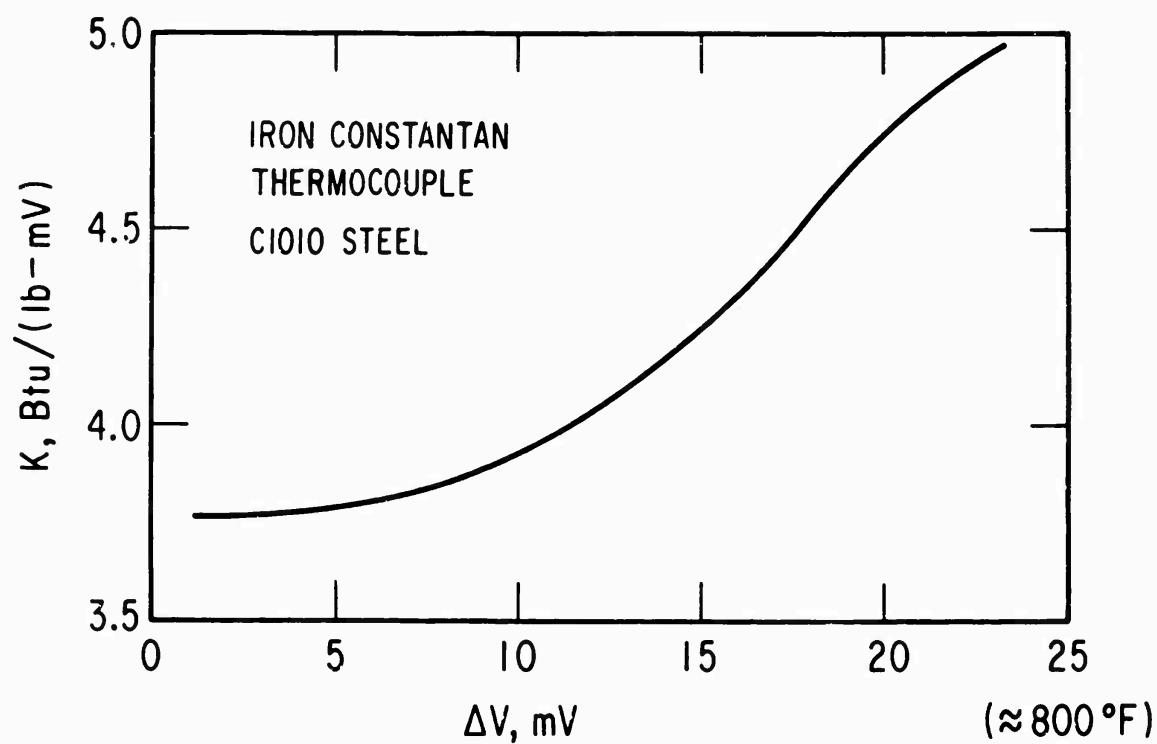


Figure 9. Calorimeter Constant at Given Thermocouple Output

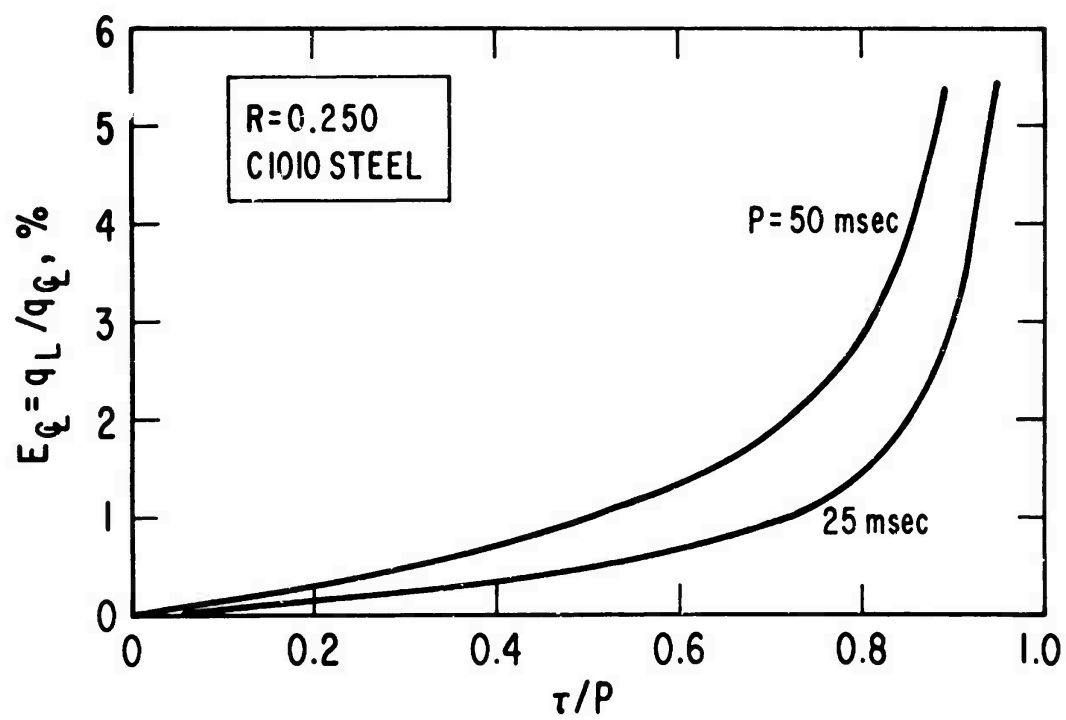


Figure 10. E_q for Sinusoidal Heat Flux Input

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13. ABSTRACT Fast-response, thin-skinned calorimeters provide a simple, rapid means of obtaining heat flux profiles of arc jet flows. A probe-sweeping technique is used to permit repeated radial profile measurements of heat flux during a single test run. It is shown that this technique is well suited for use in high heat flux environments when simplicity of calorimeter construction and data analysis is required. Such fast-response calorimeters also have application for catalytic surface measurements in nonequilibrium flows where time-dependent surface contamination is experienced. Experimental heat flux data from thin-skinned calorimeters used in arc jet flows are presented.		

KEY WORDS

Heat flux
Calorimeter
Arc jet

Abstract (Continued)