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Heat Flux Measurements

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HEAT FLUX MEASUREMENTS

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ABSTRACT

This paper discusses a new automated, computer controlled heat flux measurement facility. Continuous transient and steady-state surface heat flux values varying from about 0.3 to 6 MW/m^2 over a temperature range of 100 to 1200 K can be obtained in the facility. An application of this facility is the development of heat flux gauges for continuous fast transient surface heat flux measurement on turbine blades operating in space shuttle main engine turbopumps. The facility is also useful for durability testing at fast temperature transients.

INTRODUCTION

A unique, automated, computer controlled transient heat flux measurement facility is described. This facility is capable of partly simulating hot gas environments in the turbine section of the space shuttle main engine (SSME). It is thought that the heat flux to SSME turbine blades may be 50 to 100 times that encountered in aircraft engines (1). Also, SSME component transient surface temperatures may vary from 100 K to over 1200 K during engine startup and into quasi-steady gas temperature operation. Heat fluxes to the blades are thought to be at least 6 megawatts per square meter (MW/m^2). Thus a new facility is needed for development of durable heat flux gauges for measurement of transient surface heat flux in this very high, rapid transient heat flux environment.

Standards for calibration of heat flux measurement facilities are not available from the National Bureau of Standards (NBS). To our knowledge development of such a standard has not been solved. NASA Lewis Research Center has a grant with Case Western Reserve University for research on the development of a rational basis for calibration of heat flux sensors. At this point in time, commerical, water-cooled, factory-calibrated gauges are available for measurement to about 10 MW/m^2 at surface temperatures which are maintained about 280 to 360 K. To further investigate the operation of our facility over a temperature range of 100 to 1200 K, durable miniature plug-type gauges were fabricated from a high temperature nickel-base alloy.

A description of the new computer-controlled heat flux measurement facility is presented. An argon arc-lamp is used in this facility to produce a focused radiant heat source. Plots of transient and steady-state heat flux data obtained in the facility are presented. Uncertainties associated with the measurement system are discussed.

SYMBOLS

C_p	specific heat at constant pressure, J/kg K
k	thermal conductivity, W/mK
L	length of thermoplug, cm
$\dot{Q}$	thermal power per unit volume, MW/m^3
$\dot{q}$	absorbed surface heat flux, MW/m^2
T	absolute temperature, K
t	sample time, sec
Z	distance along axis of thermoplug, m; thermocouple locations, m
ρ	density, kg/m^3

Subscripts

c	conducted
s	stored

TRANSIENT VARIABLE PROPERTY THERMAL ANALYSIS FOR OBTAINING HEAT FLUX WITH PLUG-TYPE GAUGES

Figure 1 shows a schematic of a plug-type heat flux gauge mounted into a flat metal nickel-base alloy specimen. The thermoplug (Fig. 1) is cylindrical with one end or active surface exposed to an external environment. Although the energy source may be generated by any means, a thermal radiation energy source is used in this investigation. The thermoplug is insulated on all surfaces except the active surface. Therefore conduction heat transfer within the thermoplug is assumed one-dimensional. Heat flux is calculated from measured thermoplug temperatures using a temperature variant thermal property IHCP (Inverse Heat Conduction Problem) method developed in Ref. 1 to measure heat flux.

A relevant heat transfer equation (1) is the heat storage equation:

$$\dot{q}_s = \int_0^L (\rho C_p \, \partial T/\partial t) dZ$$

In Eq. (1), $\partial T/\partial t$ was evaluated by differentiating least-squares curve fit equations expressing measured thermoplug temperatures as a function of time at each temperature measurement location. Thermal properties were evaluated at local temperatures measured on the thermoplug.

A brief discussion and example of the numerical procedure for solving Eq. (1) is now presented. In this example, temperature history data (Fig. 2) measured at 0.6 sec is used. A least squares curve fit of T versus t at $Z = 0.00508$ cm is $T = 521.2 - 136.9/t$ for temperature data obtained at $t = 0.369$ to 0.743 sec. Therefore, at $t = 0.6$ sec, $T = 293$ K and $\partial T/\partial t = 380.3$ K/sec. Values of C_p as a function of temperature for MAR-M-246 (HF) (DS) were obtained from Ref. 2, 3 and 4. The density of this material is also given in these references but unfortunately not as a function of temperature. Also, these references give no indication of the experimental error associated with the measurement of these properties. The uncertainties in values of specific heat and density are probably +20 and +5 percent, resepctively. In this investigation, the specific heat was taken at the +20 percent level, and density was used at the +5 percent level. The thermal property uncertainties assumed herein are typical for many alloys. For more accurate heat transfer measurements, more accurate work on the measurement of alloy thermal properties is needed.

Then, at $T = 293$ K, specific heat = 478.6 J/kgK and density = 8866 kg/m. Therefore $\dot{Q}_s = 1614$ MW/m^3 at $Z = 0.00508$ cm. Now by the same procedure, $\dot{Q}_s =$ 1835, 1375 and 1098 MW/m at $Z = 0.0279$, 0.1750 and 0.3300 cm. These values of Z correspond to the locations of the other three thermocouples on the thermoplug. The values of $\dot{Q}_s$ versus Z computed above were plotted in figure 3 and connected with straight lines to form an irregular polygon. The area of the polygon, that is the heat flux equals 4.77 MW/m^2.

HEAT FLUX MEASUREMENT FACILITY

Apparatus

The facility consists of a test cell and a control room. A commerical (Vorter Industries Ltd.) arc-lamp system (5), a heat exchanger and a high speed three-axis positioning system are located in the cell. The lamp system comprises a lamphead attached to the side of a service module, a gas recirculation module and a water-cooled rhodium plated aluminum alloy elliptical reflector (Figs. 4 and 5). The reflector uniformly focuses thermal radiation generated by the arc onto a 1 x 4 cm test region located outside the reflector and 4 cm from the face of the reflector. The arc is positioned at one focus of the ellipse and the test region is positioned at the other focus. The gas reciculation module controls argon gas compression, regulation, water cooling and filtering. A SCR (silicon controlled rectifier) power supply, deionizer, water reservoir and water pumps are enclosed in the service module.

The lamphead (Fig. 5) contains water-cooled tungsten electrodes and a clear quartz tube. The electric arc is contained within the quartz tube. Arc stability for producing minimum arc fluctuation is attained by giving the argon gas a high rotational velocity as the gas enters the quartz tube. The swirling gas creates a radial pressure gradient with lower pressure along the center of the tube, thus stabilizing the arc on its axis. Deionized water is pumped in a spiral fashion along the inside of the tube. This water is used to cool the tube, to cool the optical reflector and to remove electrode debris from the inside of the tube. After the water has passed through the reflector and quartz tube, it is then filtered within the service module and cooled within the heat exchanger.

Control of Components and Data Acquisition

The arc-lamp and positioning system have computers built into them which are commanded by a main computer stationed in the control room. A positioning arm attached to the positioning system holds a heat flux gauge (Fig. 5). The arm also serves as a channel through which thermocouples attached to the gauge are routed to a data acquisition system, reference block and then to the main computer. At the beginning of a test, the positioning system is programmed to place the gauge into a Dewar filled with liquid nitrogen. After the gauge has reached liquid nitrogen temperature, the positioning system removes the gauge from the Dewar and places the gauge at the arc-lamp test region. After sufficient heating has been achieved, the positioning system removes the gauge from the test section and places it back into the liquid nitrogen-filled Dewar. The main computer also controls the data acquisition system which scans the incoming data. To minimize electrical noise induced into the thermocouple signal from facility components, the data acquisition system was located close to the gauge test area.

Commercial Heat Flux Gauges

Commercial, water-cooled heat flux gauges were used to directly measure surface heat flux generated by the arc-lamp. These gauges were large asymptotic (Garton gauge) calorimeters (6,7) which were 2.5 cm diameter and 3 cm long. The gauges were carefully calibrated by the manufacturer (Hy-Cal Engineering) as millivolt output versus absorbed heat flux at gauge body temperatures ranging from 280 to 360 K. The gauges were always used within this temperature range. The advertised accuracy of these gauges is about 3 percent.

Plug-Type Heat Flux Gauges

A schematic of the design of miniature plug-type heat flux gauges is shown in Fig. 1. The gauges were fabricated into the back wall of MAR-M-246 (HF) (DS) flat plate material 0.350 cm thick. This same material is used to fabricate SSME turbine blades. Trepanning was used to machine the gauges into the wall of the material. (Trepanning is a term used to indicate the machining of a circular groove into metals.) The thermoplug is naturally formed into a cylinder as the groove is partically machined through the thickness of the plate, i.e. the plug is an integral part of the floor of the annulus. The length of the thermoplug was taken as the distance from the front surface of the plate to the rear of the plug.

Since the thermoplug is an integral part of the floor of the annulus, there is no seam between the thermoplug and the wall. This is advantageous because the presence of seams would make the plug intrusive to the wall by causing disruptions in thermal boundary layers (8,9) on surfaces of blades operating in SSME turbopumps. Calculation of the uncertainty in heat flux measurement caused by a seam is very difficult, and therefore it is advantageous to eliminate seams.

The thermoplugs were formed into cylinders of 0.188 diameter and 0.330 cm length. The thickness of SSME turbine airfoils in the midchord region from root to midspan is about 0.25 to 0.51 cm. Thus the gauges were small enough to EDM into SSME airfoils.

A back cover enclosing the thermoplug and annulus (fig. 1) is welded to the wall thus trapping air within the annulus and behind the plug. This trapped air is a thermal insulator which minimizes heat transfer between the thermoplug, the surrounding wall and the back cover. The thermally insulating air also forces heat absorbed into the active surface of the gauge to be nearly one-dimensional along the thermoplug. This one dimensional condition is required for determining surface heat flux when using Eq. (1).

Chromel-Alumel therocouples are spot-welded at distances of 0.00508, 0.0279, 0.175 and 0.330 cm measured from the active or front surface of the gauge. This active surface was painted with a black high temperature paint which had the same absorptivity as the active surfaces of the commerical heat flux gauges. The Chromel-Alumel theromcouple wires are routed through the annulus to the rear of the gauge. Ceramic was placed between the bare wires and the metal walls to keep them from touching metallic parts. These small wires are spliced to Chromel-Alumel lead wire assemblies fastened to the rear surface of the flat stock material. The lead-wire assembly consists of Chromel-Alumel wires with diameter of 0.015 cm encased into two-hole ceramic tubing. The wires and ceramic tubing are swaged into a stainless steel casing to form the lead-wire assembly.

The diameter of each Chromel and Alumel thermocouple wire is 0.00762 cm. When welded together, the wires formed a cylindrical hot junction with thickness and diameter of 0.00508 and 0.0152 cm. The hot junction closest to the active surface of the gauge (surface thermocouple) is welded to the bottom of a hole drilled through the floor of the annulus along a line parallel to and 0.100 cm from the centerline of the thermoplug. This hole is drilled to a depth of 0.00508 cm from the front surface of the flat stock material. The other three hot junctions are welded to the thermoplug and are circumferentially located 120° from each other. The wires are extended from the hot junctions in a direction perpendicular to the surfaces and then routed to these lead-wire assemblies. This method of attachment can cause some heat leak along the thermocouple wires.

RESULTS AND DISCUSSION

Gardon Heat Flux Gauges

Figure 6 shows the steady-state surface heat flux measured with water-cooled commercial Gardon gauges at various arc-lamp input currents. Three different gauges were used to obtain this data on different days. Gauges 1 and 2 were designed to operate up to about 10 MW/m^2 and gauge 3 was designed to operate up to about 2.5 MW/m^2. The data are highly correlated (correlation coefficient = 0.98) suggesting that steady-state day-to-day heat flux repeatability of the facility is satisfactory as arc-lamp current is varied from 30 to 400 A. In figure 6, each symbol represents a value of the mean of 100 heat flux measurements taken on a given day at a chosen current. The 95 percent confidence interval associated with each symbol deviates ± 0.5 percent from the average value.

Figure 7 presents transient and steady-state heat flux data obtained with the commercial gauges during arc-lamp startup and into steady arc-lamp operation at 400 A. This transient and steady-state arc-lamp operation simulates an anticipated lower level of surface heat flux onto SSME turbine surfaces. A constant heat flux of about 0.15 MW/m^2 was measured during the first 0.3 sec of operation when the arc-lamp was idling at an input current of 30 A. Then at 0.3 sec, the input current was programmed to change to 400 A. This current change resulted in a heat flux rise to about 5.2 MW/m^2 at 0.7 sec which resulted in a transient output of about 12.6 MW/m^2 - sec. This transient may exist on turbine blades for SSME turbopumps. The lamp startup time period between 0.3 and 0.7 sec is defined herein as the region of transient heat flux. This flux rise is due to an increase in thermal radiant energy flowing from the electric arc onto the active surfaces of the gauges as the lamp reaches full power. A photodetector simultaneously measured an increase in millivolt output of about 3 to 54 millivolt at 0.3 to 0.7 sec (170 MV/sec) after which the photodetector output remained constant. A corrlation coefficient of 0.97 resulted from a cubic least-squares curve-fit of heat flux measured with gauges 1 and 2 versus lamp operation time in the transient region. Factors contributing to the uncertainty of heat flux data obtained with the commercial gauges in the facility are discussed in table I. The single line representing the cubic least-squares curve-fit in the transient region is associated with 100 transient heat flux data points taken on a given day at 10 randomly chosen days. The 95 percent confidence interval (at any instant of time) is ± 0.5 percent. This line then splits to show the band of maximum and minimum values of steady-state heat flux. The mean of the steady-state heat flux data (5.2 MW/m^2) is also shown in figure 7.

Prototype Miniature Plug-Type Gauges

Temperature history. Two miniature, plug-type heat flux gauges were geometrically arranged within a flat metal specimen and were positioned to fit within the uniformly illuminated test region. Thermocouples placed adjacent to the gauges along the front and back walls of the flat metal specimen measured no temperature variation along the surfaces of these walls. Thermoplug temperatures measured at four positions along the length of the plug are shown in figure 2 when the arc-lamp was operated 400 A. Each curve representing transient temperature data taken at identical locations on the two thermoplugs was repeated three times using three separate thermocouple installations on the same two gauges. The 95 percent confidence interval (at any time) was about ±0.5 percent. Because the thermoplugs are insulated on all surfaces except the active surfaces, the heat absorbed into the active surfaces is generally conducted in a one-dimensional manner into the cooler interior of the thermoplug. Therefore, as shown in figure 2, at any given time the temperature should decrease at increasing lengths of the plug. However prior to these tests, a plug-type gauge was installed in the facility which exhibited a reverse trend at longer times. That is, temperatures measured at the rear of the thermoplug were about 5 percent higher than the surface temperature. This problem was alleviated by reducing the length of the thermoplug by about 20 percent.

Heat flux history. Heat flux values measured in the facility with the miniature plug-type gauges are also presented in figure 7 for arc-lamp operation at 400 A. Each symbol represents the mean of 3 repeated measurements taken with 3 separate thermocouple installations on each gauge. The 95 percent confidence interval was about ±0.5 percent. Satisfactory agreement of heat flux measured with these plug-type gauges and the water-cooled Gardon gauges was achieved in the transient region and into the steady-state region up to about 2.6 sec of arc-lamp operation time. After 2.6 sec of arc-lamp operation time, the heat flux measured with plug-type gauges unsatisfactorily deviates more than 20 percent from the steady-state Gardon gauge measurements. According to Eq. (1), heat flux output is a function of gauge thermal properties and temperature gradient. Therefore this decrease of heat flux can be caused by use of inaccurate property measurements or from deviations in measured values of temperature gradient due to unwanted heat leaks from the plug. More measurements of the temperature variation of thermal properties over a broad range are needed for improved heat transfer analysis. Transient, variable property, two and three-dimensional analysis is very difficult; this work is being performed in a grant with Case Western Reserve University. At this point in time, steady-state, constant property calculations for assessing heat leaks suggest that radiation, conduction and convection could lead to a maximum uncertainty in measured heat flux of about 10 percent as shown in table I. These plug-type gauges were cycled 8 times between 100 and 1200 K. No deleterious durability effects were observed during these cycling tests.

Facility Measurement Uncertainty

Information about the uncertainty of the heat flux data obtained in the facility is given in table I. This uncertainty was determined by combining the uncertainty of appropriate elements contributing to the facility heat flux measurement from 0 to 2.6 sec of arc-lamp operation time. Many of these elements have been previously discussed.

Table I shows that the water-cooled gauges contribute less dispersion of heat flux data. However these water-cooled gauges can not be used to investigate facility operation from liquid nitrogen temperature to 1200 K. Therefore plug-type gauges were also used in this investigation.

As shown in table I, a major difficulty in obtaining heat flux measurements with the plug-type gauges is that there is a large uncertainty (20 percent) in thermal property data for MAR-M-246 (HF) (DS). Much more temperature dependent thermal property data for MAR-M-246 (HF) (DS) should be obtained so that heat flux data accuracy can be more carefully evaluated.

The calculated dispersion (Table I) is about 27 percent. The calculated dispersion reasonably agrees with the maximum experimental dispersion of 20 percent shown in figure 7 at 2.7 sec of arc-lamp operation time.

CONCLUDING REMARKS

A unique, automated, computer controlled heat flux measurement facility has been developed and is operational. The facility is being used in continuing heat flux gauge research to develop methods for measuring local absorbed transient and steady-state surface heat fluxes. The facility is also useful for durability testing at fast temperature transients.

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TABLE I. - ELEMENTS CONTRIBUTING TO FACILITY HEAT FLUX MEASUREMENT UNCERTAINTY

	Estimated maximum uncertainty of ith element, ± percent (*difficult estimate)
A. Element, A_i, contributing to facility heat flux measurement uncertainty:	
1. Effect of electrical noise from facility components on thermocouple temperature measurements.	3
2. Ability of data acquisition system to correctly process data.	1
3. Ability of positioning system to repeatedly set gauge at focus.	2
4. Day-to-day repeatability of arc-lamp intensity as determined with a photodetector.	5
5. Advertised accuracy of photodetector.	1
6. Uncertainty of commercial water-cooled Gardon gauges.	3*
$\sum A_i^2 = 49$ percent	
B. Element, B_i, contributing to facility heat flux measurement uncertainty:	
1. Effect of electrical noise from facility components on thermocouple temperature measurements.	3
2. Ability of data acquistion system to correctly process data.	1
3. Ability of positioning system to repeatedly set gauge at focus.	2
4. Day-to-day repeatability of arc-lamp intensity as determined with.	5
5. Advertised accuracy of the photodetector.	1
6. Uncertainty in calculation procedure for determination of heat flux using internal temperature measurements on plug-type heat flux gauges:	
a. Curve fitting.	5
b. Accuracy of literature specific heat values	20*
c. Accuracy of literature density values	5*
d. Thermocouple accuracy	2
e. Measurement accuracy of thermocouple junction on thermoplug	2
f. Uncertainty of $\partial T/\partial t$ value due to large temperature gradient along finite thermocouple junction	10*
g. Uncertainty of $\partial T/\partial t$ due to heat losses (radiation, conduction,	10*
$\sum B_i^2 = 698$ percent	
C. Expected root-mean-square uncertainty of facility operation $\left(\sum A_i^2 + B_i^2\right)^{1/2} = 27$ percent	

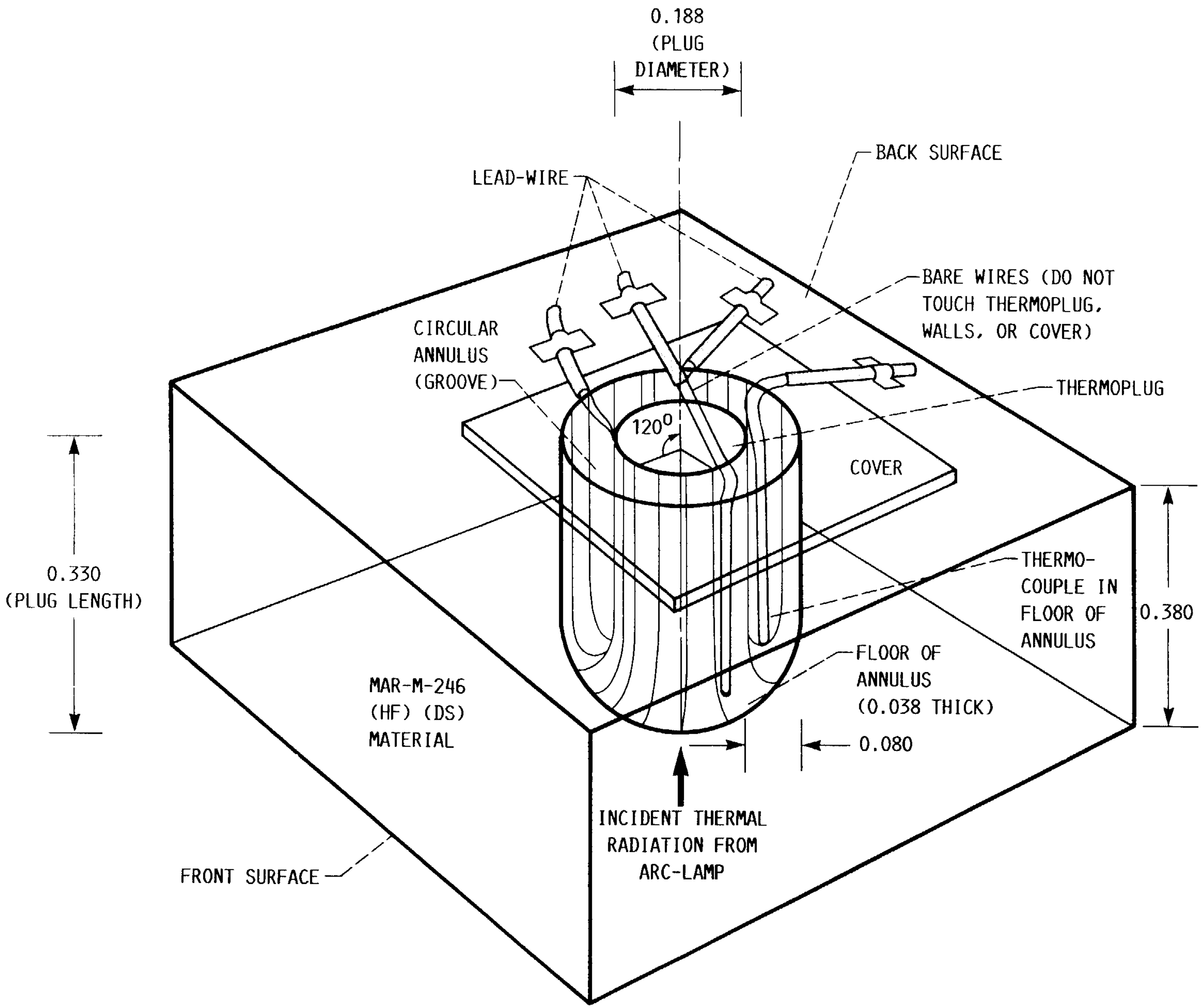

FIGURE 1. - PLUG-TYPE HEAT FLUX GAUGE. (DIMENSIONS IN CENTIMETERS).

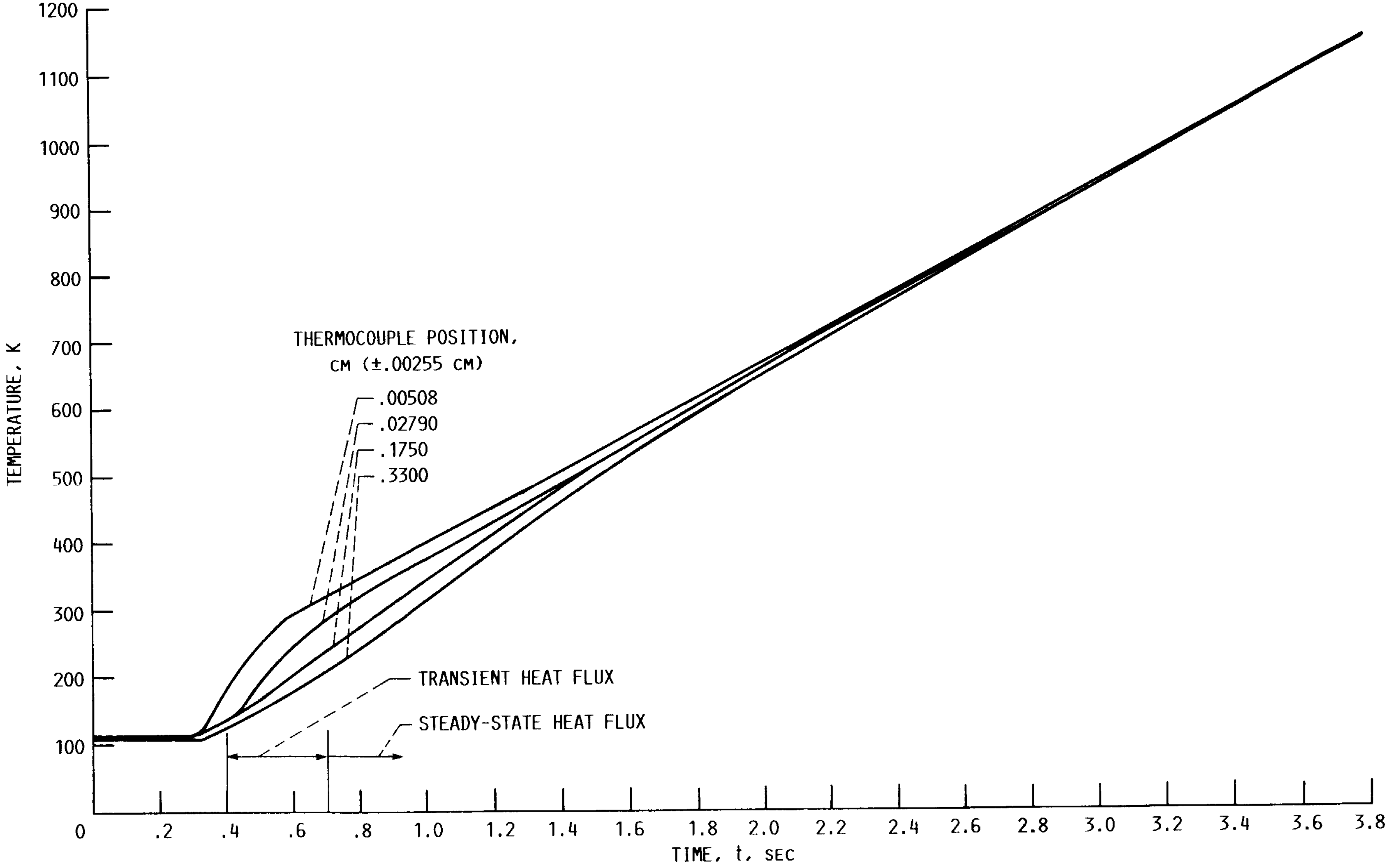

FIGURE 2. - TEMPERATURE HISTORY OF THERMOPLUG (ARC—LAMP CURRENT = 400 AMPS).

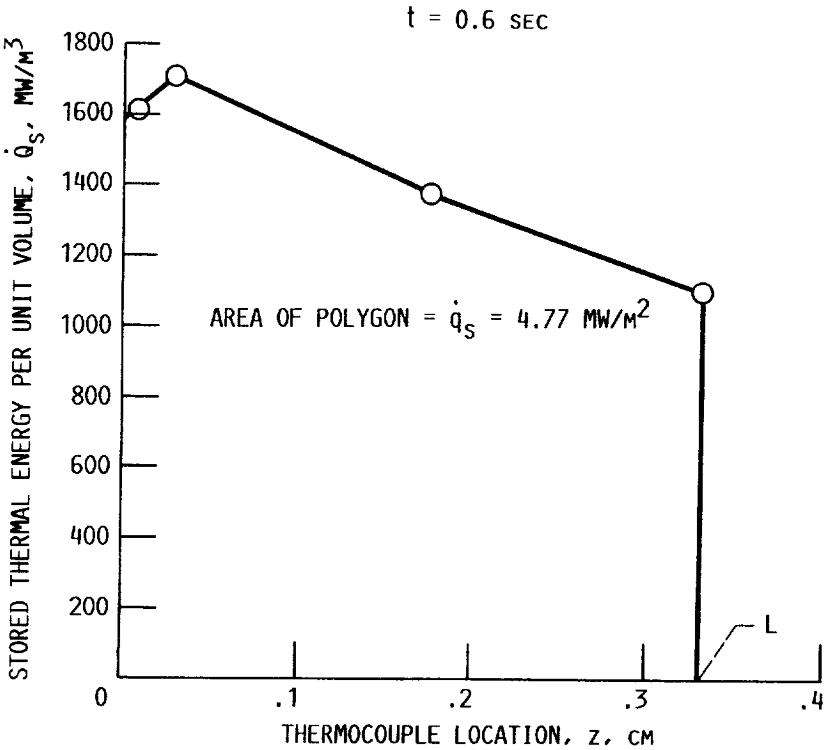

FIGURE 3. - DETERMINATION OF STORED HEAT FLUX, $\dot{q}_S$ FROM LOCAL VALUES OF THERMAL ENERGY PER UNIT VOLUME, $\dot{Q}_S$.

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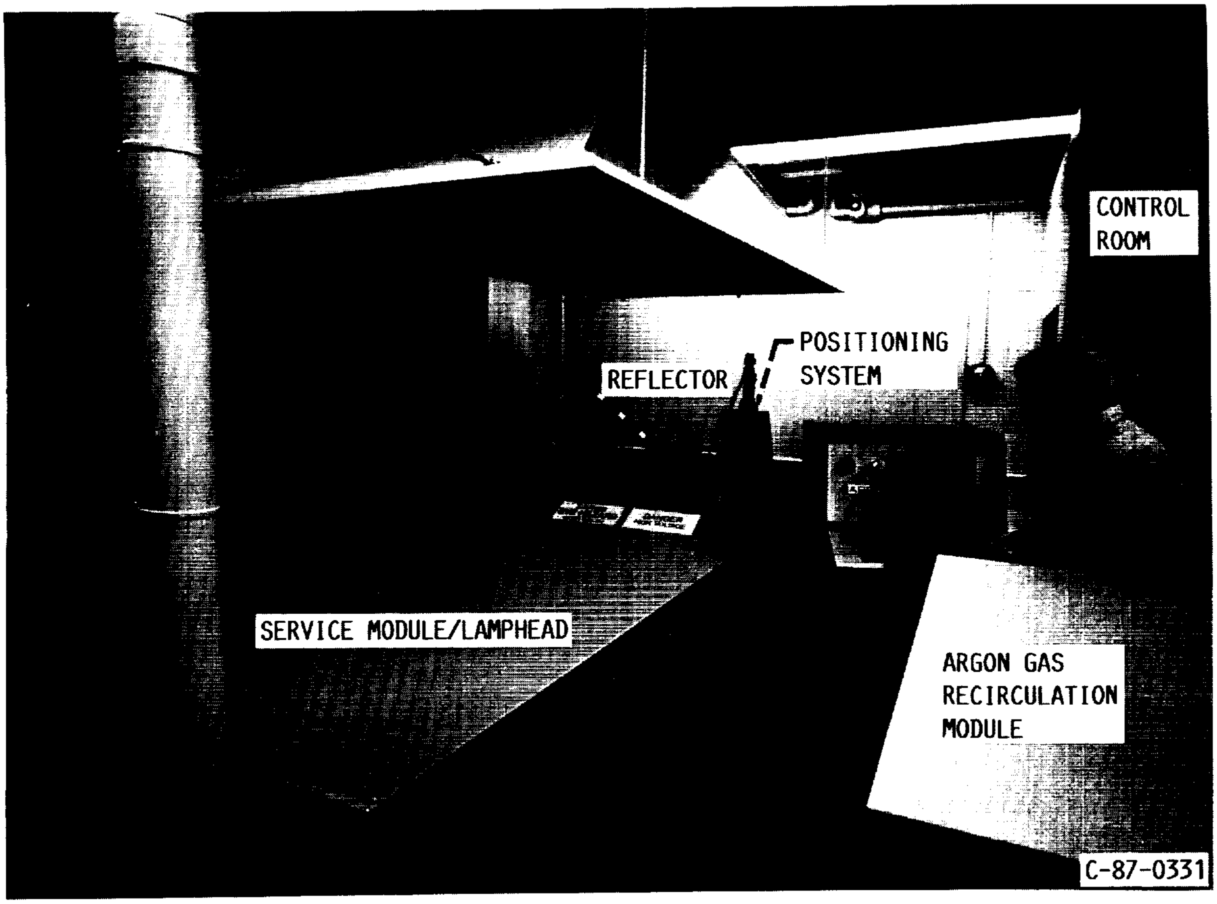

FIGURE 4. - VIEW OF TEST CELL.

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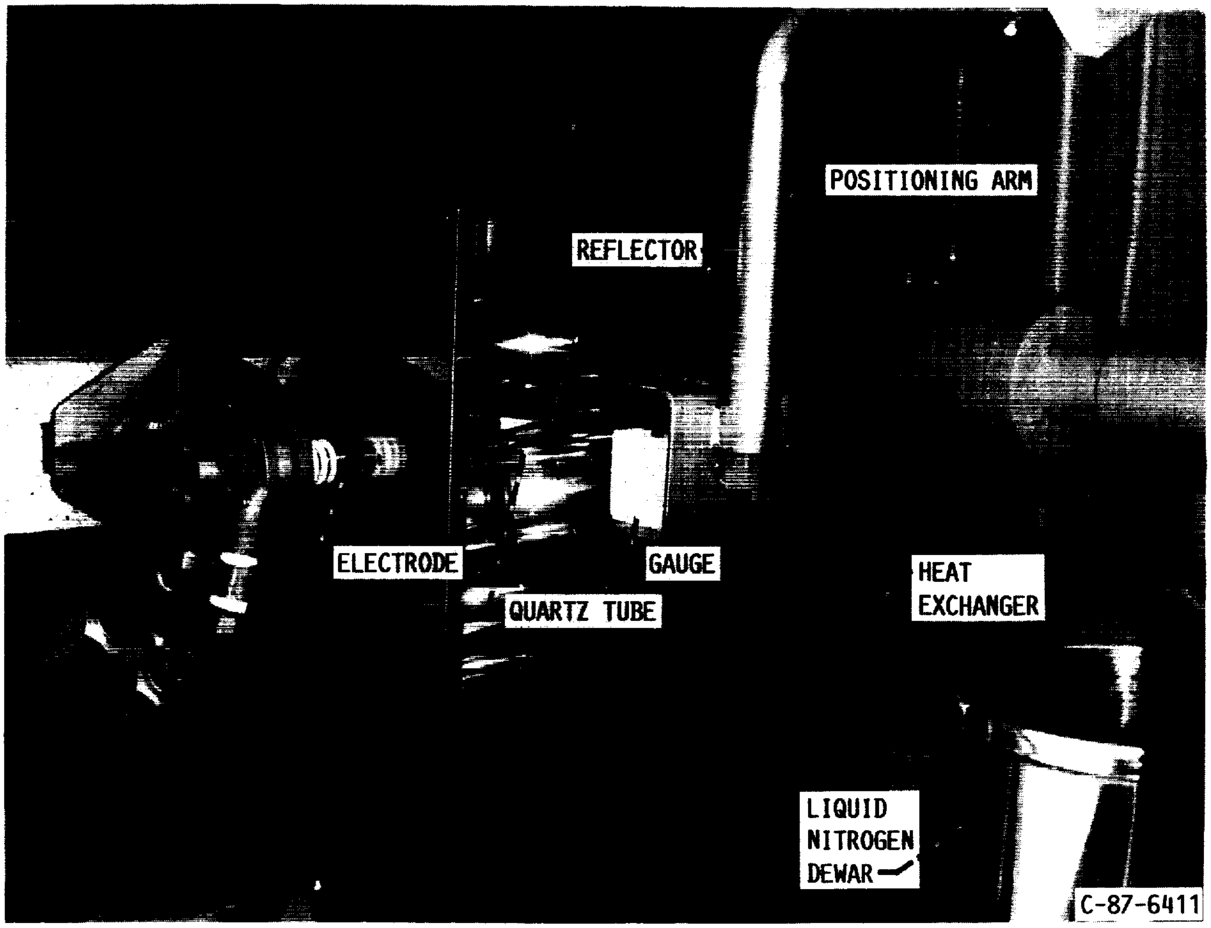

FIGURE 5. - LAMPHEAD AND POSITIONING ARM.

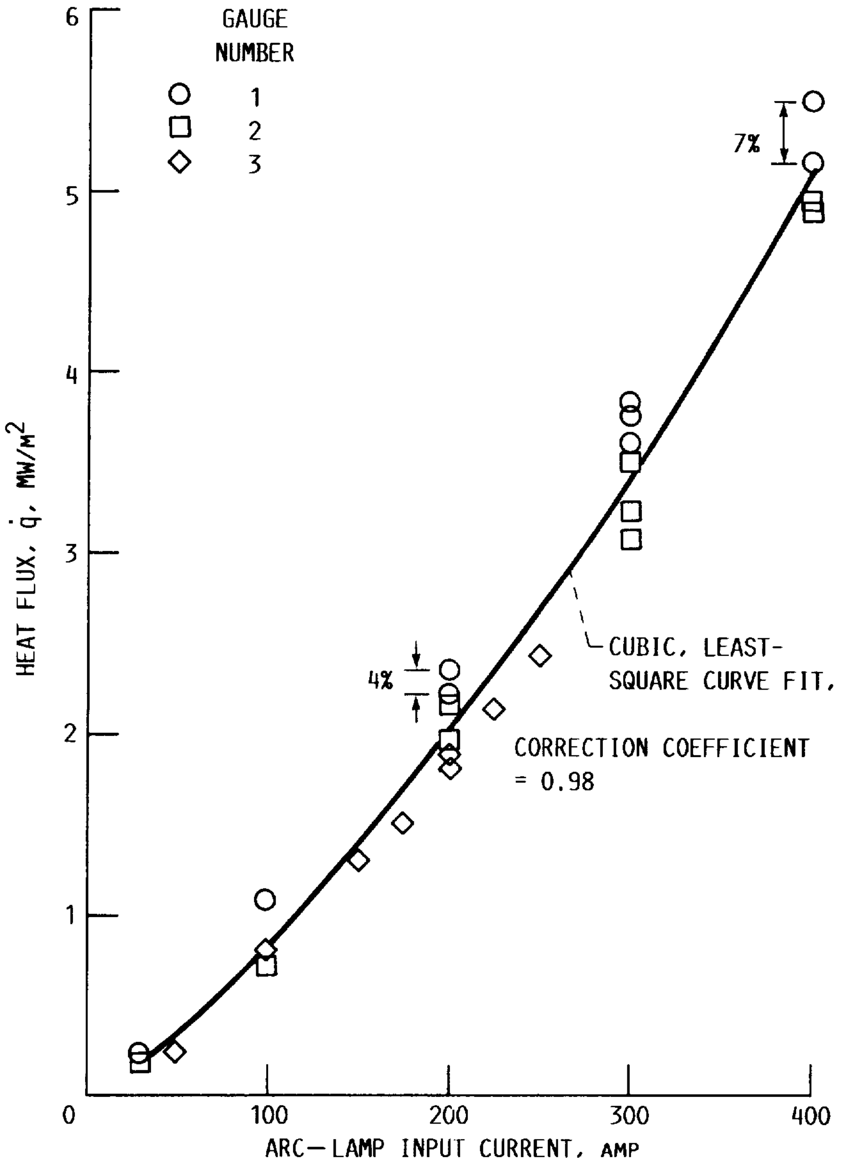

FIGURE 6. - STEADY-STATE HEAT FLUX MEASURED WITH THREE COMMERCIAL GAUGES.

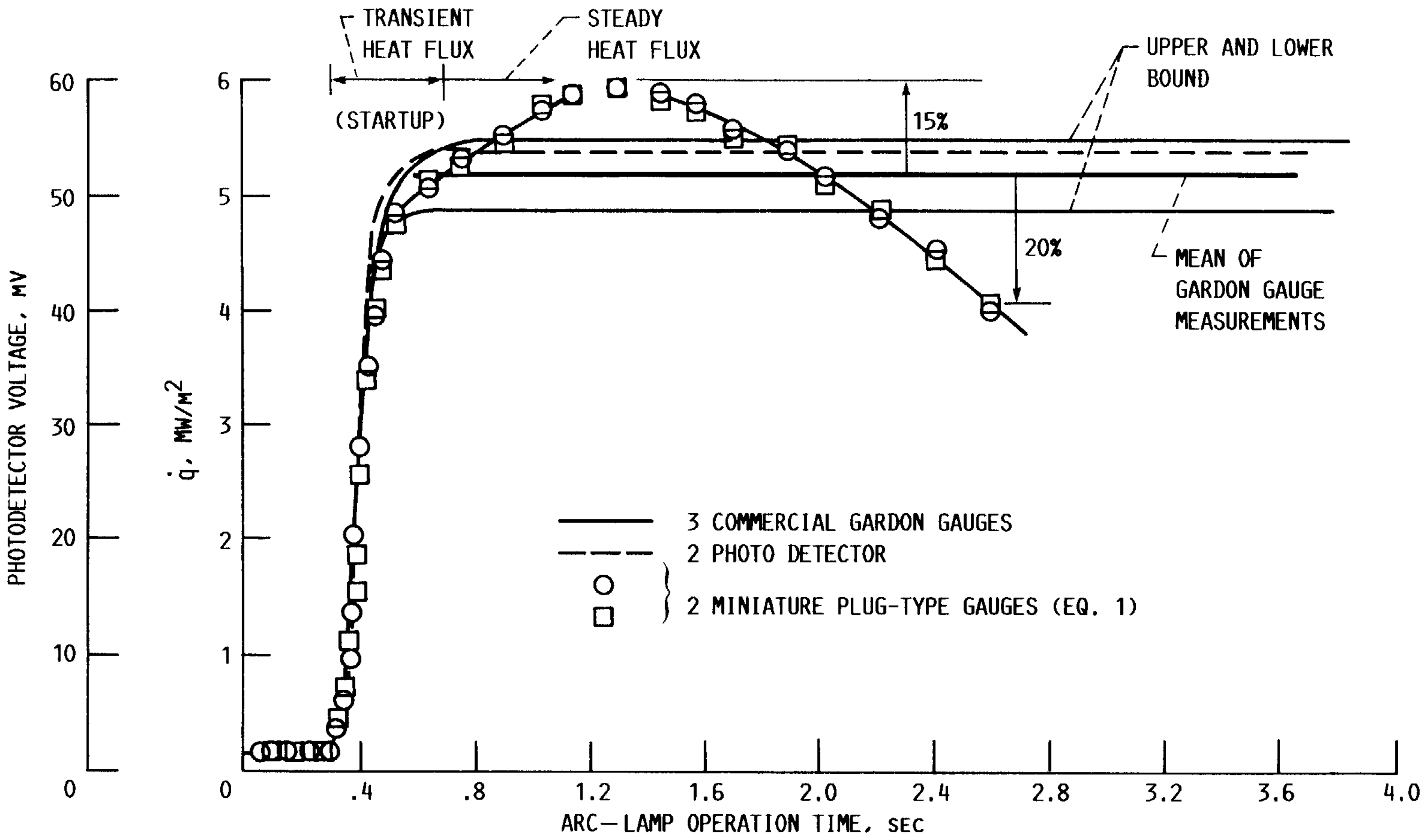

FIGURE 7. - HEAT FLUX HISTORIES MEASURED WITH GARDON AND MINIATURE PLUG-TYPE GAUGES (LAMP CURRENT = 400 AMPS).

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16. Abstract

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