AEDC-TR-83-13

c.1

Determination of the Uncertainty of Experimental Heat-Flux Calibrations

C. T. Kidd
Calspan Field Services, Inc.

August 1983

Final Report for Period October 1, 1981 — September 30, 1982

Approved for public release; distribution unlimited.

ARNOLD ENGINEERING DEVELOPMENT CENTER
ARNOLD AIR FORCE STATION, TENNESSEE
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

NOTICES

APPROVAL STATEMENT

This report has been reviewed and approved.

Marshall K. Kingery

MARSHALL K. KINGERY
Directorate of Technology
Deputy for Operations

Approved for publication:

FOR THE COMMANDER

Marion L. Laster

MARION L. LASTER
Director of Technology
Deputy for Operations

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

Field	Entry
1. REPORT NUMBER	AEDC-TR-83-13
2. GOVT ACCESSION NO.	
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle)	DETERMINATION OF THE UNCERTAINTY OF EXPERIMENTAL HEAT-FLUX CALIBRATIONS
5. TYPE OF REPORT & PERIOD COVERED	Final Report for Period Oct. 1, 1981 - Sept. 30, 1982
6. PERFORMING ORG. REPORT NUMBER	
7. AUTHOR(s)	C. T. Kidd, Calspan Field Services, Inc.
8. CONTRACT OR GRANT NUMBER(s)	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	Arnold Engineering Development Center/DOT Air Force Systems Command Arnold Air Force Station, TN 37389
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS	65807F
11. CONTROLLING OFFICE NAME AND ADDRESS	Arnold Engineering Development Center/DOS Air Force Systems Command Arnold Air Force Station, TN 37389
12. REPORT DATE	August 1983
13. NUMBER OF PAGES	60
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	
15. SECURITY CLASS (of this report)	Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	N/A

16 DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17 DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18 SUPPLEMENTARY NOTES

Available in Defense Technical Information Center (DTIC).

19 KEY WORDS (Continue on reverse side if necessary and identify by block number)

heat flux	standard deviation
calibration	bias
slug calorimeter	temperature measurement
transfer standard	uncertainty

20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

A description and the results of a study of the uncertainty associated with experimental calibration of heat-flux transducers/gages performed at the Arnold Engineering Development Center (AEDC) are given. Determination of an overall or total calibration uncertainty was achieved by combining the results of different groups of experimental calibrations performed at the AEDC and the National Bureau of Standards (NBS), respectively.

(Continued)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

The first group of calibration data was obtained by calibrating six heat-flux transducers fabricated "in-house" at the AEDC versus calibration standard slug calorimeters also fabricated at the AEDC. The radiant heat source used in the calibrations was a nine-unit (1-kw max/unit) quartz tube lamp bank. A classical precision term was calculated for each of the six transducers from the results of these experimental calibrations.

Acquisition of the second group of calibration data was achieved by sending the same six transducers to the Fire Research Center of the NBS in Washington, D. C. for experimental calibration services. Thus, traceability to NBS heat-flux standards was achieved. A radiant heat source was also used by the NBS and the calibrations were performed in a manner similar to the procedures employed at the AEDC. Calibration data obtained at the AEDC and the NBS were compared to determine a bias value for each of the six transducers. A total uncertainty value for each transducer was calculated by combining the precision and bias terms. The average total uncertainty calculated for the six transducers was nominally ±3 percent.

PREFACE

The research reported herein was performed at the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC). The Air Force project manager was M. K. Kingery. The results were obtained by Calspan Field Services, Inc., operating contractor for the aerospace flight dynamics testing effort at the AEDC, AFSC, Arnold Air Force Station, Tennessee, 37389, under AEDC Project No. D228VW (Calspan Project No. V32L-B2). The manuscript was submitted for publication on February 17, 1983.

CONTENTS

ILLUSTRATIONS

TABLES

APPENDIXES

1.0 INTRODUCTION

Several different sensors and/or techniques are utilized for the measurement of aerodynamic heating in the continuous wind tunnels of the von Kármán Gas Dynamics Facility (VKF) at the Arnold Engineering Development Center (AEDC) (Ref. 1). These include discrete transducers such as Gardon gages (Refs. 2 and 3) and Schmidt-Boelter gages (Refs. 4 and 5), surface temperature sensors such as thin-film resistance thermometers (Refs. 6 and 7) and coaxial surface thermocouples (Refs. 3 and 8), calorimetric devices such as thin-skin models (Ref. 3) and individual slug calorimeters (Refs. 9 and 10), and infrared imaging systems for thermal mapping (Ref. 11). Regardless of the sensor or technique employed for these measurements, the experimental calibration of the device should be traceable to common heat-flux standards.

Heat-transfer rate or heat flux is perhaps the least tangible fundamental aerodynamic parameter measured in wind tunnel testing. Because of the elusive quality of the parameter, it is difficult to appraise the accuracy of heat-flux calibrations. Prior to October 1977, the National Bureau of Standards (NBS) neither maintained calibrated heat sources or heat-flux measurement standards, nor provided heat-flux transducer calibration services. Therefore, heat-flux calibration traceability to NBS standards was not possible. The heat-flux transducer designer usually inherited the added responsibility of establishing reliable calibration standards and calibration systems.

With regard to the experimental calibration of transducers for wind tunnel heat-flux measurements, standards were established at the AEDC in 1963. These standards are slug-calorimeter transducers with fine-wire thermocouple temperature sensors. The experimental calibrations of all heat-flux transducers employed for wind tunnel measurements at the AEDC are traceable to the slug-calorimeter standards.

Because of the excellent heat storage properties of the slug calorimeter, it takes an excessively long period of time for the calorimetric mass to return to ambient temperature after exposure to the heat source. Because of the amount of time involved and the data reduction technique (measurement of slope), the use of the slug-calorimeter standards on a routine basis is impractical. In order to alleviate this problem, the heat-flux calibration is transferred from the slug-calorimeter standards to transfer-standard transducers. Transfer standards used with the radiant heat-flux calibration facilities at the AEDC are 1/4-in.-diam conventional Gardon gages (Ref. 2) and Schmidt-Boelter gages (Ref. 4). The transfer standards are used to measure the heat-flux level from the heat source for routine calibrations. The basic principle of operation and physical configurations of the transfer standards and many transducers used in wind tunnel tests are identical. Therefore, a high degree of operational compatibility exists between the transfer standards and test transducers for routine calibration procedures.

In the October 1977 edition of the *Optical Radiation News*, the NBS offered heat-flux calibration services on a very limited basis and over a low range of heat-flux levels (Ref. 12). Although several inquires were made to the NBS since late 1977 regarding heat-flux calibration services, only recently were these services made available to the AEDC. Six heat-flux transducers fabricated and calibrated at the AEDC were subsequently sent to the Fire Research Center (FRC) of the NBS for calibration. The results of NBS calibrations were received about June 1, 1982, and are discussed in this report.

As a result of the heat-flux calibrations performed at the NBS, the AEDC now has traceability to NBS standards. A comparison of the calibration results obtained from the NBS with results obtained at the AEDC was made in order to calculate a total calibration uncertainty value.

2.0 AEDC HEAT-FLUX CALIBRATIONS

The apparatus/hardware and procedures/methods utilized in performing experimental heat-flux transducer calibrations at the AEDC are described in this section. Results of the AEDC calibration of the six heat-flux transducers also calibrated at the NBS are included.

2.1 APPARATUS

The apparatus used for the calibrations described in this report is basically the same as that used in model material thermophysical property measurements. This hardware is shown in Fig. 1. A schematic diagram illustrating the procedure utilized in the experimental calibration of transfer-standard gages is shown in Fig. 2.

2.1.1 Transfer Standards

Transducers described in this report are used as transfer-standard gages and consist of four 1/4-in.-diam conventional Gardon gages and two 1/4-in.-diam Schmidt-Boelter gages. These transducers were designed and fabricated at the AEDC.

2.1.1.1 Gardon Gages

The mechanism of heat transfer in the Gardon gage is by radial heat conduction. Its principle of operation is well known and is widely documented (Refs. 2, 3, 5, and 13). Gardon gages feature a self-generating output directly proportional to the heat flux incident on the sensing surface and excellent calibration stability. Limitations are low output at low heat-flux levels (≤ 0.5 Btu/ft^2-sec) and only fair durability. Gardon gages find widespread use as transfer standards in radiant heat-flux calibration facilities. A sketch of the Gardon gage used in these experiments is shown in Fig. 3.

2.1.1.2 Schmidt-Boelter Gages

Axial heat conduction through layers of different materials is the heat-transfer mechanism in the Schmidt-Boelter gages (Refs. 4, 5, and 13). These sensors are not as widely used as Gardon gages for transfer standards, but they are reliable instruments which feature self-generating output directly proportional to incident heat flux, good sensitivity, excellent calibration stability, and excellent durability. It is expected that Schmidt-Boelter gages will replace Gardon gages in many applications as the technical community becomes increasingly aware of their operational advantages. Figure 4 shows the construction details of the Schmidt-Boelter gage used as a transfer standard.

2.1.2 Heat-Flux Measurement Standards

As previously stated, all experimental heat-flux transducer calibrations performed at the AEDC are traceable to slug-calorimeter standards. A slug calorimeter is comprised of a thermally insulated calorimetric mass with provisions for measuring its back-surface temperature history. The basic principle of operation of the slug calorimeter is simple and well documented (Refs. 5, 13, and 14). Implied in the theoretical concept of the slug calorimeter is that all of the heat flux incident on the sensing surface of the instrument during the period of measurement is stored in the calorimetric mass (slug). The expression utilized for the measurement of heat-flux data is

$$\dot{q} = \varrho \, \ell \, C_p \frac{dT_{back}}{dt} \tag{1}$$

where

$\dot{q}$ = heat flux or heat-transfer rate, Btu/ft^2-sec
ϱ = density of calorimetric mass, lb/ft^3
ℓ = thickness of calorimetric mass, ft
C_p = specific heat of calorimetric mass, Btu/lb-°F
T_{back} = back-surface temperature of calorimetric mass, °F
t = time, sec

Practical advantages of using the slug calorimeter as a heat-flux measurement standard can be realized by examination of Eq. (1). Density (ϱ) and specific heat (C_p) are the only thermophysical properties whose absolute values must be known. Both the thickness (ℓ) of the calorimetric mass and the time intervals can be measured to 0.10-percent accuracy. A section drawing of the slug calorimeter used in the calibrations is shown in Fig. 5.

2.1.2.1 Analytical Considerations

Equation (1) defines the ideal slug-calorimeter relationship between the heat flux incident on the sensing surface of the calorimetric mass and the back-surface temperature history. Implied in this relationship is that heat is received only at the sensing surface and no heat is lost from the calorimetric mass during the time period of interest. These restrictions must be met so that the use of Eq. (1) will yield accurate heat-flux measurements. The slug calorimeter shown in Fig. 5 was designed with the aid of a finite-element, two-dimensional heat-conduction code designated TRAX (Ref. 15). Analytical results graphically illustrated in Appendix A show that the physical dimensions and thermal properties of the calorimetric mass and mass support are important considerations in the design of an efffective slug calorimeter.

2.1.2.2 Calorimeteric Mass

A 0.50-in.-diam by 0.10-in.-thick disk of OFHC (oxygen-free high-conductivity) copper is used as the calorimetric mass in slug-calorimeter standards. OFHC copper is certified by the supplier to be 99.99-percent pure. Copper was selected as the material for the calorimetric mass because its thermal and physical properties (C_p and ϱ) are known to good accuracy ($\leq$1.0-percent error) and are well documented (Ref. 16). The specific heat of copper is nearly constant over the temperature range of interest, $\Delta T \leq 50°F$ (Ref. 16). The thickness of the copper disk can be measured to an accuracy of 0.0001 in. or 0.1-percent error with a precision micrometer.

2.1.2.3 Temperature Sensors

Fine-gage (0.003-in.-diam) thermocouple wires with Teflon® insulation are used to measure the time-resolved temperature rise of the calorimetric mass in the slug-calorimeter standards. These thermocouple pairs are installed by swaging the individual wires into the backside of the copper disk. Two different American National Standards Institute (ANSI) type thermocouple wire pairs were installed on two of the calorimeters. Slug-calorimeter standards with Chromel® -constantan (ANSI type E), iron-constantan (ANSI type J), and Chromel-Alumel® (ANSI type K) thermocouples or combinations of these were fabricated and used in the experimental calibrations described in this report.

2.1.3 Heat-Source Hardware

The heat source (and associated hardware) utilized in the calibrations is a quartz tube lamp bank (see Figs. 1 and 2) normally used in conjunction with model material thermophysical property measurements. Nine 1,000-w (3/8-in.-diam by 12-in.) tungsten filament lamps spaced 0.5 in. apart comprise the lamp bank. The heat source is capable of supplying incident heat-flux levels up to 15 Btu/ft^2-sec to a test transducer/material specimen. Longitudinal and transverse normalized heat-flux maps are shown in Figs. 6 and 7, respectively, to define areas of constant heat flux. Large (15- by 3.5- by 0.06-in.) double-decked, spring-loaded, mechanically operated shutters shield the heat source from the heat-flux sensors until the shutters are actuated. The transfer-standard transducers and slug calorimeter are located about 2.75 in. below the lamp bank in a 2- by 2- by 1-in. mounting block. There are provisions for water cooling the lamp bank hardware and blowing cool air onto the test transducer/material specimen after heating.

2.1.4 Data Acquisition System

The data acquisition system used in these experiments is a Preston GMAD-3 analog-to-digital (A/D) converter operating under the control of a Digital Equipment Corporation (DEC) PDP-11/10 minicomputer (see Fig. 2). For the measurements described in this report, the system was configured to accept up to six channels of analog data at a sampling rate of ten points per second for a total time period of 15 sec. There are provisions on the A/D converter system for individual channel zero and gain adjustments. Simple manual inputs can be made to the system either at a teletype terminal or by thumbwheel switches on a console panel. A paper tape containing all the digital data is generated by the system at the conclusion of each calibration data run. Calibration data on the paper tape are processed by the facility computer (DECsystem-10) and stored on disk file for future reference.

2.1.5 Reference Junction Compensators

An Omega-CJ cold-junction compensator (see Fig. 2) was used with each backside thermocouple to simulate effectively a thermocouple cold-junction temperature of 32°F (0°C). The cold-junction compensators have a stability of ±0.2°C. Cold-junction compensators were available for ANSI types E, J, and K thermocouples.

2.2 EXPERIMENTAL CALIBRATION PROCEDURES

Experimental calibrations described in this report were performed in radiation heat-flux facilities. As stated in Section 2.1.3, the radiant heat source utilized for the AEDC calibrations is comprised of nine 1,000-w quartz tube lamps. Quartz transmits a constant percentage of its radiant energy over a wavelength from 0 to about 3 μ (Ref. 17). The percentage transmittance of quartz begins to decrease rapidly just past 3 μ and is fully cut off (zero transmittance) at a wavelength just below 5 μ. In order to comply with the requirements of effective calibration procedures, a thin ($\approx$0.0005-in.) coating whose absorptivity is (1) high, (2) constant, and (3) known to good accuracy was applied to the sensing surface of each sensor. Krylon® No. 1602 ultra-flat black spray enamel is the coating used at the AEDC. The absorptivity of the Krylon coating has been measured with a Beckman® DK-2A spectroreflectometer on several occasions and was determined to be 0.97 ($\leq \pm$ 1-percent uncertainty) for wavelengths of 0.5 to 6.0 μ. The Krylon coating showed no signs of variance from the constant 0.97 absorptivity at either end of the spectrum.

Four transfer-standard gages were generally calibrated against one slug-calorimeter standard. All sensors were mounted in a single 2.0- by 2.0- by 1.0-in. stainless-steel block with the slug calorimeter in the center of the block and two 1/4-in.-diam transfer standards located on each end of the block on 1.5-in. spacing on the longitudinal centerline of the heat source. The slug calorimeter had one or two different fine-wire thermocouples for measuring the slope of the time-resolved back-surface temperature rise. With the heat-flux sensors fully covered by the mechanical shutters, the lamp bank was turned on and allowed to remain on for about 60 sec in order to permit the lamps to reach full operating temperature at the desired voltage (or heat-flux) setting. The data acquisition system was turned on at this time. After a delay time period of from 3 to 5 sec, the heat-flux sensors were simultaneously irradiated by the lamp bank by actuating the mechanical shutters. The computer automatically turned off the data acquisition system and generated a paper tape containing the digital data after acquiring data for a total time period of 15 sec. Electrical power to the lamp bank was turned off manually. Temperatures of various parts of the heat-source hardware were continuously monitored by a scanning digital thermometer. After the heat source and its component parts and the slug calorimeter returned to ambient temperature, the calibration procedure was repeated as required. This experimental calibration procedure is illustrated in the schematic diagram shown in Fig. 2.

2.3 EXPERIMENTAL RESULTS

Results of the experimental calibrations of six transfer-standard gages performed at the AEDC are shown in this section. These results are presented in tabular format and include the calculation of a classical precision term for each of the six gages. A sample calibration data run involving a slug calorimeter with two different backside thermocouples and four transfer-standard Gardon gages is analyzed in its entirety from the measurement of the timewise output signals for each sensor to the calculation of individual gage scale factors.

2.3.1 Data Processing

For each calibration data run, a PDP-11/10 minicomputer generates a paper tape containing all the digital data in approximately 900 digital words. Analog inputs are processed as 12-bit words. The paper tape is transferred to a DECsystem-10 computer where the data are stored on a disk file and are processed into appropriate engineering units.

2.3.1.1 Timewise Output Signals

Converting the timewise digital data into engineering units is the first step in data processing. A tabulated computer printout of six analog inputs in engineering units (mv) at 0.10-sec intervals for a total time period of 15 sec is provided as part of the reduced data. Further operations on the data are performed on an as-required basis. Timewise analog data in engineering units are required in routine Gardon and Schmidt-Boelter gage calibrations. However, obtaining indicated heat flux from slug calorimeters requires a conversion from sensor output to temperature plus a measurement of the slope of the time-resolved temperature history.

Table 1 is part of a standard data printout for a typical calibration run (Group No. 8012). Columns 2 through 7 contain the timewise output signals from four Gardon gages and two slug-calorimeter thermocouples. The appropriate Gardon gage designation (Columns 3, 5, 6, and 7) and thermocouple type (Columns 2 and 4) are indicated above the columns. The reader's attention is directed to Columns 3, 5, 6, and 7 to observe that all four Gardon gage outputs indicate essentially zero output signal until the elapsed time reaches just over 5 sec. The Gardon gage outputs begin to rise and stabilize at a nearly constant level from about 7.2 sec until the end of the data acquisition period at 15.2 sec. Observation of Columns 2 and 4 reveals that both thermocouple outputs start at a level greater than 1.0 mv and maintain that constant level until the elapsed time reaches just over 5 sec. At about 5 sec, the slug-calorimeter outputs begin to rise linearly with time until the end of the calibration data run. The sequence of events described above corresponds to (1) turning on the data acquisition system at time zero, (2) actuating the mechanical shutters to irradiate the heat-flux sensors at a time of about 5 sec, and (3) turning off the data acquisition system at time equals 15.2 sec.

An explanation of the items listed in Columns 8, 9, 10, and 11 in Table 1 is in order. These items represent reduced data, but are indicators only and are not used in calibration data calculations. QDOT1 and QDOT2 (Columns 8 and 9) are reduced heat-flux data and are calculated by multiplying the scale factors for Gardon gages GG33 and GG24, determined by the NBS calibration, by their appropriate timewise output signal levels. QDOTR1/2 (Column 10) is simply the ratio of the reduced heat-flux levels for Gardon gages GG33 and GG24, respectively. EQUIP TEMP (Column 11) represents the reduced temperature of the slug calorimeter as indicated by the iron-constantan thermocouple.

2.3.1.2 Millivoltage to Temperature Conversion Data

In March 1974, the National Bureau of Standards issued a new reference standard for thermocouple temperature-emf equivalents (Ref. 18). This publication, based on the International Practical Temperature Scale of 1968 (IPTS-68), replaced NBS Circular 561 which was previously used for various thermocouple combinations. Coefficients for converting thermocouple millivoltage measurements to equivalent temperatures are given in Ref. 18 for all the thermocouple pairs (ANSI types E, J, and K) utilized for obtaining the experimental data described in this report. These coefficients were computed by using the standard least-squares curve-fit technique with polynomial degrees of two through five. The equations selected for the measurements described in this report are for five-degree polynomials written as

$$T = a_0 + a_1E + a_2E^2 + a_3E^3 + a_4E^4 + a_5E^5 \tag{2}$$

where E is in mv, T is in °F, and a_1 through a_5 are in °F/mv. The selected range is from 0 to 300°F, and the error range is from −0.03 to 0.02°F.

Table 2 shows the timewise back-surface temperature histories from both a Chromel-constantan (ANSI type E) and an iron-constantan (ANSI type J) thermocouple for the same calibration data run (Group No. 8012) considered in Section 2.3.1.1. These temperature histories are shown in Columns 4 and 8, respectively, and were calculated by applying the appropriate coefficients (a_1 through a_5) in Eq. (2) to the respective output signal histories in Columns 3 and 7. These coefficients were checked as described in Section 2.3.1.3 and adjusted as required.

2.3.1.3 Thermocouple Wire Calibration

During initial calibration of the transfer-standard gages versus slug-calorimeter standards, differences of up to two percent in indicated heat flux, as determined from different thermocouple wire pairs on the same slug calorimeter, were measured. This difference was considered unacceptable. Therefore, a 6-ft length of wire from the same spool from which the slug-calorimeter wire for each of the three types of thermocouples was taken was sent to the AEDC Central Instrument Laboratory for temperature versus emf calibration. A platinum resistance thermometer traceable to NBS was employed as the temperature standard. Results of this calibration are generally summarized as follows: at a temperature (174°F) of about 100°F above room temperature, Chromel-constantan (ANSI type E) indicated 0.43°F high, iron-constantan (ANSI type J) indicated 2.92°F low, and Chromel-Alumel (ANSI type K) indicated 0.13°F low. The coefficients (a_1 through a_5) in the five-degree polynomial used to reduce the data from the respective thermocouples were adjusted to reflect the results of the thermocouple wire calibration.

2.3.1.4 Slope of Time-Resolved Temperature History

Having obtained the back-surface temperature history of a slug calorimeter exposed to calibration heat flux, the next step in data processing is measuring the slope of the time-resolved temperature data. This can be accomplished by either of two methods: machine calculations/plots or hand-reduced data/plots.

2.3.1.4.1 Machine-Reduced Data/Plots

Measurement of the slope of time-resolved temperature data on the DECsystem-10 facility computer is accomplished by doing a sliding sectional curve fit of a second order polynomial and applying the least-squares method (Ref. 19). Five points on either side of the center point were used in curve fitting the temperature-time data. Columns 5 and 9 in Table 2 show the calculated slope of the slug-calorimeter back-surface temperature history for ANSI type E and J thermocouples, respectively, for the same calibration run (Group No. 8012) considered in previous sections of this report. As previously noted, the temperature rises and slopes are essentially zero until a time of just over 5 sec has elapsed since the data acquisition system was turned on. At this time, the slopes begin to rise and reach a relatively constant level at a time of about 6 sec and are maintained until a time of 11.5 sec, at which the slopes begin to decrease rapidly.

It is assumed that the heat source is supplying constant heat flux over the entire exposure period. Under ideal conditions, the experimenter would be able to obtain a valid measurement of the slope at any time point during the exposure period. However, because of system electrical noise, fluctuations in power supply voltage, room air currents, etc., a more effective method of slope measurement is to take the average of individual data points over a reasonable time period. The method used with the AEDC calibration data is to take the average of the calculated slopes beginning at the time point at which the temperature rise reached 6.0°F and continuing over the next four seconds. From Table 2 it can be seen that the time point at which the temperature rise measured by the type E thermocouple exceeds 6.0°F is 7.0 sec.

Figures 8 and 9 are machine plots of the slug-calorimeter back-surface temperature history for type E and J thermocouples, respectively, for Group No. 8012. There are several parameters printed on each plot. Most of these are self-explanatory, but the parameter, QDOT, may be confusing. QDOT is the average of QDOT Avg (Column 2, Table 2) from the initial data taking time point ($t = 7.0$ sec) and continuing over the next four seconds. ESLOPE (see Fig. 8) is the measurement of the slope of the back-surface temperature history from $t = 7.0$ to 11.0 sec, and QINDE is the corresponding indicated heat-flux level calculated by multiplying ESLOPE by $\rho \ell C_p$ [see Eq. (1)]. Note the good agreement between ESLOPE in Fig. 8 and JSLOPE in Fig. 9. This is indicative of the agreement of indications from Chromel-constantan and iron-constantan thermocouples on the same calorimetric mass.

2.3.1.4.2. Hand-Reduced Data/Plots

Although the indicated heat-flux data from slug-calorimeter back-surface temperature histories are obtained from machine-reduced data as described in the previous section, accuracy of these data may be checked by comparison with hand-reduced data. With reference to Figs. 10 and 11, plots were made of the slug-calorimeter back-surface temperature rise versus time for Group No. 8012. Individual data points (circular symbols) were plotted at 0.50-sec intervals in Figs. 10 and 11. The solid line represents the best straight line through the individual data points. The time period over which the slope is measured should roughly cover the same time period as the machine plots. Comparison of ESLOPE in Fig.8 with dT_E/dt in Fig. 10 and JSLOPE in Fig. 9 with dT_J/dt in Fig. 11 shows excellent agreement. This enhances the credibility of the machine-reduced data.

2.3.2 Calculation of Transducer Scale Factors

Individual transducer scale factors are calculated by dividing the heat flux indicated by the measurement of the slope of the slug-calorimeter back-surface temperature history by the outputs of the transducers at the same time point. For the calibration data run (Group No. 8012) under consideration, the transducer outputs were measured at the mid-point (9 sec) of the time interval over which the slopes were measured. Because there were two different types of thermocouples on the slug calorimeter for this calibration run, there were two data points generated for each of the four transducers. Two other slug calorimeters were used in the experimental calibrations. One had a Chromel-constantan thermocouple and a Chromel-Alumel thermocouple attached to the back surface of the calorimetric mass. The other had only one Chromel-constantan thermocouple.

A large number of calibration data runs (59) was performed in order to generate a valid statistical analysis. Table 3 contains all the AEDC experimental data used to calculate the heat-flux calibration uncertainty presented in this report. With reference to Table 3, the heat fluxes indicated by the slug-calorimeter standards are shown in Columns 1 through 3, and the corresponding transducer outputs are shown in Columns 4 through 9.

The reader will notice there are numerous values of -1.000 indicated for both heat-flux and transducer output. It was stated in Section 2.1.4 that the data acquisition system was configured to accommodate only six analog inputs simultaneously. Since three slug calorimeters and six transfer-standard gages were involved in the experimental calibrations, all could not be electrically operational for any one calibration data run. The normal practice was to utilize one slug calorimeter with two different types of backside thermocouples and four transfer-standard gages. The slug-calorimeter thermocouples and transfer-standard gages which were not electrically hooked up for any particular calibration run were coded with a -1.000 value. The computer program was coded to ignore any parameter with a value of -1.000.

Table 4 shows the scale factors for each of the six heat-flux transducers calculated from the experimental data shown in Table 3. The highest number of data points for any particular transducer was 68; the lowest number was 46. No effort was made to separate data taken with different slug calorimeters and/or thermocouple temperature sensors. Therefore, there will be no bias term in the calculation of transducer heat-flux uncertainty using only the AEDC experimental data. A precision uncertainty term was calculated for each individual transducer from the scale factors shown in Table 4.

2.3.3 Calculation of Uncertainty

As stated in the previous section, calculation of the uncertainty of the AEDC experimental calibration data will involve only a precision term for each transducer. Appendix B presents the classical definition of uncertainty. Precision is simply defined as the variation of repeated measurements of the same quantity. The sample standard deviation (S) is used as an index of the precision. The parameter of interest here is the scale factor, SF (see Section 2.3.2), of each of the six heat-flux transducers. Standard deviation of individual transducer scale factors is defined as

$$S = \sqrt{\sum_{i=1}^{N} \frac{(SF_i - \overline{SF})^2}{N}} \tag{3}$$

where

S = standard deviation, Btu/ft^2-sec/mv

N = number of samples

SF_i = any scale factor, Btu/ft^2-sec/mv

$\overline{SF}$ = mean value of scale factors for any individual transducer, Btu/ft^2-sec/mv

i = index

Table 5 shows the calculated mean values and standard deviations of the AEDC experimental calibration data for each of the six heat-flux transducers also calibrated at the NBS. For comparison purposes, the standard deviations for each transducer were normalized by conversion to percentage standard deviation. The individual values range from a low value of 0.77 percent for Schmidt-Boelter gage SB21 to a high value of 1.46 percent for Schmidt-Boelter gage SB22.

3.0 NBS HEAT-FLUX CALIBRATIONS

Calibration of the six transfer-standard heat-flux transducers, fabricated by the AEDC, at the NBS was coordinated with Mr. J. R. Lawson, a physical scientist in the FRC. Information in this report regarding the apparatus used by the NBS in the performance of these calibrations is somewhat sketchy. This information was obtained from private communication (several telephone calls and one letter) between the author and Mr. Lawson.

A fact of primary importance is that the calibrations of the transducers are not certified by the NBS because they were performed by calibrating against an NBS transfer standard. This transfer standard was calibrated by the Optical Physics Division of the NBS in August 1977 (Ref. 12). The calibration of the transfer standard in 1977 was certified by the NBS. Therefore, while the calibrations of the AEDC transducers are traceable to certified NBS heat-flux standards, the calibrations cannot be regarded as NBS certified.

3.1 APPARATUS

The radiant heat source used for the NBS calibrations was a 2,000-w tungsten halogen lamp located inside an ellipsoidal collector. The source was built by Tamarack Scientific Company and was modified at the NBS to ensure proper optical alignment of the heat-flux transducers. The voltage and current stability to the radiant heat source was ensured by a precision direct-current (d-c) power supply. An NBS-calibrated precision millivoltmeter was used to measure the output of the heat-flux transducers and the transfer standard. A digital thermometer was used to monitor the heat-sink temperature of the transducers. The heat-flux level from the radiant heat source was measured with NBS transfer-standard SN 124421, a Gardon gage-type sensor. The transducers were properly aligned with the radiant heat source with a specially constructed mounting plate. The transducers were pinned in place with the front surface flush with the surface of the mounting plate.

3.2 EXPERIMENTAL CALIBRATION PROCEDURES

The high-absorptivity coating (see Section 2.2) applied to the sensing surfaces of the transducers prior to their initial calibration was allowed to remain on the transducers for the NBS calibration. Care was taken to protect this surface coating from any damage or deterioration prior to or during the NBS calibrations.

In contrast with the AEDC procedures, the experimental calibrations at the NBS were performed by irradiating one transducer at a time. After the transducer was properly aligned relative to the heat source, the transducer was irradiated by applying d-c power to the radiant lamp. The desired heat-flux level was achieved by carefully monitoring the voltage applied to the lamp. After the incident heat flux had stabilized (≤ 5.0 sec), the transducer output signal was measured and recorded. This procedure was repeated at different heat-flux levels for a total of ten data points per transducer. After obtaining the complete calibration data for each transducer, this transducer was removed from the mounting plate and replaced with another. The calibration procedure was repeated for each transducer including the NBS transfer standard.

3.3 EXPERIMENTAL RESULTS

All of the calibration data obtained by the NBS for the six transfer-standard gages are shown in tabulated form in Table 6. The NBS uses the metric system of units and heat flux is indicated in w/cm^2. Conversion of heat flux in metric units to English units (Btu/ft^2-sec) is shown in adjacent columns in Table 6. Note that the independent variable is "*incident* heat flux" and the dependent variable is "instrument output." Since the AEDC transducer sensing-surface absorptivity is 0.97, the true transducer scale factor is obtained by dividing the incident heat flux by the instrument output and multiplying the quotient by 0.97.

Table 7 shows the results of obtaining the best straight-line curve fit through all the NBS calibration data points for each transducer. The form of the equation is given in Column 2. Because of the very low output signals of the Gardon gages at the lower heat-flux levels, the data for heat-flux levels of 0.10 and 0.20 w/cm^2 were not considered to be reliable and, consequently, were not included in the curve fit of the data for the equation (see footnote 1 in Table 7) for each Gardon gage. Figures 12 and 13 show the plotted calibration data for one Schmidt-Boelter gage and one Gardon gage, respectively. The symbols represent individual data points, and the full line represents the best straight-line curve fit through each of the data points. The reader should be reminded that the data shown in Column 2 of Table 7 and in Figs. 12 and 13 are in metric units.

The value listed in the third column of Table 7 is the transducer scale factor and is the parameter of interest for comparison with calibrations performed at the AEDC. The scale factor for each gage was calculated by taking the slope of the best straight-line curve fit through the calibration data and multiplying by the sensing-surface absorptivity. In the calculation of Gardon gage scale factors, the data for the two lowest heat-flux levels were not included. Note that the scale factors listed in Column 3 of Table 7 have been converted to English units.

4.0 CALCULATION OF TOTAL UNCERTAINTY

The total uncertainty of heat-flux calibrations performed on six heat-flux transducers calibrated by the NBS and by the AEDC was calculated according to the relationship given in Appendix B. The equation for total uncertainty (U) is

$$U = \pm(B + t_{95}S) \tag{4}$$

where B is bias, t_{95} is the ninety-fifth percentile point for the two-tailed Student's "t" distribution, and S is standard deviation. Bias (B) is defined as the difference between the true value and the average of many repeated measurements.

The scale factor of each transducer determined by the experimental calibration performed by the NBS (see Section 3.0) will be regarded as the true or correct value. These values for each transducer are listed in Table 7. Mean values of the scale factors determined by the AEDC experimental calibrations are shown in Table 5. The percentage bias values determined by comparison of the NBS and the AEDC scale factors are listed in Table 8.

The percentage standard deviations of individual heat-flux transducer calibrations were determined from the AEDC experimental data and are listed in Table 5. The t_{95} value in Eq. (4) is determined by the size of the sample and will be assumed to be 2.0, since the size of the smallest sample was 46 repetitions.

The percentage total uncertainty value of each of the six transducers is listed in Table 8. The average total uncertainty of the six heat-flux transducers calibrated at the NBS and at the AEDC is ±2.98 (nominally ±3 percent). Since three different slug calorimeters with three different types of thermocouples (ANSI types E, J, and K) were involved in determining the precision term, the calculated average uncertainty is considered to reflect excellent agreement with the NBS results.

5.0 CONCLUSIONS

In any area of measurement, traceability to NBS standards is a definite attribute and almost a necessity in the performance of experimental calibrations. Traceability to NBS standards greatly enhances the credibility of any experimental calibration technique. Regardless of how detailed and/or sophisticated a calibration technique may be, there always remains an aura of doubt if there is no traceability to NBS standards. Such has been the case with experimental heat-flux calibrations at the AEDC until June 1982.

Slug-calorimeter standards were established for heat-flux transducer experimental calibrations at the AEDC in 1963. Since that date, calibration techniques have been improved, two-dimensional analytical methods have been utilized in the design of slug-calorimeter standards, and transfer-standard gages have been calibrated at other facilities for comparison with AEDC results. All of these factors have contributed to building confidence in calibration techniques employed at the AEDC, but still there was no traceability to NBS standards.

Heat-flux transducer experimental calibrations performed at the AEDC are now traceable to NBS standards. It is especially encouraging that of the six transducers calibrated at the NBS, the largest deviation in scale factors between the AEDC and the NBS data was 1.19 percent (see Table 8). Two of the transducer scale factors calculated from theAEDC calibration data were slightly higher than the NBS values and four were lower. A precision term for each transducer was calculated from a large sample of the AEDC calibration data ($\geq$46 data points), and a bias term was determined by comparison of the AEDC and the NBS mean value scale factors. The precision and bias terms were combined to calculate a total uncertainty value for each transducer. The average total uncertainty value for the six transducers is nominally $\pm$3 percent.

REFERENCES

1. *Test Facilities Handbook (Eleventh Edition).* "von Kármán Gas Dynamics Facility, Vol. 3. " Arnold Engineering Development Center, April 1981.

2. Gardon, R. "An Instrument for the Direct Measurement of Intense Thermal Radiation." *The Review of Scientific Instruments,* Vol. 24, May 1953, pp. 366-370.

3. Trimmer, L. L., Matthews, R. K., and Buchanan, T. D. "Measurement of Aerodynamic Heat Rates at the AEDC von Kármán Facility." Fifth International Congress on Instrumentation in Aerospace Simulation Facilities, September 1973, pp. 35-44.

4. Kidd, C. T. "A Durable, Intermediate Temperature, Direct Reading Heat-Flux Transducer for Measurements in Continuous Wind Tunnels." AEDC-TR-81-19 (AD-A107729), November 1981.

5. Carnahan, K. R., Hartman, G. J., and Neuner, G. J. "Development of TPS Flight Test and Operational Instrumentation." Aerotherm Report FR-75-135, January 1975.

6. Miller, C. G., III. "Comparison of Thin-Film Resistance Heat-Transfer Gages with Thin-Skin Transient Calorimeter Gages in Conventional Wind Tunnels." NASA Technical Memorandum 83197, December 1981.

7. Wittliff, C. E. "Space Shuttle Leading Edge Heat-Transfer Investigation in the Calspan 96-in. Hypersonic Wind Tunnel." Seventh International Congress on Instrumentation in Aerospace Simulation Facilities, September 1977, pp. 101-112.

8. Hedlund, E. R., Hill, J. A. F., Ragsdale, W. C., and Voisinet, R. L. P. "Heat-Transfer Testing in the NSWC Hypervelocity Wind Tunnel Utilizing Co-Axial Surface Thermocouples." NSWC MP 80-151, March 1980.

9. Ledford, R. L., Smotherman, W. E., and Kidd, C. T. "Recent Developments in Heat-Transfer-Rate, Pressure, and Force Measurements for Hotshot Tunnels." AEDC-TR-66-228 (AD-645764), January 1967.

10. Holden, M. S. "Boundary-Layer Transition and Surface Roughness Effects in Hypersonic Flow." Calspan Report No. 6430-A-1, February 1981.

11. Stallings, D. W., Matthews, R. K., and Jenke, L. M. "Recent Developments in Aerothermodynamic Test Techniques at the AEDC von Kármán Gas Dynamics Facility." Eighth International Congress on Instrumentation in Aerospace Simulation Facilities, September 1979.

12. Radiometric Physics Division Staff of NBS. "A New Facility for Radiant Heat-Flux Transducer Calibrations." *Optical Radiation News*, No. 22, October 1977, p. 3.

13. Baines, D. J. "A Comparative Theoretical Evaluation of Five Commonly Used Types of Unsteady Heat-Flux Sensors." Department of Supply, Australian Defense Scientific Service, Weapons Research Establishment Report HSA27, January 1970.

14. Schultz, D. L. and Jones, T. V. "Heat-Transfer Measurements in Short-Duration Hypersonic Facilities." AGARD-AG-165, February 1973.

15. Rochelle, J. K. "TRAX—A Finite-Element Computer Program for Transient Conduction Analysis of Axisymmetric Bodies." University of Tennessee Space Institute Masters Thesis, June 1973.

16. Touloukian, Y. S., ed., *Thermophysical Properties of High Temperature Solid Materials*, Vol. 1: Elements. Thermophysical Properties Research Center, Purdue University, The MacMillan Company, New York, 1967.

17. Rall, D. L. and Stempel, F. C. "A Discussion of the Standardized Procedure for Calibrating Heat-Flux Transducers." Proceedings of the 19th Annual ISA Conference and Exhibit, October 1964 (ISA Paper 16.7-1-64).

18. Powell, R. L. et al. "Thermocouple Reference Tables Based on the IPTS-68." NBS Monograph 125, March 1974.

19. Selby, S. M. *Standard Mathematical Tables* (18th Edition). Chemical Rubber Company, Cleveland, Ohio, 1970.

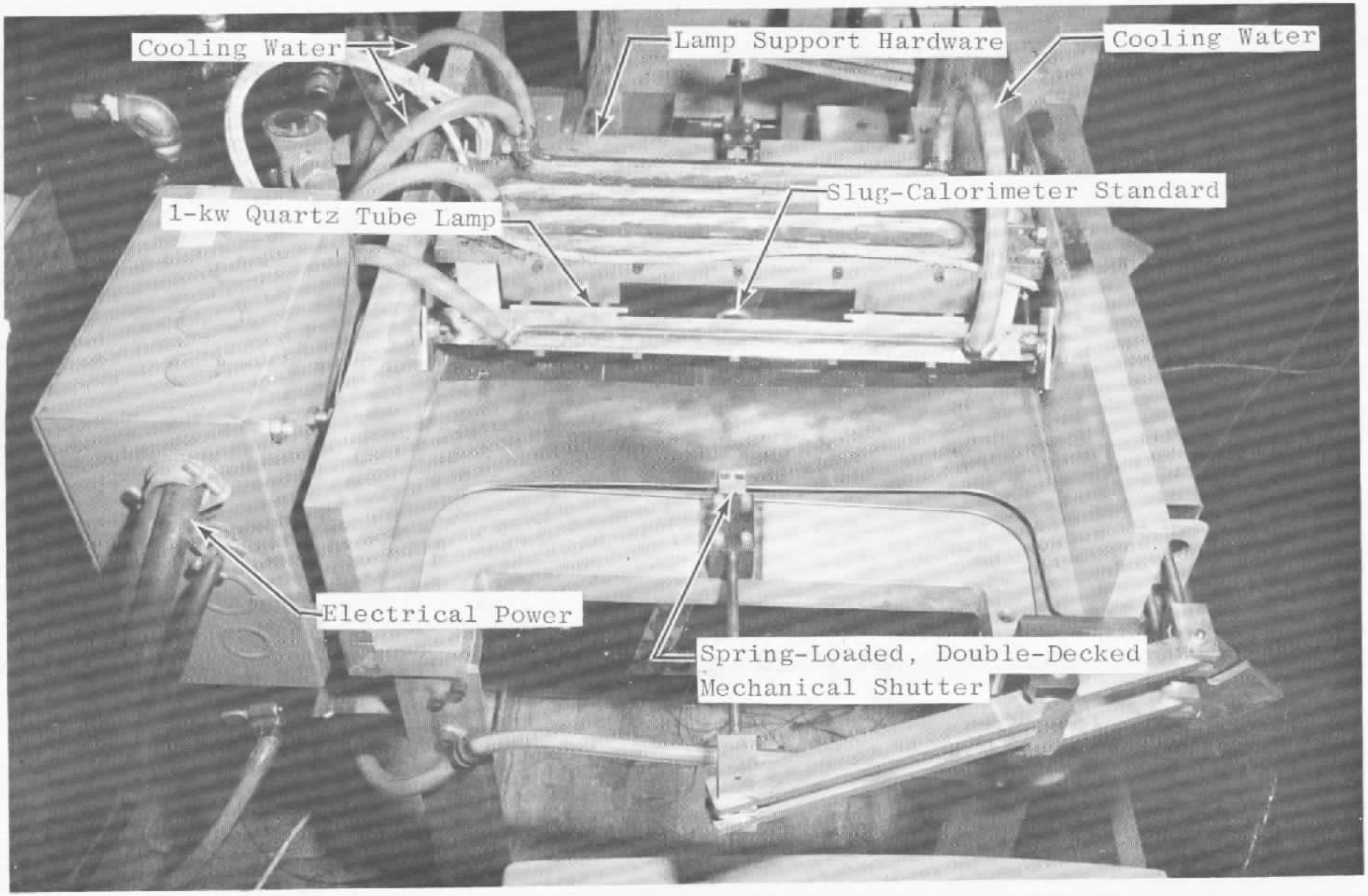


Figure 1. Heat-flux transducer radiant calibration system.

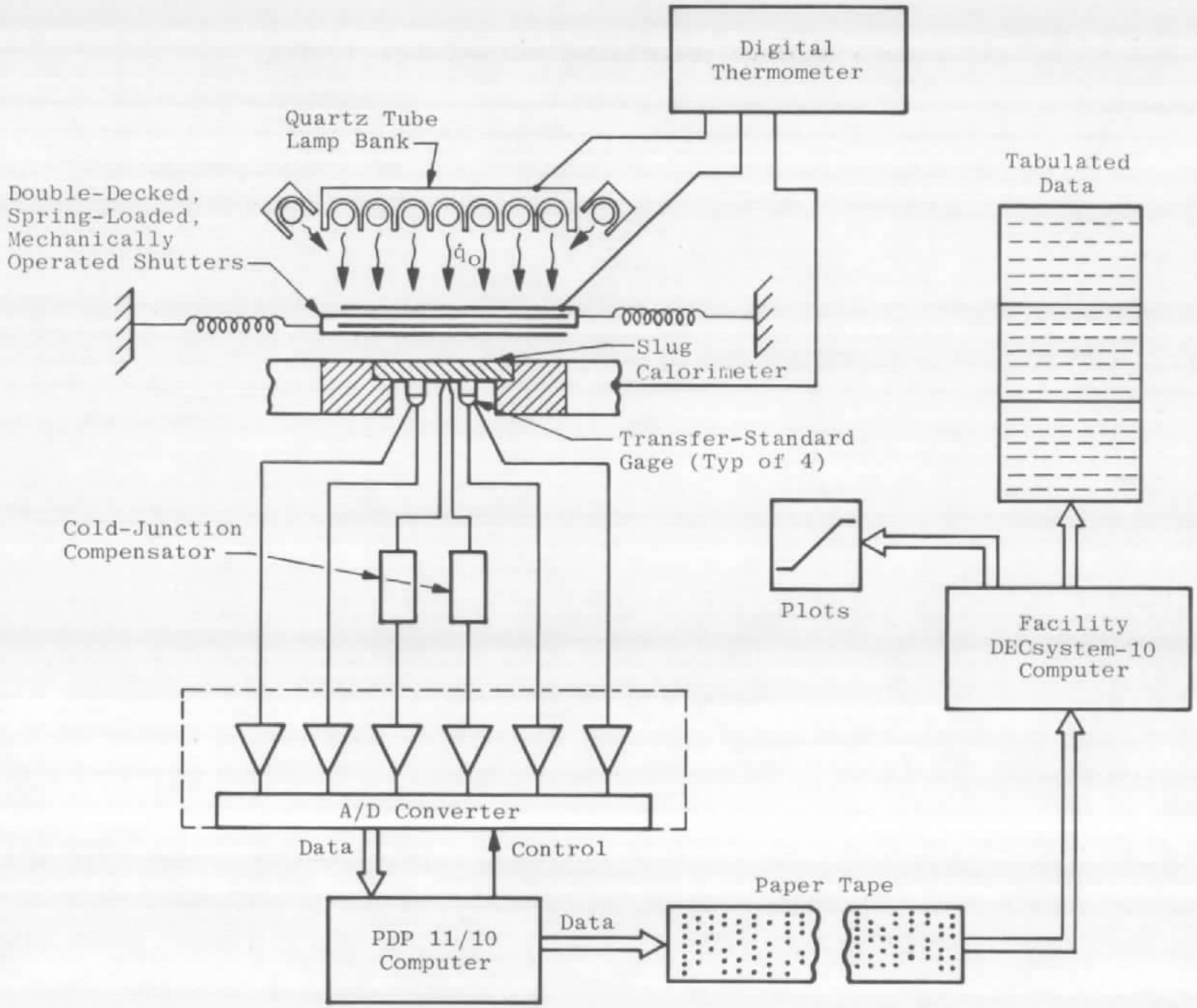


Figure 2. Schematic diagram of the AEDC experimental calibration procedure.

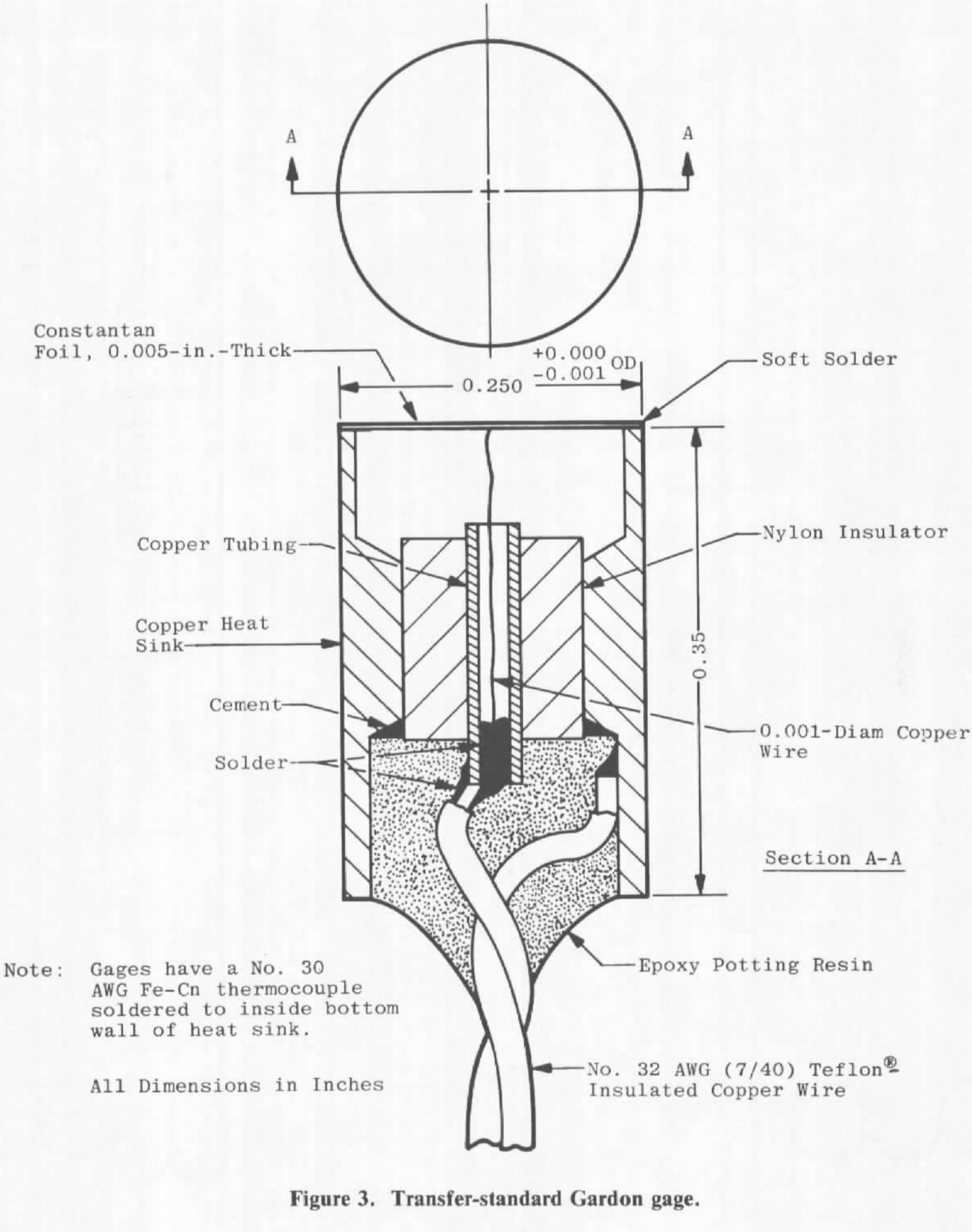
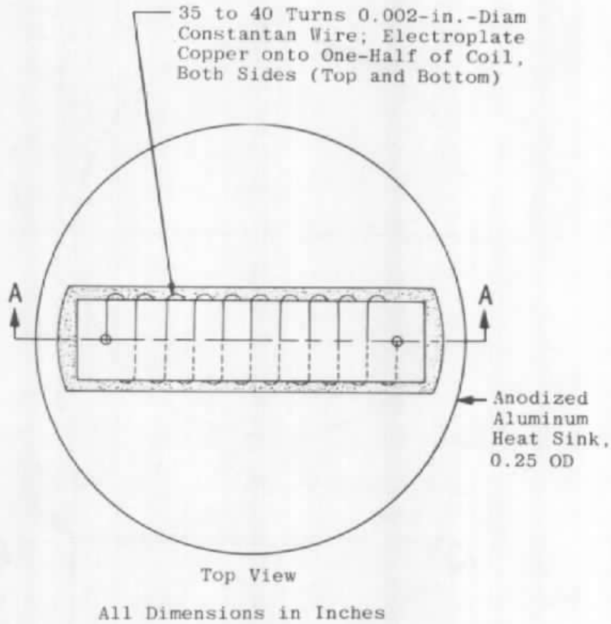


Figure 3. Transfer-standard Gardon gage.



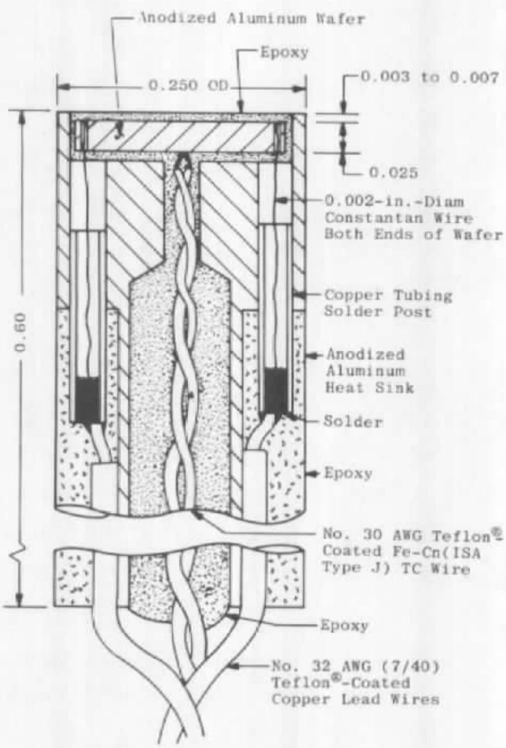


Figure 4. Section drawing of Schmidt-Boelter gage.

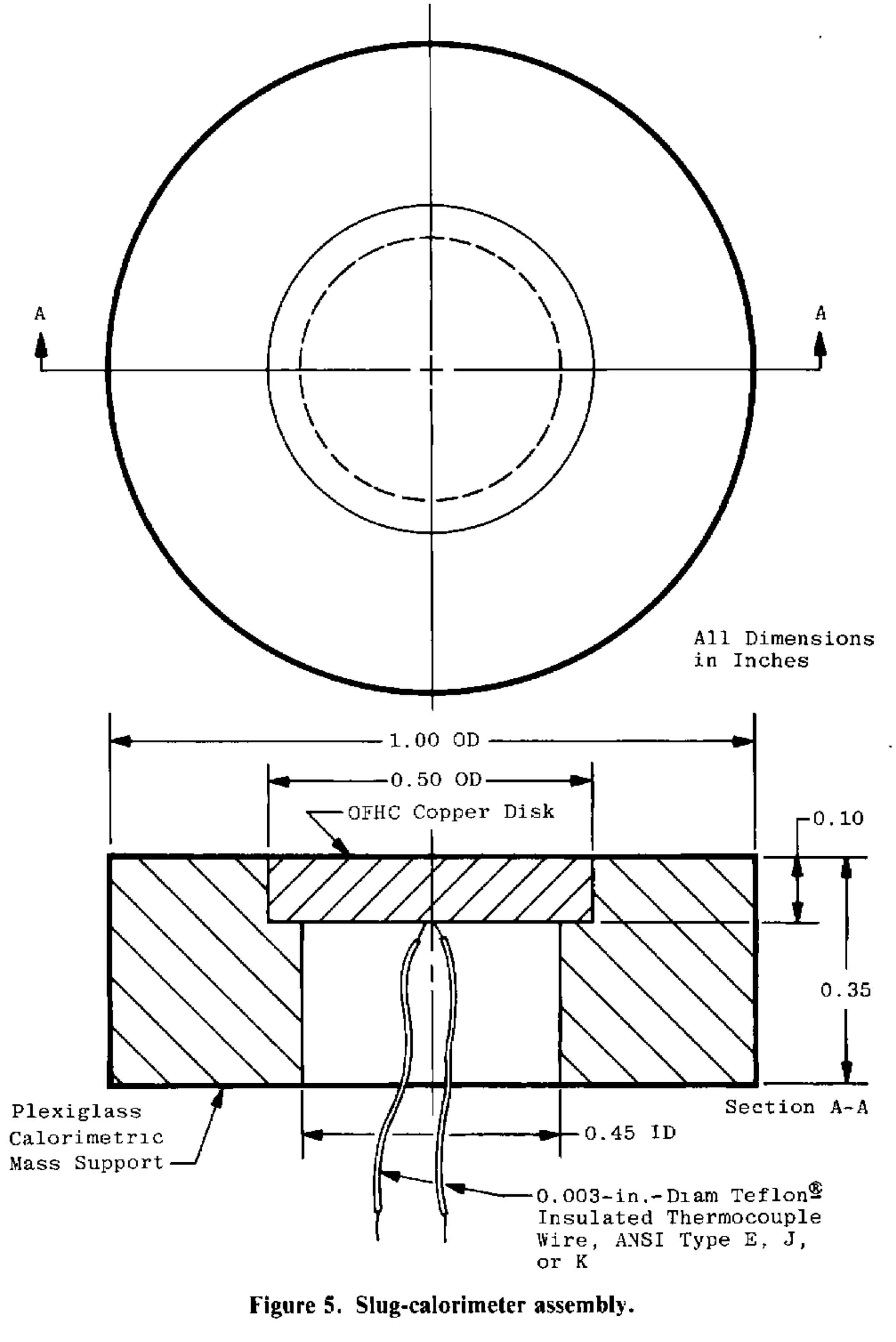


Figure 5. Slug-calorimeter assembly.

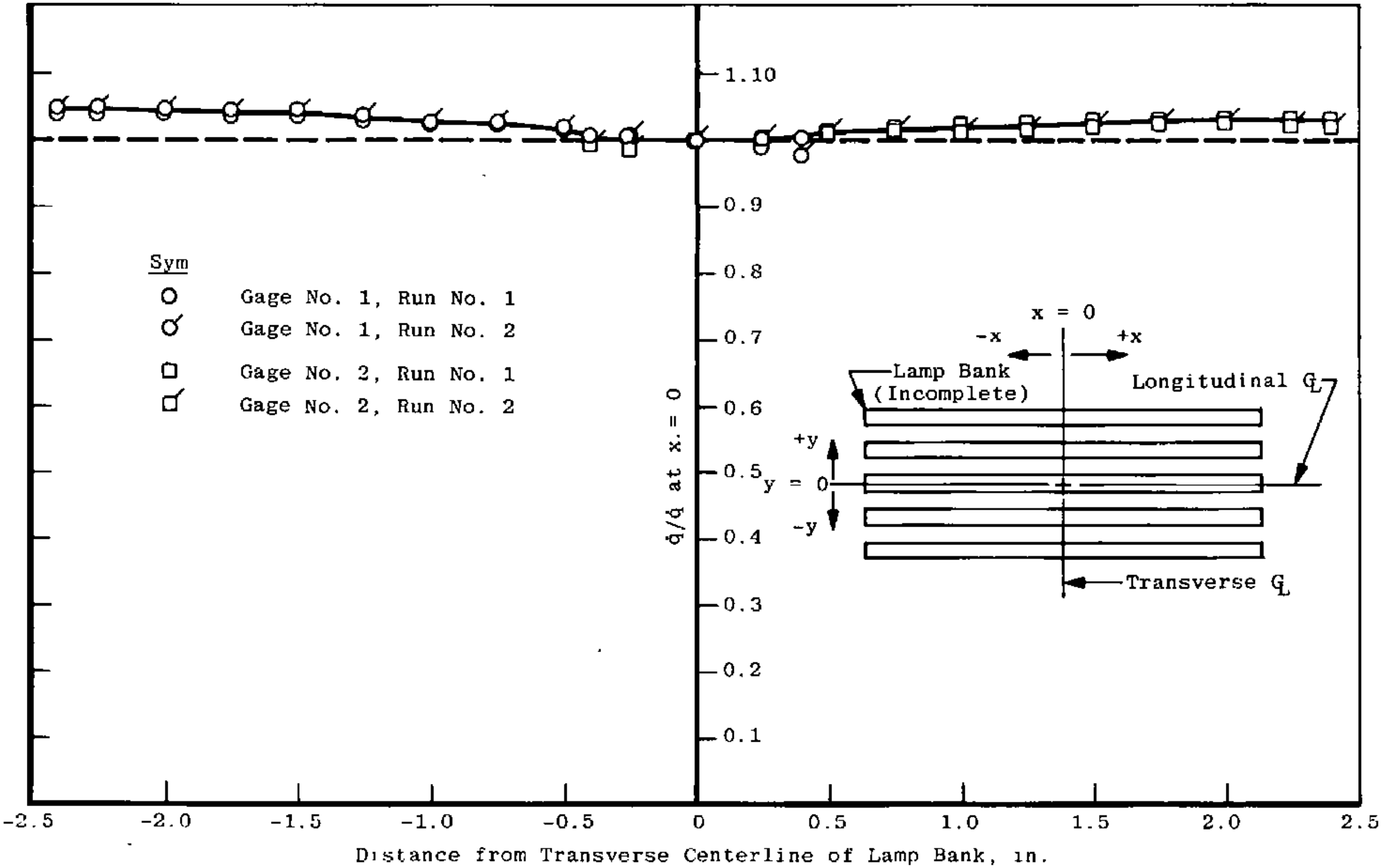


Figure 6. Longitudinal heat-flux map of model materials calibrator lamp bank.

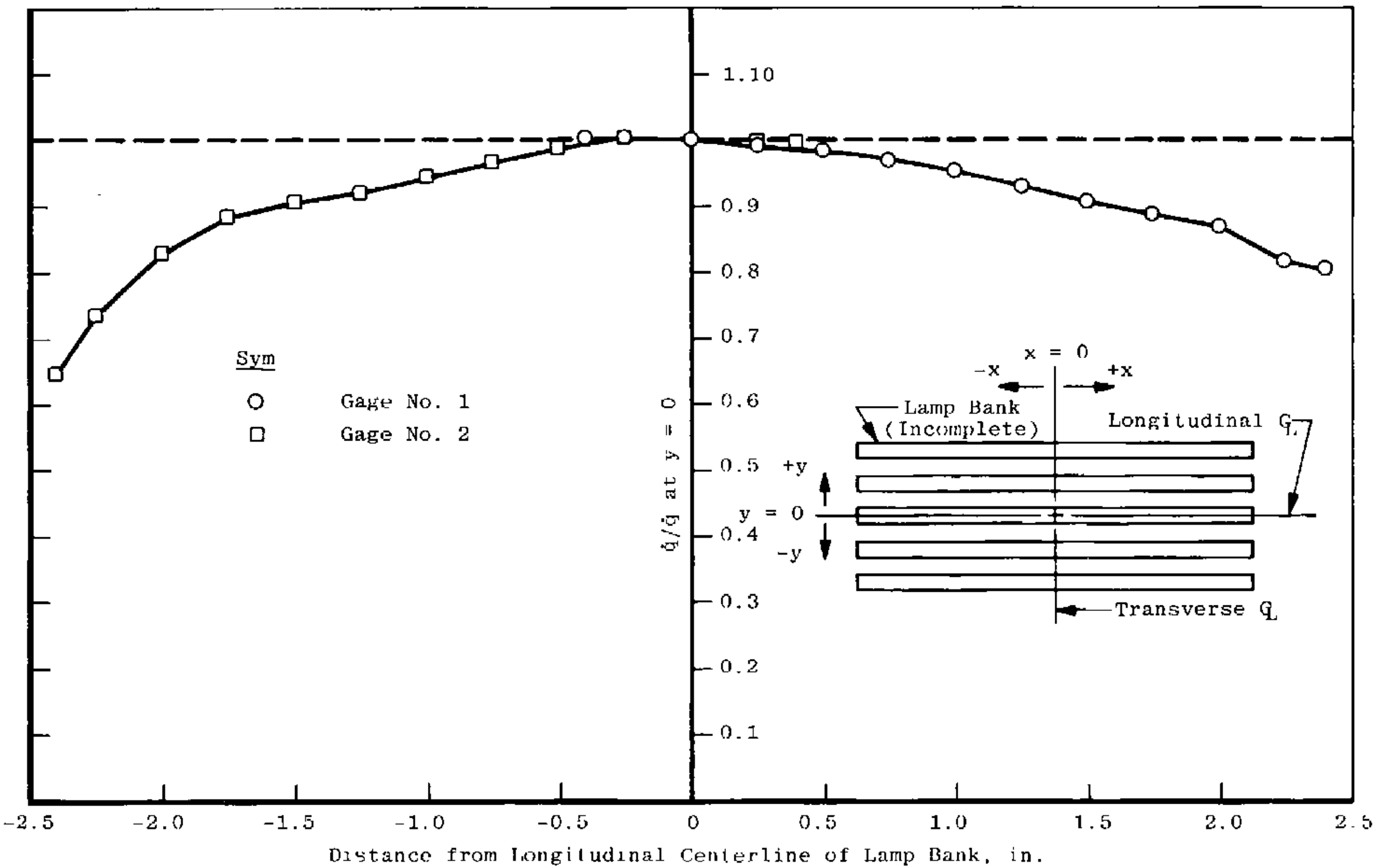


Figure 7. Transverse heat-flux map of model materials calibrator lamp bank.

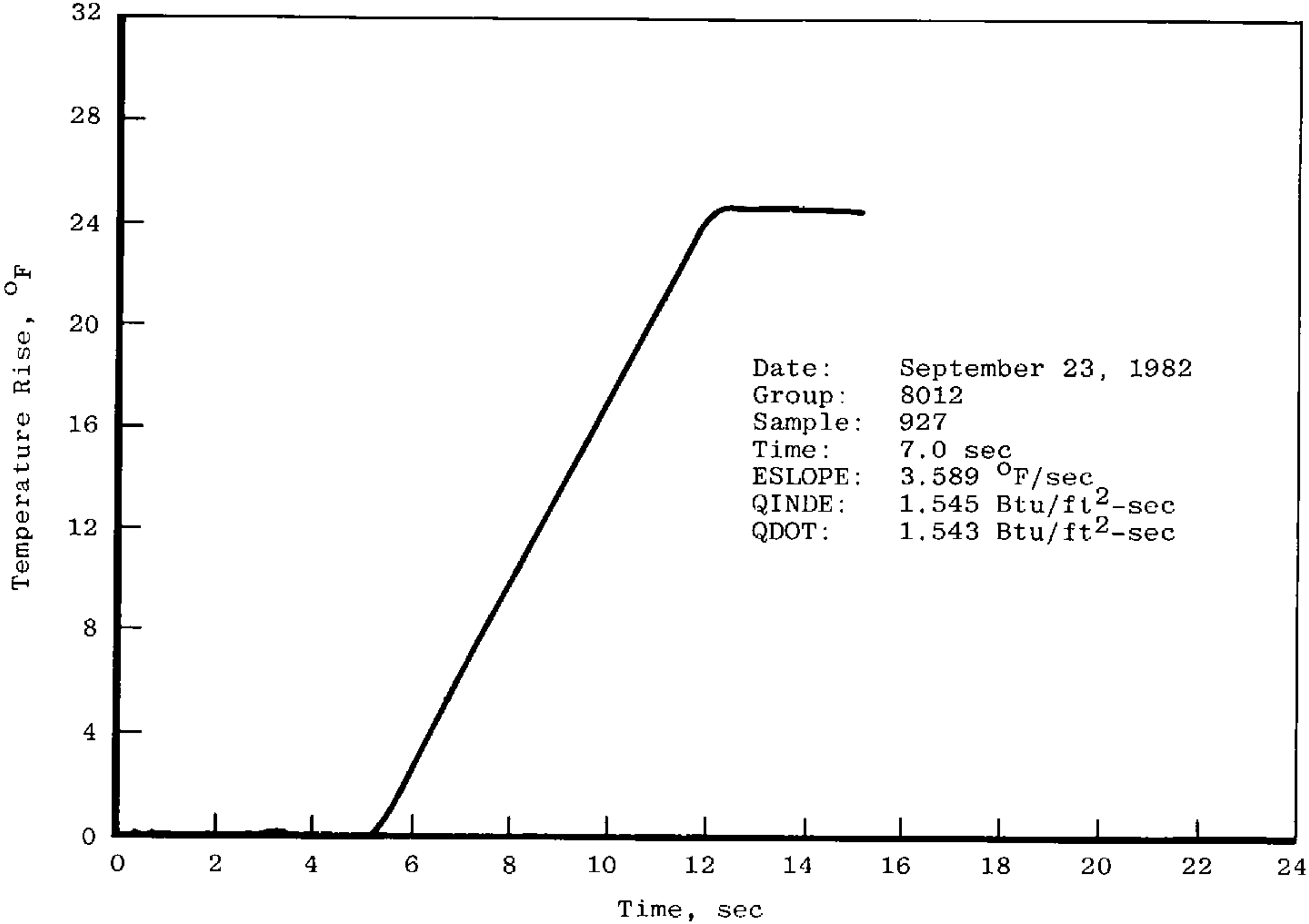


Figure 8. Slug-calorimeter back-surface temperature history, type E thermocouple.

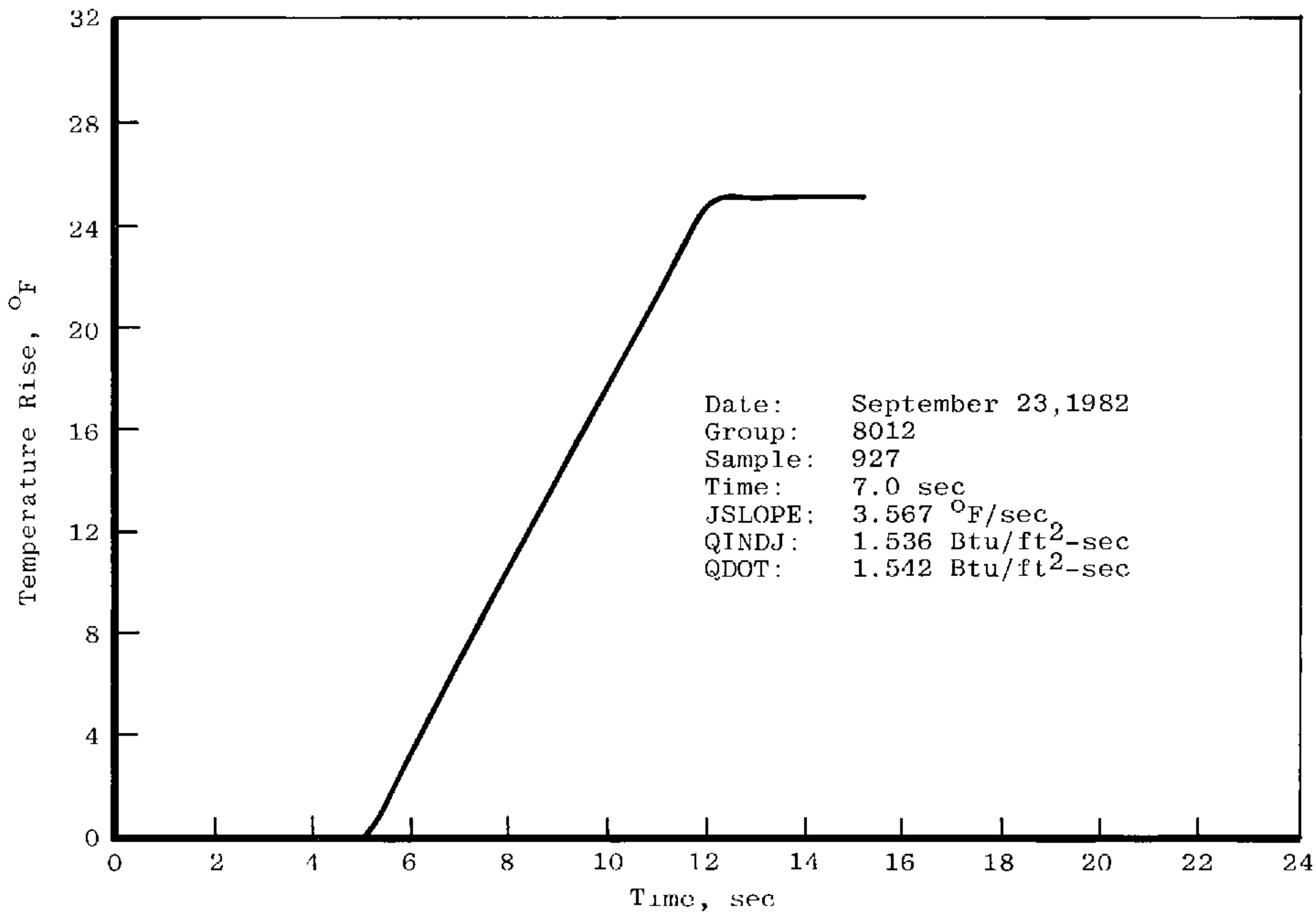


Figure 9. Slug-calorimeter back-surface temperature history, type J thermocouple.

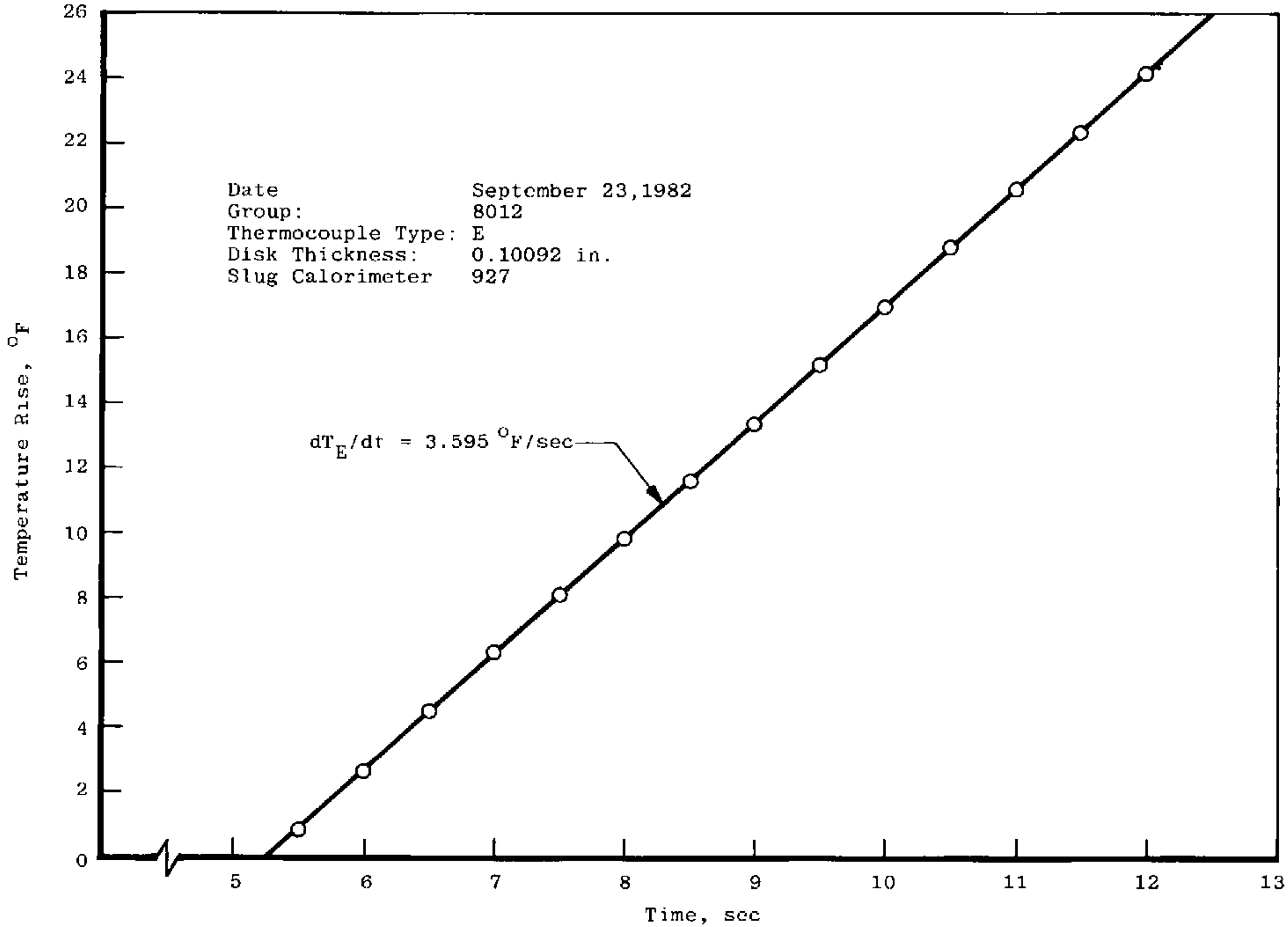


Figure 10. Hand-reduced slug-calorimeter data, type E thermocouple.

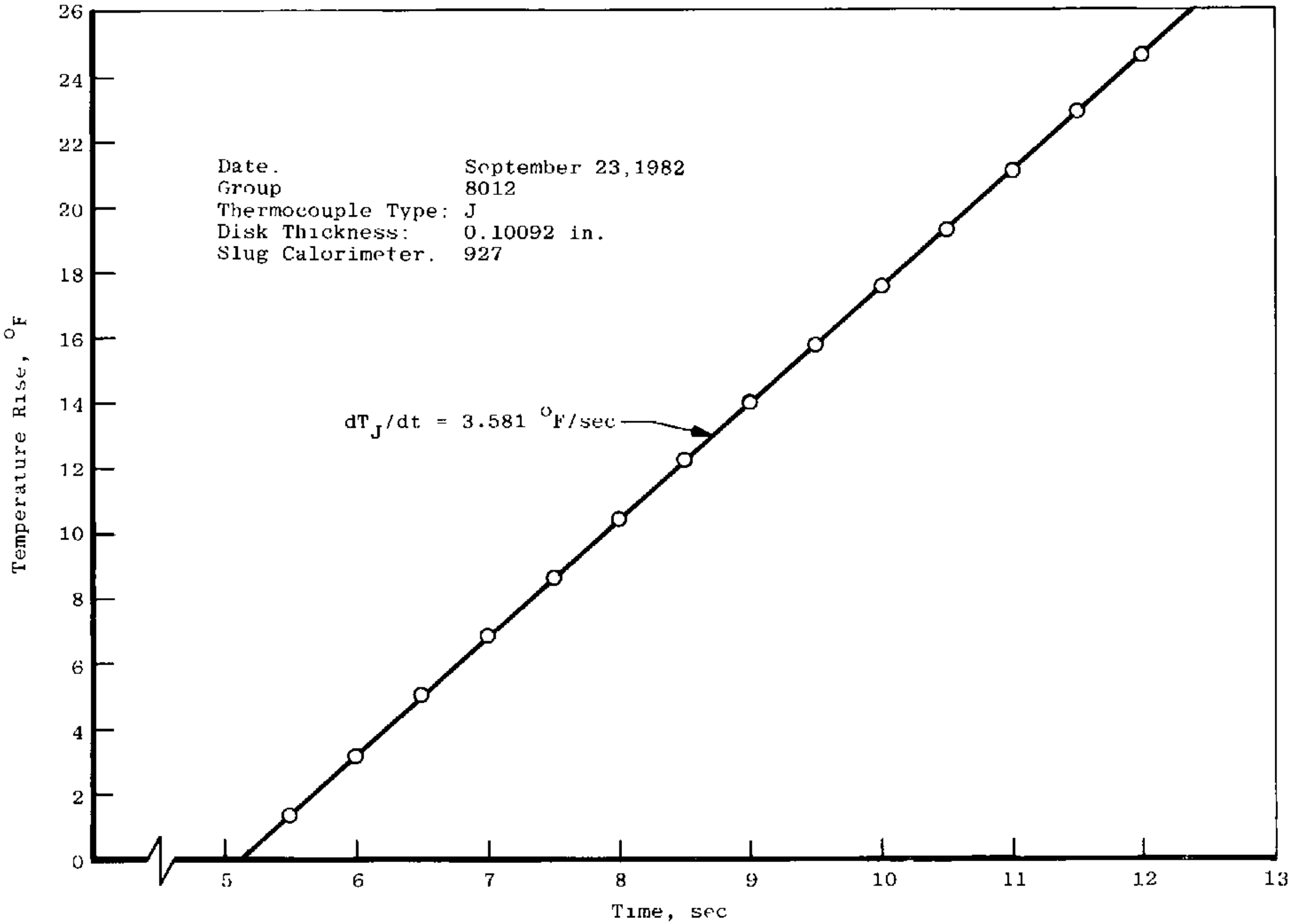


Figure 11. Hand-reduced slug-calorimeter data, type J thermocouple.

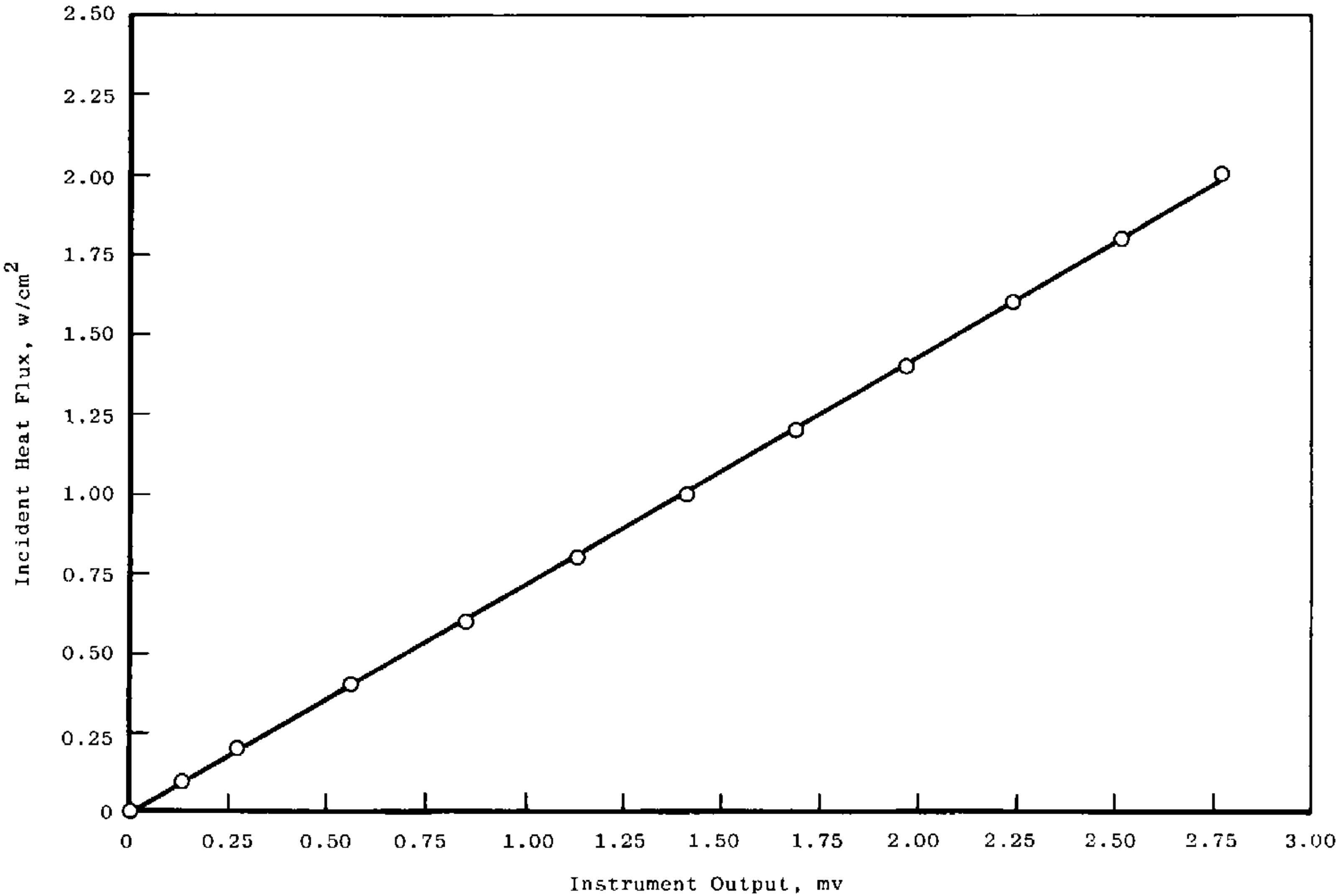


Figure 12. NBS calibration data, SB21.

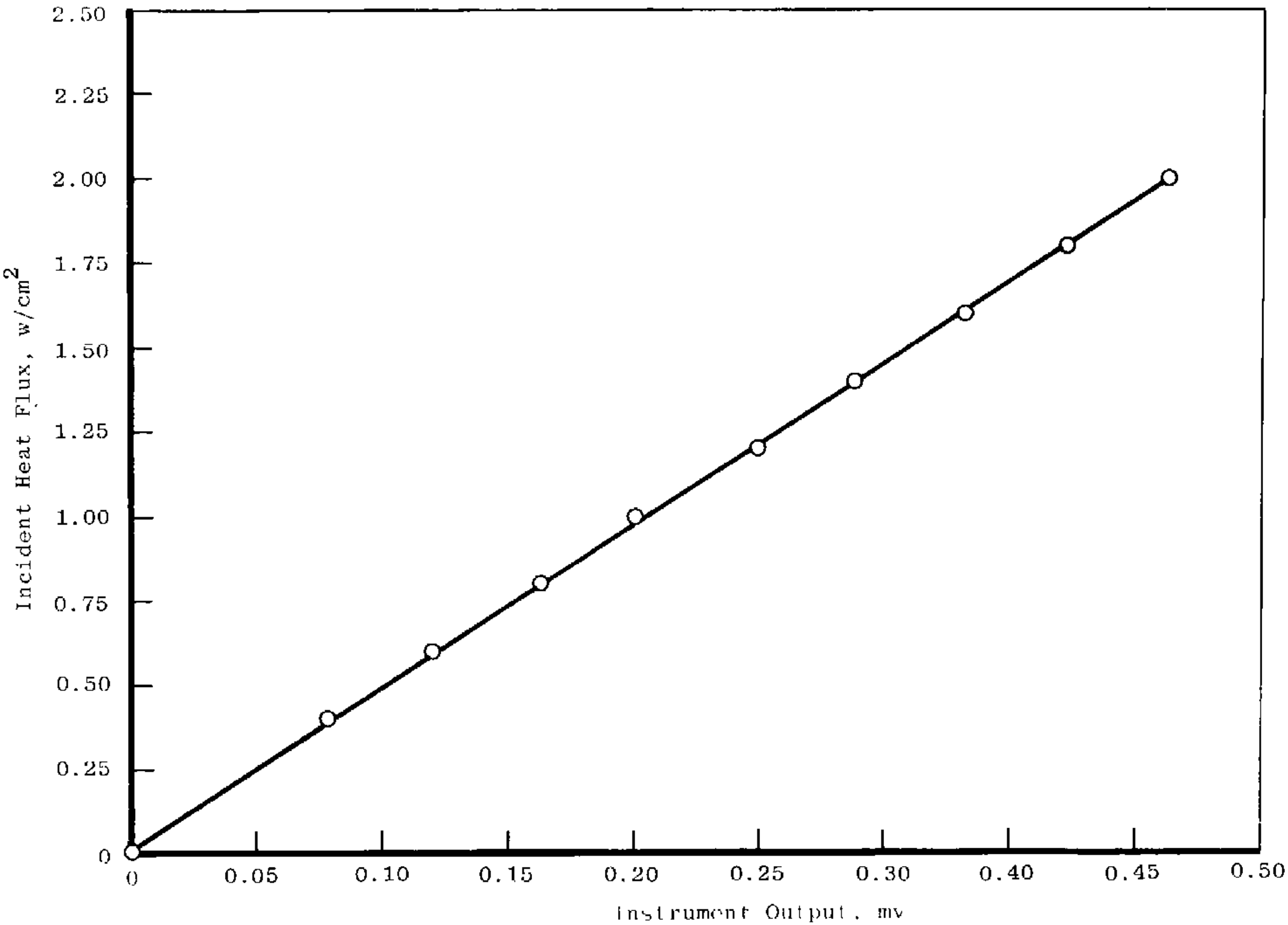


Figure 13. NBS calibration data, GG27.

Table 1. Calibration Data: Timewise Analog Output Signals

Date: September 23, 1982				Sample No. 927 Group No. 8012			No-Load Voltage (VAC): 102 Sensing-Surface Absorptivity: 0.97			
1	2	3	4	5	6	7	8	9	10	11
Time, sec	E-TC EOUT1, mv	GG29 EOUT2, mv	J-TC EOUT3, mv	GG24 EOUT4, mv	GG33 EOUT5, mv	GG27 EOUT6, mv	GG33 QDOT1, Btu/ft^2-sec	GG24 QDOT2, Btu/ft^2-sec	QDOTR1/2	Equip. Temp, °F
0.1	1.314	0.008	1.093	0.002	0.001	0.001	0.002	0.006	0.344	69.775
0.2	1.312	-0.016	1.091	-0.002	0.001	-0.001	0.002	-0.006	-0.344	69.723
0.3	1.315	0.008	1.093	0.000	-0.001	-0.001	-0.004	0.000		69.775
0.4	1.311	-0.016	1.091	0.000	-0.001	0.001	-0.004	0.000		69.723
0.5	1.314	-0.016	1.091	0.000	-0.001	-0.001	-0.004	0.000		69.723
0.6	1.313	-0.018	1.091	0.000	-0.001	-0.000	-0.003	0.001	-6.160	69.714
0.7	1.314	-0.015	1.091	0.000	-0.001	-0.000	-0.004	0.002	-2.326	69.716
0.8	1.313	-0.016	1.091	0.000	-0.001	-0.000	-0.005	0.001	-3.952	69.712
0.9	1.314	-0.014	1.091	0.000	-0.001	-0.000	-0.005	0.001	-4.737	69.717
1.0	1.313	-0.011	1.091	0.000	-0.001	0.000	-0.005	0.001	-7.545	69.718
1.1	1.313	-0.009	1.091	0.000	-0.001	-0.000	-0.005	0.000	-38.608	69.724
1.2	1.313	-0.008	1.091	-0.000	-0.001	-0.000	-0.004	-0.001	4.396	69.731
1.3	1.313	-0.008	1.091	-0.000	-0.001	-0.000	-0.003	-0.000	8.859	69.729
1.4	1.313	-0.009	1.091	0.000	-0.001	-0.000	-0.003	0.001	-2.352	69.723
1.5	1.313	-0.011	1.091	0.000	-0.000	-0.001	-0.001	0.001	-1.021	69.708
1.6	1.313	-0.014	1.090	0.000	-0.000	-0.001	-0.002	0.002	-1.078	69.695
1.7	1.314	-0.016	1.090	0.000	-0.001	-0.000	-0.002	0.001	-1.537	69.703
1.8	1.314	-0.015	1.091	0.000	-0.001	-0.000	-0.003	0.001	-2.097	69.709
1.9	1.314	-0.016	1.091	0.000	-0.000	-0.000	-0.001	0.001	-1.208	69.715
2.0	1.314	-0.014	1.091	-0.000	-0.000	0.000	-0.001	-0.000	11.931	69.719
2.1	1.315	-0.013	1.091	-0.000	-0.000	0.000	-0.001	-0.000	6.775	69.738
2.2	1.315	-0.010	1.091	-0.000	-0.000	0.000	-0.001	-0.000	2.329	69.732
2.3	1.316	-0.005	1.092	0.000	-0.000	0.000	-0.001	0.000	-3.050	69.744
2.4	1.315	-0.003	1.091	0.000	-0.000	0.000	-0.001	0.002	-0.653	69.738
2.5	1.315	-0.002	1.091	0.000	-0.000	-0.000	-0.001	0.001	-0.463	69.726
2.6	1.314	0.002	1.091	0.000	-0.000	-0.000	-0.002	0.001	-1.424	69.714
2.7	1.314	0.002	1.091	0.000	-0.001	-0.000	-0.002	0.001	-2.256	69.713
2.8	1.314	0.002	1.091	0.000	-0.001	0.000	-0.002	0.001	-3.398	69.709
2.9	1.315	0.001	1.091	0.000	-0.001	-0.000	-0.002	0.000	-18.330	69.706
3.0	1.315	-0.005	1.090	-0.000	-0.001	-0.000	-0.003	-0.001	5.613	69.699
3.1	1.317	-0.005	1.091	0.000	-0.000	-0.001	-0.001	0.000		69.720
3.2	1.317	-0.007	1.091	0.000	-0.000	-0.000	-0.001	0.000		69.720
3.3	1.318	-0.004	1.091	0.000	-0.000	-0.000	-0.001	0.000		69.732
3.4	1.317	-0.008	1.091	0.000	-0.000	-0.000	-0.001	0.000		69.722
3.5	1.315	-0.007	1.091	0.000	-0.000	-0.000	-0.002	0.001	-2.979	69.714
3.6	1.313	-0.001	1.091	-0.000	-0.001	-0.000	-0.002	-0.000	19.360	69.707
3.7	1.312	-0.002	1.090	-0.000	-0.001	0.000	-0.003	-0.001	4.054	69.698
3.8	1.310	-0.002	1.090	-0.000	-0.001	0.000	-0.003	-0.001	3.482	69.684
3.9	1.311	0.001	1.090	-0.000	-0.001	0.000	-0.005	-0.001	3.842	69.680
4.0	1.310	-0.004	1.090	-0.000	-0.001	-0.000	-0.005	-0.001	6.264	69.677

Table 1. Continued

Date: September 23, 1982				Sample No. 927 Group No. 8012			No-Load Voltage (VAC): 102 Sensing-Surface Absorptivity: 0.97			
1	2	3	4	5	6	7	8	9	10	11
Time, sec	E-TC EOUT1, mv	GG29 EOUT2, mv	J-TC EOUT3, mv	GG24 EOUT4, mv	GG33 EOUT5, mv	GG27 EOUT6, mv	GG33 QDOT1, Btu/ft²-sec	GG24 QDOT2, Btu/ft²-sec	QDOTR1/2	Equip. Temp, °F
4.1	1.311	-0.004	1.090	-0.000	-0.001	-0.000	-0.004	-0.002	2.286	69.687
4.2	1.311	-0.006	1.090	-0.000	-0.001	0.000	-0.004	-0.001	4.336	69.686
4.3	1.311	-0.002	1.090	-0.000	-0.001	0.000	-0.004	-0.001	7.021	69.678
4.4	1.311	-0.003	1.090	-0.000	-0.001	-0.000	-0.004	-0.001	3.830	69.677
4.5	1.312	-0.002	1.090	-0.000	-0.001	0.000	-0.004	-0.001	6.410	69.684
4.6	1.311	-0.003	1.090	-0.000	-0.001	0.000	-0.004	-0.002	2.437	69.680
4.7	1.311	-0.006	1.090	-0.001	-0.001	0.000	-0.004	-0.003	1.398	69.683
4.8	1.311	-0.004	1.088	-0.002	-0.002	-0.000	-0.007	-0.009	0.774	69.621
4.9	1.310	-0.013	1.088	-0.010	-0.009	-0.009	-0.036	-0.040	0.896	69.612
5.0	1.310	-0.018	1.089	-0.013	-0.013	-0.014	-0.053	-0.053	1.015	69.660
5.1	1.311	-0.010	1.093	-0.004	-0.007	-0.005	-0.027	-0.017	1.580	69.795
5.2	1.314	0.015	1.099	0.021	0.015	0.020	0.061	0.083	0.730	70.011
5.3	1.320	0.058	1.108	0.062	0.052	0.060	0.212	0.244	0.868	70.307
5.4	1.329	0.113	1.119	0.114	0.101	0.114	0.413	0.451	0.915	70.672
5.5	1.340	0.170	1.130	0.174	0.158	0.175	0.645	0.686	0.939	71.072
5.6	1.352	0.225	1.143	0.233	0.217	0.237	0.865	0.921	0.960	71.483
5.7	1.365	0.279	1.154	0.287	0.271	0.291	1.103	1.131	0.976	71.878
5.8	1.377	0.322	1.163	0.325	0.312	0.332	1.271	1.284	0.989	72.194
5.9	1.389	0.344	1.174	0.345	0.335	0.351	1.363	1.362	1.001	72.550
6.0	1.401	0.358	1.184	0.357	0.348	0.362	1.418	1.410	1.005	72.901
6.1	1.414	0.363	1.195	0.365	0.357	0.369	1.453	1.442	1.008	73.273
6.2	1.426	0.369	1.206	0.371	0.363	0.374	1.477	1.463	1.010	73.638
6.3	1.440	0.376	1.217	0.374	0.368	0.377	1.496	1.478	1.012	74.015
6.4	1.452	0.383	1.228	0.377	0.371	0.380	1.510	1.488	1.014	74.385
6.5	1.465	0.386	1.236	0.379	0.373	0.382	1.519	1.496	1.015	74.747
6.6	1.477	0.389	1.249	0.380	0.375	0.383	1.527	1.502	1.017	75.115
6.7	1.489	0.394	1.260	0.382	0.376	0.384	1.532	1.507	1.017	75.482
6.8	1.501	0.398	1.270	0.383	0.377	0.384	1.536	1.510	1.017	75.834
6.9	1.513	0.400	1.281	0.384	0.378	0.384	1.539	1.514	1.016	76.194
7.0	1.524	0.401	1.291	0.385	0.379	0.385	1.540	1.518	1.015	76.543
7.1	1.537	0.399	1.302	0.385	0.379	0.385	1.541	1.521	1.014	76.910
7.2	1.549	0.399	1.312	0.385	0.379	0.385	1.543	1.521	1.014	77.274
7.3	1.561	0.399	1.323	0.386	0.379	0.385	1.543	1.522	1.014	77.637
7.4	1.573	0.399	1.334	0.386	0.380	0.385	1.545	1.522	1.015	78.000
7.5	1.585	0.399	1.344	0.386	0.380	0.385	1.545	1.523	1.015	78.358
7.6	1.597	0.399	1.355	0.386	0.380	0.385	1.547	1.523	1.015	78.722
7.7	1.609	0.399	1.365	0.386	0.380	0.384	1.548	1.523	1.016	79.076
7.8	1.620	0.399	1.376	0.386	0.381	0.384	1.549	1.524	1.016	79.428
7.9	1.631	0.399	1.386	0.386	0.381	0.384	1.549	1.524	1.017	79.782
8.0	1.642	0.399	1.396	0.386	0.381	0.384	1.549	1.524	1.016	80.135

Table 1. Continued

Date: September 23, 1982				Sample No. 927 Group No. 8012			No-Load Voltage (VAC): 102 Sensing-Surface Absorptivity: 0.97			
1	2	3	4	5	6	7	8	9	10	11
Time, sec	E-TC EOUT1, mv	GG29 EOUT2, mv	J-TC EOUT3, mv	GG24 EOUT4, mv	GG33 EOUT5, mv	GG27 EOUT6, mv	GG33 QDOT1, Btu/ft^2-sec	GG24 QDOT2, Btu/ft^2-sec	QDOTR1/2	Equip. Temp, $^\circ$F
8.1	1.654	0.399	1.407	0.386	0.381	0.384	1.549	1.524	1.016	80.501
8.2	1.666	0.399	1.418	0.386	0.381	0.385	1.549	1.524	1.016	80.864
8.3	1.678	0.399	1.429	0.386	0.380	0.385	1.547	1.525	1.014	81.226
8.4	1.691	0.399	1.439	0.387	0.380	0.385	1.547	1.527	1.013	81.586
8.5	1.704	0.399	1.450	0.387	0.381	0.385	1.549	1.529	1.013	81.945
8.6	1.716	0.399	1.460	0.387	0.381	0.385	1.550	1.529	1.014	82.296
8.7	1.729	0.399	1.470	0.387	0.381	0.385	1.551	1.529	1.015	82.651
8.8	1.741	0.399	1.481	0.387	0.382	0.385	1.553	1.529	1.016	83.013
8.9	1.753	0.399	1.492	0.387	0.382	0.385	1.555	1.528	1.017	83.365
9.0	1.764	0.399	1.502	0.387	0.383	0.385	1.557	1.528	1.018	83.726
9.1	1.776	0.399	1.513	0.387	0.383	0.386	1.558	1.527	1.020	84.090
9.2	1.788	0.399	1.523	0.387	0.383	0.386	1.559	1.527	1.021	84.445
9.3	1.801	0.399	1.534	0.387	0.383	0.386	1.560	1.529	1.020	84.812
9.4	1.813	0.399	1.544	0.388	0.383	0.386	1.560	1.531	1.019	85.153
9.5	1.827	0.399	1.555	0.388	0.384	0.385	1.561	1.532	1.019	85.509
9.6	1.839	0.399	1.565	0.388	0.384	0.385	1.561	1.533	1.018	85.856
9.7	1.852	0.399	1.576	0.389	0.384	0.386	1.561	1.536	1.016	86.219
9.8	1.864	0.399	1.586	0.390	0.384	0.385	1.561	1.538	1.015	86.563
9.9	1.876	0.399	1.596	0.390	0.384	0.386	1.562	1.539	1.015	86.900
10.0	1.887	0.399	1.606	0.390	0.384	0.385	1.562	1.540	1.014	87.253
10.1	1.899	0.399	1.617	0.390	0.384	0.385	1.563	1.541	1.014	87.613
10.2	1.910	0.399	1.627	0.391	0.384	0.385	1.563	1.542	1.014	87.967
10.3	1.924	0.399	1.638	0.391	0.384	0.385	1.564	1.545	1.013	88.334
10.4	1.936	0.399	1.648	0.391	0.385	0.385	1.565	1.545	1.013	88.676
10.5	1.949	0.399	1.659	0.391	0.385	0.385	1.565	1.545	1.013	89.031
10.6	1.961	0.399	1.669	0.392	0.385	0.386	1.566	1.547	1.012	89.396
10.7	1.974	0.399	1.680	0.392	0.385	0.386	1.567	1.548	1.013	89.764
10.8	1.986	0.399	1.691	0.392	0.385	0.386	1.567	1.546	1.013	90.116
10.9	1.998	0.399	1.701	0.391	0.385	0.386	1.568	1.545	1.015	90.475
11.0	2.010	0.399	1.712	0.391	0.386	0.386	1.569	1.545	1.016	90.836
11.1	2.022	0.399	1.723	0.392	0.386	0.386	1.570	1.545	1.016	91.199
11.2	2.034	0.399	1.733	0.391	0.386	0.386	1.571	1.545	1.017	91.550
11.3	2.047	0.399	1.744	0.391	0.386	0.386	1.572	1.545	1.017	91.904
11.4	2.059	0.399	1.754	0.392	0.387	0.386	1.573	1.546	1.018	92.255
11.5	2.072	0.399	1.764	0.392	0.387	0.386	1.575	1.547	1.018	92.608
11.6	2.084	0.399	1.775	0.392	0.387	0.386	1.577	1.549	1.018	92.965
11.7	2.098	0.399	1.787	0.393	0.388	0.386	1.577	1.550	1.018	93.354
11.8	2.111	0.399	1.798	0.393	0.388	0.386	1.578	1.550	1.018	93.746
11.9	2.124	0.399	1.809	0.393	0.388	0.386	1.579	1.551	1.018	94.097
12.0	2.133	0.399	1.817	0.393	0.388	0.387	1.579	1.550	1.019	94.391

Table 1. Concluded

Date: September 23, 1982			Sample No. 927 Group No. 8012				No-Load Voltage (VAC): 102 Sensing-Surface Absorptivity: 0.97			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Time, sec	E-TC EOUT1, mv	GG29 EOUT2, mv	J-TC EOUT3, mv	GG24 EOUT4, mv	GG33 EOUT5, mv	GG27 EOUT6, mv	GG33 QDOT1, Btu/ft^2-sec	GG24 QDOT2, Btu/ft^2-sec	QDOTR1/2	Equip. Temp, °F
12.1	2.141	0.399	1.824	0.393	0.388	0.387	1.579	1.551	1.018	94.608
12.2	2.146	0.399	1.828	0.392	0.388	0.387	1.577	1.548	1.019	94.744
12.3	2.149	0.399	1.830	0.392	0.387	0.387	1.576	1.547	1.019	94.815
12.4	2.149	0.399	1.830	0.391	0.387	0.388	1.573	1.545	1.019	94.834
12.5	2.148	0.399	1.829	0.391	0.386	0.388	1.571	1.542	1.018	94.802
12.6	2.145	0.399	1.828	0.390	0.385	0.388	1.568	1.539	1.019	94.755
12.7	2.144	0.399	1.828	0.389	0.384	0.388	1.565	1.536	1.018	94.739
12.8	2.144	0.399	1.827	0.389	0.384	0.388	1.563	1.535	1.018	94.730
12.9	2.144	0.399	1.827	0.389	0.384	0.388	1.561	1.534	1.018	94.719
13.0	2.145	0.399	1.827	0.389	0.384	0.389	1.561	1.535	1.017	94.717
13.1	2.146	0.399	1.827	0.389	0.384	0.389	1.563	1.537	1.017	94.720
13.2	2.147	0.399	1.827	0.390	0.384	0.389	1.565	1.540	1.016	94.735
13.3	2.148	0.399	1.828	0.390	0.385	0.388	1.568	1.541	1.017	94.747
13.4	2.148	0.399	1.828	0.391	0.386	0.388	1.571	1.543	1.018	94.765
13.5	2.148	0.399	1.829	0.392	0.387	0.388	1.574	1.545	1.019	94.778
13.6	2.147	0.399	1.829	0.392	0.387	0.388	1.576	1.546	1.019	94.788
13.7	2.146	0.399	1.829	0.392	0.387	0.388	1.576	1.546	1.019	94.791
13.8	2.145	0.399	1.829	0.392	0.388	0.388	1.578	1.547	1.020	94.797
13.9	2.145	0.399	1.830	0.392	0.388	0.388	1.578	1.547	1.020	94.804
14.0	2.145	0.399	1.829	0.392	0.388	0.388	1.580	1.547	1.021	94.797
14.1	2.144	0.399	1.829	0.392	0.388	0.388	1.580	1.547	1.021	94.797
14.2	2.144	0.399	1.829	0.392	0.388	0.388	1.580	1.546	1.022	94.800
14.3	2.144	0.399	1.829	0.391	0.388	0.387	1.579	1.544	1.023	94.798
14.4	2.144	0.399	1.829	0.391	0.388	0.387	1.577	1.542	1.023	94.796
14.5	2.144	0.399	1.829	0.390	0.387	0.387	1.575	1.540	1.023	94.787
14.6	2.144	0.399	1.829	0.390	0.386	0.386	1.572	1.538	1.022	94.782
14.7	2.143	0.399	1.829	0.389	0.385	0.386	1.569	1.536	1.021	94.780
14.8	1.921	0.442	1.982	0.428	0.424	0.423	1.725	1.690	1.021	99.957
14.9	2.142	0.399	1.828	0.389	0.385	0.386	1.567	1.536	1.020	94.752
15.0	2.142	0.399	1.830	0.389	0.385	0.386	1.567	1.536	1.020	94.804
15.1	2.142	0.399	1.830	0.389	0.385	0.387	1.567	1.536	1.020	94.804
15.2	2.142	0.399	1.830	0.389	0.387	0.387	1.573	1.536	1.024	94.804
15.3	4.785	-0.114	0.000	-0.076	-0.076	-0.055	-0.308	-0.301	1.024	32.000

Table 2. Slug-Calorimeter Indicated Heat-Flux Data

Date: September 23, 1982		Sample No.: 927 Group No.: 8012				No-Load Voltage (VAC): 102 Sensing-Surface Absorptivity: 0.97			
		Chromel®-Constantan Thermocouple				Iron-Constantan Thermocouple			
1 Time, sec	2 QDOT Avg, Btu/ft^2-sec	3 TC Output, mv	4 Slug Temp Rise, ^oF	5 Slope dT/dt, ^oF/sec	6 Indicated Heat Flux, Btu/ft^2-sec	7 TC Output, mv	8 Slug Temp Rise, ^oF	9 Slope dT/dt, ^oF/sec	10 Indicated Heat Flux, Btu/ft^2-sec
0.1	0.004	1.314	0.0182	0.0000	0.000	1.093	0.0261	0.0000	0.000
0.2	-0.002	1.312	-0.0273	0.0000	0.000	1.091	-0.0261	0.0000	0.000
0.3	-0.002	1.315	0.0638	0.0000	0.000	1.093	0.0261	0.0000	0.000
0.4	-0.002	1.311	-0.0729	0.0000	0.000	1.091	-0.0261	0.0000	0.000
0.5	-0.002	1.314	0.0182	0.0064	0.003	1.091	-0.0261	-0.0492	-0.021
0.6	-0.001	1.313	-0.0076	0.0030	0.001	1.091	-0.0342	-0.0430	-0.019
0.7	-0.001	1.314	0.0107	0.0097	0.004	1.091	-0.0329	-0.0172	-0.007
0.8	-0.002	1.313	0.0080	-0.0036	-0.002	1.091	-0.0371	-0.0167	-0.007
0.9	-0.002	1.314	0.0134	0.0231	0.010	1.091	-0.0316	0.0090	0.004
1.0	-0.002	1.313	0.0048	-0.0123	-0.005	1.091	-0.0303	0.0042	0.002
1.1	-0.002	1.313	-0.0015	-0.0053	-0.002	1.091	-0.0247	-0.0054	-0.002
1.2	-0.003	1.313	-0.0016	-0.0053	-0.002	1.091	-0.0179	-0.0130	-0.006
1.3	-0.002	1.313	0.0053	0.0072	0.003	1.091	-0.0198	-0.0164	-0.007
1.4	-0.001	1.313	-0.0098	0.0184	0.008	1.091	-0.0258	-0.0184	-0.008
1.5	-0.000	1.313	0.0031	0.0315	0.014	1.091	-0.0406	-0.0161	-0.007
1.6	-0.000	1.313	0.0020	0.0470	0.020	1.090	-0.0541	-0.0046	-0.002
1.7	-0.000	1.314	0.0146	0.0545	0.023	1.090	-0.0454	0.0052	0.002
1.8	-0.001	1.314	0.0245	0.0742	0.032	1.091	-0.0399	0.0236	0.010
1.9	-0.000	1.314	0.0275	0.0836	0.036	1.091	-0.0333	0.0374	0.016
2.0	-0.001	1.314	0.0293	0.0758	0.033	1.091	-0.0297	0.0414	0.018
2.1	-0.000	1.315	0.0478	0.0573	0.025	1.091	-0.0108	0.0316	0.014
2.2	-0.001	1.315	0.0466	0.0309	0.013	1.091	-0.0171	0.0134	0.006
2.3	-0.000	1.316	0.0831	0.0071	0.003	1.092	-0.0048	-0.0037	-0.002
2.4	0.000	1.315	0.0691	-0.0018	-0.001	1.091	-0.0103	-0.0197	-0.008
2.5	0.000	1.315	0.0622	-0.0095	-0.004	1.091	-0.0224	-0.0346	-0.015
2.6	-0.000	1.314	0.0374	0.0096	0.004	1.091	-0.0346	-0.0369	-0.016
2.7	-0.001	1.314	0.0283	0.0336	0.014	1.091	-0.0357	-0.0287	-0.012
2.8	-0.001	1.314	0.0243	0.0575	0.025	1.091	-0.0399	-0.0169	-0.007
2.9	-0.001	1.315	0.0471	0.0817	0.035	1.091	-0.0430	-0.0030	-0.001
3.0	-0.002	1.315	0.0505	0.0758	0.033	1.090	-0.0492	0.0060	0.003
3.1	-0.001	1.317	0.1122	0.0423	0.018	1.091	-0.0289	0.0074	0.003
3.2	-0.001	1.317	0.1170	-0.0185	-0.008	1.091	-0.0283	-0.0002	-0.000
3.3	-0.001	1.318	0.1323	-0.0988	-0.043	1.091	-0.0165	-0.0133	-0.006
3.4	-0.000	1.317	0.1064	-0.1662	-0.072	1.091	-0.0263	-0.0276	-0.012
3.5	-0.000	1.315	0.0614	-0.2197	-0.095	1.091	-0.0348	-0.0423	-0.018
3.6	-0.001	1.313	0.0075	-0.2485	-0.107	1.091	-0.0420	-0.0532	-0.023
3.7	-0.002	1.312	-0.0340	-0.2342	-0.101	1.090	-0.0510	-0.0525	-0.023
3.8	-0.002	1.310	-0.0800	-0.1991	-0.086	1.090	-0.0650	-0.0521	-0.022

Table 2. Continued

Date: September 23, 1982		Sample No.: 927 Group No.: 8012				No-Load Voltage (VAC): 102 Sensing-Surface Absorptivity: 0.97			
		Chromel®-Constantan Thermocouple				Iron-Constantan Thermocouple			
(1) Time, sec	(2) QDOT Avg, Btu/ft^2-sec	(3) TC Output, mv	(4) Slug Temp Rise, ^{o}F	(5) Slope dT/dt, ^{o}F/sec	(6) Indicated Heat Flux, Btu/ft^2-sec	(7) TC Output, mv	(8) Slug Temp Rise, ^{o}F	(9) Slope dT/dt, ^{o}F/sec	(10) Indicated Heat Flux, Btu/ft^2-sec
3.9	-0.003	1.311	-0.0685	-0.1398	-0.060	1.090	-0.0685	-0.0416	-0.018
4.0	-0.003	1.310	-0.0837	-0.0737	-0.032	1.090	-0.0714	-0.0285	-0.012
4.1	-0.003	1.311	-0.0598	-0.0212	-0.009	1.090	-0.0615	-0.0185	-0.008
4.2	-0.003	1.311	-0.0610	0.0136	0.006	1.090	-0.0627	-0.0079	-0.003
4.3	-0.002	1.311	-0.0557	0.0284	0.012	1.090	-0.0707	-0.0282	-0.012
4.4	-0.003	1.311	-0.0554	0.0072	0.003	1.090	-0.0713	-0.0530	-0.023
4.5	-0.002	1.312	-0.0469	-0.0096	-0.004	1.090	-0.0645	-0.0517	-0.022
4.6	-0.003	1.311	-0.0533	-0.0159	-0.007	1.090	-0.0689	0.0113	0.005
4.7	-0.004	1.311	-0.0507	0.0295	0.013	1.090	-0.0658	0.1669	0.072
4.8	-0.008	1.311	-0.0562	0.1469	0.063	1.088	-0.1277	0.4272	0.184
4.9	-0.038	1.310	-0.0851	0.3555	0.153	1.088	-0.1363	0.7927	0.341
5.0	-0.053	1.310	-0.0899	0.6693	0.288	1.089	-0.0887	1.2495	0.538
5.1	-0.022	1.311	-0.0529	1.0702	0.461	1.093	0.0463	1.7698	0.762
5.2	0.072	1.314	0.0382	1.5331	0.660	1.099	0.2618	2.3039	0.992
5.3	0.228	1.320	0.2178	2.0208	0.870	1.108	0.5581	2.7834	1.198
5.4	0.432	1.329	0.4677	2.4823	1.069	1.119	0.9235	3.1625	1.362
5.5	0.665	1.340	0.8035	2.8854	1.242	1.130	1.3237	3.4300	1.477
5.6	0.903	1.352	1.1565	3.2139	1.384	1.143	1.7345	3.5936	1.547
5.7	1.117	1.365	1.5416	3.4449	1.483	1.154	2.1298	3.6683	1.579
5.8	1.277	1.377	1.9118	3.5998	1.550	1.163	2.4457	3.6830	1.586
5.9	1.362	1.389	2.2535	3.6802	1.584	1.174	2.8014	3.6633	1.577
6.0	1.414	1.401	2.6213	3.7096	1.597	1.184	3.1520	3.6365	1.566
6.1	1.447	1.414	3.0045	3.7239	1.603	1.195	3.5240	3.6247	1.561
6.2	1.470	1.426	3.3645	3.7237	1.603	1.206	3.8890	3.6364	1.566
6.3	1.487	1.440	3.7711	3.7151	1.599	1.217	4.2668	3.6604	1.576
6.4	1.499	1.452	4.1383	3.7036	1.594	1.228	4.6365	3.6607	1.576
6.5	1.508	1.465	4.5102	3.6677	1.579	1.238	4.9982	3.6498	1.571
6.6	1.514	1.477	4.8826	3.6446	1.569	1.249	5.3660	3.6340	1.565
6.7	1.519	1.489	5.2429	3.6183	1.558	1.260	5.7332	3.6223	1.559
6.8	1.523	1.501	5.5796	3.5902	1.546	1.270	6.0856	3.6109	1.555
6.9	1.527	1.513	5.9366	3.5808	1.542	1.281	6.4454	3.6071	1.553
7.0	1.529	1.524	6.2780	3.5708	1.537	1.291	6.7940	3.6053	1.552
7.1	1.531	1.537	6.6696	3.5635	1.534	1.302	7.1609	3.6052	1.552
7.2	1.532	1.549	7.0123	3.5631	1.534	1.312	7.5254	3.6050	1.552
7.3	1.532	1.561	7.3779	3.5525	1.529	1.323	7.8885	3.6049	1.552
7.4	1.533	1.573	7.7339	3.5283	1.519	1.334	8.2516	3.5994	1.550
7.5	1.534	1.585	8.0842	3.4957	1.505	1.344	8.6092	3.5920	1.546
7.6	1.535	1.597	8.4333	3.4643	1.491	1.355	8.9734	3.5825	1.542

Table 2. Continued

Date: September 23, 1982 — Sample No.: 927 — Group No.: 8012 — No-Load Voltage (VAC): 102 — Sensing-Surface Absorptivity: 0.97

		Chromel®-Constantan Thermocouple				Iron-Constantan Thermocouple			
(1) Time, sec	(2) QDOT Avg, Btu/ft²-sec	(3) TC Output, mv	(4) Slug Temp Rise, °F	(5) Slope dT/dt, °F/sec	(6) Indicated Heat Flux, Btu/ft²-sec	(7) TC Output, mv	(8) Slug Temp Rise, °F	(9) Slope dT/dt, °F/sec	(10) Indicated Heat Flux, Btu/ft²-sec
7.7	1.536	1.609	8.7860	3.4522	1.486	1.365	9.3271	3.5785	1.541
7.8	1.536	1.620	9.1121	3.4448	1.483	1.376	9.6789	3.5781	1.540
7.9	1.536	1.631	9.4520	3.4591	1.489	1.386	10.0332	3.5801	1.541
8.0	1.536	1.642	9.7794	3.4880	1.502	1.396	10.3868	3.5849	1.543
8.1	1.536	1.654	10.1413	3.5186	1.515	1.407	10.7519	3.5851	1.543
8.2	1.536	1.666	10.4862	3.5675	1.536	1.418	11.1157	3.5877	1.545
8.3	1.536	1.678	10.8487	3.6125	1.555	1.429	11.4769	3.5906	1.546
8.4	1.537	1.691	11.2251	3.6367	1.566	1.439	11.8369	3.5874	1.544
8.5	1.539	1.704	11.5993	3.6425	1.568	1.450	12.1968	3.5834	1.543
8.6	1.539	1.716	11.9557	3.6266	1.561	1.460	12.5469	3.5794	1.541
8.7	1.540	1.729	12.3516	3.6062	1.553	1.470	12.9024	3.5766	1.540
8.8	1.541	1.741	12.7032	3.5909	1.546	1.481	13.2647	3.5802	1.541
8.9	1.541	1.753	13.0495	3.5792	1.541	1.492	13.6163	3.5768	1.540
9.0	1.543	1.764	13.3889	3.5911	1.546	1.502	13.9771	3.5744	1.539
9.1	1.543	1.776	13.7355	3.6066	1.553	1.513	14.3416	3.5695	1.537
9.2	1.543	1.788	14.0827	3.6248	1.561	1.523	14.6968	3.5653	1.535
9.3	1.544	1.801	14.4681	3.6613	1.576	1.534	15.0637	3.5545	1.530
9.4	1.546	1.813	14.8374	3.6811	1.585	1.544	15.4042	3.5387	1.524
9.5	1.546	1.827	15.2354	3.6746	1.582	1.555	15.7599	3.5219	1.516
9.6	1.547	1.839	15.5965	3.6517	1.572	1.565	16.1071	3.5125	1.512
9.7	1.548	1.852	15.9740	3.6104	1.554	1.576	16.4708	3.5091	1.511
9.8	1.549	1.864	16.3430	3.5830	1.543	1.586	16.8143	3.5138	1.513
9.9	1.550	1.876	16.6825	3.5611	1.533	1.596	17.1510	3.5207	1.516
10.0	1.551	1.887	17.0049	3.5498	1.528	1.606	17.5040	3.5234	1.517
10.1	1.552	1.899	17.3527	3.5585	1.532	1.617	17.8648	3.5333	1.521
10.2	1.553	1.910	17.6892	3.5732	1.538	1.627	18.2182	3.5469	1.527
10.3	1.554	1.924	18.0939	3.6024	1.551	1.638	18.5850	3.5635	1.534
10.4	1.555	1.936	18.4457	3.6384	1.566	1.648	18.9273	3.5762	1.540
10.5	1.555	1.949	18.8213	3.6532	1.573	1.659	19.2823	3.5811	1.542
10.6	1.556	1.961	19.1845	3.6538	1.573	1.669	19.6469	3.5856	1.544
10.7	1.558	1.974	19.5541	3.6368	1.566	1.680	20.0156	3.5876	1.545
10.8	1.557	1.986	19.9245	3.6114	1.555	1.691	20.3678	3.5856	1.544
10.9	1.557	1.998	20.2870	3.6072	1.553	1.701	20.7261	3.5854	1.544
11.0	1.557	2.010	20.6215	3.6024	1.551	1.712	21.0876	3.5757	1.539
11.1	1.558	2.022	20.9914	3.6002	1.550	1.723	21.4501	3.5647	1.535
11.2	1.558	2.034	21.3324	3.6145	1.556	1.733	21.8010	3.5717	1.538
11.3	1.559	2.047	21.7061	3.6453	1.569	1.744	22.1553	3.5981	1.549
11.4	1.560	2.059	22.0705	3.6803	1.584	1.754	22.5067	3.6142	1.556

Table 2. Concluded

Date: September 23, 1982 | Sample No. 927, Group No.: 8012 | No-Load Voltage (VAC): 102, Sensing-Surface Absorptivity: 0.97

(1) Time, sec	(2) QDOT Avg, Btu/ft^2-sec	Chromel®-Constantan Thermocouple (3) TC Output, mv	(4) Slug Temp Rise, °F	(5) Slope dT/dt, °F/sec	(6) Indicated Heat Flux, Btu/ft^2-sec	Iron-Constantan Thermocouple (7) TC Output, mv	(8) Slug Temp Rise, °F	(9) Slope dT/dt, °F/sec	(10) Indicated Heat Flux, Btu/ft^2-sec
11.5	1.561	2.072	22.4425	3.6745	1.582	1.764	22.8592	3.5973	1.549
11.6	1.563	2.084	22.7967	3.5978	1.549	1.775	23.2166	3.5202	1.516
11.7	1.564	2.098	23.1923	3.4367	1.480	1.787	23.6058	3.3599	1.447
11.8	1.564	2.111	23.5866	3.1643	1.362	1.798	23.9977	3.1006	1.335
11.9	1.565	2.124	23.9579	2.7982	1.205	1.809	24.3488	2.7464	1.182
12.0	1.565	2.133	24.2400	2.3377	1.006	1.817	24.6425	2.3031	0.992
12.1	1.565	2.141	24.4729	1.8141	0.781	1.824	24.8595	1.7992	0.775
12.2	1.563	2.146	24.6139	1.2735	0.548	1.828	24.9958	1.2875	0.554
12.3	1.561	2.149	24.6841	0.7875	0.339	1.830	25.0663	0.8228	0.354
12.4	1.559	2.149	24.7001	0.4014	0.173	1.830	25.0851	0.4419	0.190
12.5	1.557	2.148	24.6537	0.1397	0.060	1.829	25.0535	0.1633	0.070
12.6	1.553	2.145	24.5853	-0.0118	-0.005	1.828	25.0066	-0.0101	-0.004
12.7	1.551	2.144	24.5514	-0.0568	-0.024	1.828	24.9899	-0.0882	-0.038
12.8	1.549	2.144	24.5476	-0.0338	-0.015	1.827	24.9810	-0.0981	-0.042
12.9	1.548	2.144	24.5653	0.0247	0.011	1.827	24.9702	-0.0613	-0.026
13.0	1.548	2.145	24.5892	0.0891	0.038	1.827	24.9684	-0.0039	-0.002
13.1	1.550	2.146	24.6194	0.1230	0.053	1.827	24.9713	0.0456	0.020
13.2	1.552	2.147	24.6501	0.1029	0.044	1.827	24.9863	0.0723	0.031
13.3	1.554	2.148	24.6661	0.0575	0.025	1.828	24.9982	0.0894	0.038
13.4	1.557	2.148	24.6702	0.0032	0.001	1.828	25.0166	0.0996	0.043
13.5	1.560	2.148	24.6612	-0.0491	-0.021	1.829	25.0296	0.0941	0.040
13.6	1.561	2.147	24.6420	-0.0960	-0.041	1.829	25.0390	0.0804	0.035
13.7	1.561	2.146	24.6030	-0.1278	-0.055	1.829	25.0423	0.0621	0.027
13.8	1.562	2.145	24.5915	-0.1410	-0.061	1.829	25.0482	0.0439	0.019
13.9	1.563	2.145	24.5846	-0.1368	-0.059	1.830	25.0554	0.0257	0.011
14.0	1.564	2.145	24.5751	-0.1200	-0.052	1.829	25.0487	0.0090	0.004
14.1	1.564	2.144	24.5602	-0.0960	-0.041	1.829	25.0487	-0.0050	-0.002
14.2	1.563	2.144	24.5516	-0.0738	-0.032	1.829	25.0511	-0.0151	-0.007
14.3	1.561	2.144	24.5418	-0.0554	-0.024	1.829	25.0493	-0.0354	-0.015
14.4	1.560	2.144	24.5394	-0.0585	-0.025	1.829	25.0476	-0.0489	-0.021
14.5	1.558	2.144	24.5370	-0.0573	-0.025	1.829	25.0386	-0.0310	-0.013
14.6	1.555	2.144	24.5367	-0.0538	-0.023	1.829	25.0332	-0.0168	-0.007
14.7	1.553	2.143	24.5311	-0.0519	-0.022	1.829	25.0314	-0.0031	-0.001
14.8	1.551	2.144	24.5472	-11.1869	-4.816	1.828	25.0036	-11.3774	-4.898
14.9	1.551	2.142	24.5026	-20.0954	-8.652	1.828	25.0036	-20.4753	-8.815
15.0	1.551	2.142	24.5026	-26.7740	-11.527	1.830	25.0551	-27.2969	-11.752
15.1	1.551	2.142	24.5026	-31.2231	-13.442	1.830	25.0551	-31.8463	-13.711
15.2	1.554	2.142	24.5026	-33.4418	-14.398	1.830	25.0551	-34.1225	-14.691

Table 3. AEDC Heat-Flux Transducer Experimental Calibration Data

QDOT E-TC, Btu/ft^2-sec	QDOT J-TC, Btu/ft^2-sec	QDOT K-TC, Btu/ft^2-sec	EO-SB21, mv	EO-SB22, mv	EO-GG24, mv	EO-GG27, mv	EO-GG29, mv	EO-GG33, mv
0.8190	0.8060	-1.0000	-1.0000	1.3210	-1.0000	0.2040	0.2000	-1.0000
1.5040	1.5110	-1.0000	-1.0000	2.4640	-1.0000	0.3800	0.3700	-1.0000
1.7310	1.7110	-1.0000	-1.0000	-1.0000	-1.0000	0.4400	0.4330	-1.0000
1.1970	-1.0000	-1.0000	1.1800	1.9500	-1.0000	0.3010	0.2960	-1.0000
1.6170	-1.0000	-1.0000	1.5920	2.6300	-1.0000	0.4050	0.3980	0.4150
1.1100	-1.0000	-1.0000	1.0870	1.8000	-1.0000	0.2770	0.2720	0.2850
0.9310	-1.0000	-1.0000	0.9290	1.5260	-1.0000	0.2360	0.2260	-1.0000
1.2720	-1.0000	0.3190	1.2540	-1.0000	-1.0000	0.3220	0.3180	0.3290
1.8700	-1.0000	0.4660	1.8490	-1.0000	-1.0000	0.4710	0.4660	0.4800
1.2190	-1.0000	0.3030	1.2030	-1.0000	-1.0000	0.3090	0.3040	0.3170
0.8660	-1.0000	0.2130	0.8520	-1.0000	-1.0000	0.2120	0.2120	0.2200
1.8030	-1.0000	0.4460	1.7730	-1.0000	-1.0000	0.4510	0.4500	0.4640
2.0780	-1.0000	0.5130	2.0630	-1.0000	-1.0000	0.5230	0.5200	0.5290
1.6170	-1.0000	0.4060	1.5910	-1.0000	-1.0000	0.4100	0.4050	0.4150
1.7720	1.7530	0.4420	-1.0000	-1.0000	-1.0000	0.4460	0.4440	-1.0000
1.2800	1.2810	0.3160	-1.0000	-1.0000	-1.0000	0.3210	0.3210	-1.0000
1.5450	1.5360	0.3820	-1.0000	-1.0000	-1.0000	0.3870	0.3840	0.3990
1.6820	1.6710	0.4180	-1.0000	-1.0000	-1.0000	0.4250	0.4190	0.4310
1.8110	1.8120	0.4460	-1.0000	-1.0000	-1.0000	0.4650	0.4540	0.4640
1.4550	1.4580	0.3640	-1.0000	-1.0000	-1.0000	0.3630	0.3630	-1.0000
1.6850	1.6740	0.4120	-1.0000	-1.0000	-1.0000	0.4190	0.4100	-1.0000
1.5007	1.5007	0.3650	-1.0000	-1.0000	-1.0000	0.3750	0.3670	0.3820
1.0890	-1.0000	0.2690	-1.0000	-1.0000	-1.0000	0.2770	0.2710	0.2900
1.8410	-1.0000	0.4540	-1.0000	-1.0000	-1.0000	0.4660	0.4540	0.4730
1.9480	1.9300	0.4840	-1.0000	-1.0000	-1.0000	0.4960	0.4840	-1.0000
0.9940	-1.0000	0.2430	-1.0000	-1.0000	-1.0000	0.2510	0.2420	-1.0000
1.5160	-1.0000	0.3770	-1.0000	-1.0000	-1.0000	0.3850	0.3750	-1.0000
1.5880	-1.0000	0.3940	-1.0000	-1.0000	-1.0000	0.4040	0.3920	0.4150
1.4390	1.4290	-1.0000	-1.0000	2.3500	1.7910	-1.0000	-1.0000	0.3710
1.2120	1.1910	-1.0000	-1.0000	1.9590	1.4980	-1.0000	-1.0000	0.3090
1.0760	1.0590	-1.0000	-1.0000	1.7370	1.3300	-1.0000	-1.0000	0.2740
1.5040	1.5000	-1.0000	-1.0000	2.4520	1.8770	-1.0000	-1.0000	0.3900
1.8250	1.8300	-1.0000	-1.0000	2.9950	2.2850	-1.0000	-1.0000	0.4750
2.0060	1.9960	-1.0000	-1.0000	3.2700	2.5030	-1.0000	-1.0000	0.5180
1.2370	1.2270	-1.0000	-1.0000	2.0150	1.5430	-1.0000	-1.0000	0.3170
1.6280	1.6270	-1.0000	-1.0000	2.6590	2.0310	-1.0000	-1.0000	0.4210
1.3660	1.3700	-1.0000	-1.0000	2.2360	1.7170	-1.0000	-1.0000	0.3600
1.1700	-1.0000	-1.0000	-1.0000	1.9280	1.4800	-1.0000	-1.0000	0.3040
1.5440	1.5310	-1.0000	-1.0000	2.5280	1.9360	-1.0000	-1.0000	0.3960
1.5300	-1.0000	-1.0000	1.5150	2.5100	1.9270	-1.0000	-1.0000	0.3940
1.8110	-1.0000	-1.0000	-1.0000	2.9550	2.2620	-1.0000	-1.0000	0.4640
1.3370	-1.0000	-1.0000	-1.0000	2.1820	1.6690	-1.0000	-1.0000	0.3420
1.6400	-1.0000	-1.0000	-1.0000	2.6840	2.0600	-1.0000	-1.0000	0.4220
1.2510	-1.0000	-1.0000	1.2530	2.0610	1.5770	-1.0000	-1.0000	0.3250
1.2760	-1.0000	-1.0000	1.2670	2.1120	1.6150	-1.0000	-1.0000	0.3330
1.2910	1.2830	-1.0000	-1.0000	2.0740	-1.0000	0.3240	0.3170	0.3300
1.9630	1.9520	0.4840	-1.0000	-1.0000	2.4450	0.4960	-1.0000	0.5020
1.0340	1.0370	0.2540	-1.0000	-1.0000	1.2660	0.2560	-1.0000	0.2650
1.2260	1.2120	0.3040	-1.0000	-1.0000	-1.0000	0.3110	0.3030	-1.0000
1.8050	-1.0000	0.4530	-1.0000	-1.0000	-1.0000	0.4610	0.4500	-1.0000
1.1790	-1.0000	0.2930	-1.0000	-1.0000	-1.0000	0.2980	0.2900	-1.0000
1.5980	-1.0000	0.4000	-1.0000	-1.0000	-1.0000	0.4050	0.3980	-1.0000
0.9055	0.9065	-1.0000	-1.0000	1.4690	-1.0000	0.2260	0.2220	-1.0000
1.2920	1.2920	0.3230	-1.0000	-1.0000	1.6660	-1.0000	-1.0000	-1.0000
1.6450	1.6440	0.4150	-1.0000	-1.0000	2.1190	-1.0000	-1.0000	-1.0000
0.9510	0.9430	0.2380	-1.0000	-1.0000	1.2120	-1.0000	-1.0000	-1.0000
1.3840	1.3780	0.3460	-1.0000	-1.0000	1.7360	0.3580	-1.0000	-1.0000
1.1800	1.1730	0.2890	-1.0000	-1.0000	1.4400	0.2940	-1.0000	-1.0000
1.7560	1.7650	0.4290	-1.0000	-1.0000	2.1400	-1.0000	0.4360	-1.0000

Table 4. Calculation of Experimental Scale Factors for the AEDC Heat-Flux Transducers

SB21, Btu/ft^2-sec/mv	SB22, Btu/ft^2-sec/mv	GG24, Btu/ft^2-sec/mv	GG27, Btu/ft^2-sec/mv	GG29, Btu/ft^2-sec/mv	GG33, Btu/ft^2-sec/mv	Number of Data Samples
0.6200	0.8035	4.0147	4.0950	3.8964	3.9875	1
0.6104	0.8091	3.9579	4.0649	3.8947	4.0129	2
0.6138	0.8090	3.9341	3.9977	3.8663	4.0231	3
0.6148	0.8013	3.9767	4.0439	3.8958	4.0657	4
0.6167	0.7987	3.9926	4.0628	3.8454	4.0426	5
0.6101	0.8014	4.0072	4.0809	3.9364	4.0507	6
0.6123	0.8017	3.9449	4.1195	3.8858	3.9828	7
0.6187	0.8016	3.9503	4.0000	3.9282	4.0090	8
0.6195	0.7956	3.9703	4.0129	3.8964	4.0506	9
0.6134	0.7905	3.9450	4.0099	3.8722	4.0445	10
0.6093	0.7975	4.0849	4.0849	3.9025	4.0239	11
0.6135	0.7940	3.9978	4.0067	3.9030	4.0605	12
0.6139	0.8006	3.9732	3.9962	3.9285	3.9973	13
0.6123	0.8011	3.9439	3.9926	3.7552	4.0898	14
0.6109	0.7961	3.9731	3.9910	3.8922	4.1115	15
0.6068	0.7933	3.9875	3.9875	3.8265	4.0483	16
0.6108	0.7901	3.9922	4.0234	3.8787	4.0551	17
0.6096	0.8029	3.9576	4.0143	3.9223	4.0248	18
0.6129	0.8167	3.8946	3.9890	3.9270	4.0905	19
0.6127	0.7755	4.0083	4.0083	3.8564	4.0212	20
0.6110	0.7763	4.0215	4.1098	3.8421	4.0305	21
0.6070	0.7847	4.0019	4.0891	3.8726	4.0558	22
0.6042	0.7972	3.9314	4.0184	3.9022	4.0709	23
0.6225	0.8194	3.9506	4.0551	3.8670	4.0329	24
0.6164	0.8206	3.9274	4.0248	3.7944	3.9845	25
0.6101	0.7979	3.9602	4.1074	3.8487	4.0239	26
0.6132	0.7951	3.9377	4.0427	3.8990	3.9950	27
0.6081	0.7962	3.9307	4.0510	3.8832	4.0000	28
0.6080	0.7991	3.9846	4.0726	3.9030	3.9639	29
0.6097	0.8009	3.9577	4.0462	3.9094	3.9958	30
0.6117	0.7974	4.0391	4.0111	3.8863	4.0000	31
0.6110	0.7952	3.9421	4.0655	3.8492	4.0830	32
0.6104	0.8011	3.9154	4.0151	3.8318	4.0932	33
0.6089	0.7979	3.9564	4.0788	3.9121	3.9661	34
0.6119	0.7908	3.9457	4.0275	3.9104	4.0538	35
0.6127	0.7984	4.0066	4.0300	3.9019	4.0209	36
0.6056	0.8191	3.8659	4.0838	3.8496	3.9976	37
0.6186	0.7755	4.0136	3.9515	3.8770	4.0628	38
0.6171	0.7758	3.9510	3.9482	3.9052	4.0055	39
0.6051	0.7781	3.9763	3.9907	3.9285	4.0631	40
0.6053	0.7938	3.8886	4.0000	3.8518	4.1115	41
0.6039	0.8146	3.9305	3.9881	3.8544	3.9876	42
0.6088	0.8248	3.9907	3.9912	3.8650	4.0331	43
0.6036	0.7862	3.9690	4.0165	3.8462	4.0827	44
0.6080	0.7945	3.9318	4.0829	3.8526	3.9868	45
0.5999	0.7845	3.8968	4.0891	3.8533	4.0000	46
0.0	0.0	4.0165	3.9876	3.8707	3.9614	47
0.0	0.0	3.9952	4.0473	3.8646	3.9622	48
0.0	0.0	4.0019	4.0000	3.8056	3.9827	49
0.0	0.0	3.8911	4.0833	3.8662	4.0588	50
0.0	0.0	3.9599	4.0482	3.8879	4.1142	51
0.0	0.0	3.9355	3.9865	3.8884	3.9310	52
0.0	0.0	4.0508	4.0000	3.9132	3.9678	53
0.0	0.0	3.8971	3.9963	3.8361	3.9703	54
0.0	0.0	4.0111	4.1106	3.8140	4.0000	55
0.0	0.0	3.8492	3.9434	3.8115	3.9753	56
0.0	0.0	3.9898	3.9676	3.8521	4.0214	57
0.0	0.0	3.9203	3.9572	3.7949	3.9187	58
0.0	0.0	3.9309	4.0189	3.8727	0.0	59
0.0	0.0	3.9242	3.9400	3.8211	0.0	60
0.0	0.0	3.9364	3.9673	3.8998	0.0	61
0.0	0.0	3.8944	3.9284	3.8337	0.0	62
0.0	0.0	3.9257	0.0	3.8452	0.0	63
0.0	0.0	3.8932	0.0	3.8554	0.0	64
0.0	0.0	4.0189	0.0	3.8048	0.0	65
0.0	0.0	3.9313	0.0	0.0	0.0	66
0.0	0.0	3.9446	0.0	0.0	0.0	67
0.0	0.0	3.8805	0.0	0.0	0.0	68

Note: Heat flux measured with slug calorimeter with ANSI Type E, J, and K thermocouples.

Table 5. Calculation of Mean Value and Standard Deviation of Scale Factors - AEDC Experimental Data

SB21 Data Samples: 46		SB22 Data Samples: 46		GG24 Data Samples: 68	
Mean Value, Btu/ft^2-sec/mv	Standard Deviation, Btu/ft^2-sec/mv	Mean Value, Btu/ft^2-sec/mv	Standard Deviation, Btu/ft^2-sec/mv	Mean Value, Btu/ft^{2}sec/mv	Standard Deviation, Btu/ft^2-sec/mv
0.61119	0.00468 (0.766 percent)	0.79772	0.01168 (1.464 percent)	3.95775	0.04577 (1.156 percent)
GG27 Data Samples: 62		**GG29 Data Samples: 65**		**GG33 Data Samples: 58**	
Mean Value, Btu/ft^2-sec/mv	Standard Deviation, Btu/ft^2-sec/mv	Mean Value, Btu/ft^2-sec/mv	Standard Deviation, Btu/ft^2-sec/mv	Mean Value, Btu/ft^2-sec/mv	Standard Deviation Btu/ft^2-sec/mv
4.02501	0.04709 (1.170 percent)	3.86991	0.03800 (0.982 percent)	4.02339	0.04495 (1.117 percent)

Table 6. Tabulated NBS Heat-Flux Calibration Data

NBS-Calibrated Heat-Flux Meter SN 124421, mv	Incident Heat Flux		Instrument Output					
	w/cm^2	Btu/ft^2-sec	SB21, mv	SB22, mv	GG24, mv	GG27, mv	GG29, mv	GG33, mv
0.38	0.10	0.0881	0.136	0.106	0.015	0.011	0.011	0.005
0.74	0.20	0.1762	0.274	0.220	0.039	0.033	0.037	0.026
1.49	0.40	0.3523	0.564	0.445	0.085	0.078	0.082	0.082
2.23	0.60	0.5285	0.852	0.662	0.129	0.120	0.127	0.122
2.97	0.80	0.7046	1.130	0.887	0.172	0.163	0.172	0.170
3.72	1.00	0.8808	1.410	1.105	0.217	0.201	0.217	0.213
4.46	1.20	1.0569	1.690	1.320	0.259	0.250	0.260	0.255
5.20	1.40	1.2331	1.970	1.520	0.304	0.289	0.303	0.294
5.95	1.60	1.4092	2.240	1.725	0.347	0.334	0.347	0.338
6.69	1.80	1.5854	2.520	1.955	0.390	0.374	0.391	0.377
7.43	2.00	1.7615	2.770	2.150	0.430	0.415	0.434	0.416

NOTE: 1.0 w/cm^2 = 0.88077 Btu/ft^2-sec

Table 7. Linear Equations for Heat-Flux Transducers

Transducer	Form of Equation $\dot{q} = \dot{q}_o + m\,E_o$	Scale Factor[2], Btu/ft^2-sec/mv
SB21	$\dot{q} = -0.0038 + 0.7165\,E_o$	0.6121
SB22	$\dot{q} = -0.0091 + 0.9268\,E_o$	0.7918
GG24[1]	$\dot{q} = 0.0022 + 4.6199\,E_o$	3.9470
GG27[1]	$\dot{q} = 0.0196 + 4.7681\,E_o$	4.0736
GG29[1]	$\dot{q} = 0.0118 + 4.5785\,E_o$	3.9116
GG33[1]	$\dot{q} = 0.0002 + 4.7633\,E_o$	4.0695

[1] Values for 0.1 and 0.2 w/cm^2 were not used in the determination of the linear equations.

[2] Scale factors for each transducer were calculated by converting the slope, m, of the best straight-line curve fit in column 2 into English units and multiplying by sensing-surface absorptivity, 0.97.

Table 8. Uncertainty of the AEDC Experimental Heat-Flux Gage Calibrations

Serial Number	SB21	SB22	GG24	GG27	GG29	GG33
Type Gage	Schmidt-Boelter	Schmidt-Boelter	Conventional Gardon	Conventional Gardon	Conventional Gardon	Conventional Gardon
Number of Data Samples, N	46	46	68	62	65	58
$\frac{\text{Scale Factor}^{1}\text{(AEDC)}}{\text{Scale Factor (NBS)}}$	0.9985	1.007	1.0027	0.9881	0.9893	0.988
Standard Deviation[2], percent	0.77	1.46	1.16	1.17	0.98	1.12
Bias[3], percent	−0.15	0.75	0.27	−1.19	−1.07	−1.13
Uncertainty[4], percent	±1.69	±3.67	±2.59	±3.53	±3.03	±3.37

[1] Scale Factor: Ratio of Measured Absorbed Heat Flux Divided by Instrument Output for Each Gage (Mean Value of N Calibration Data Points)

[2] Standard Deviation: Classical Calculation of Deviation of Individual Gage Scale Factors Obtained from Large Sample (>30) of the AEDC Calibration Data Points,

$$S = \sqrt{\sum_{i=1}^{N} \frac{(SF_i - \overline{SF})^2}{N}}$$

[3] Bias: Percentage Difference between Mean Scale Factors Determined by the NBS and the AEDC Calibrations

[4] Uncertainty: $U = \pm(B + t_{95}S)$; B – BIAS, $t_{95} = 2$, S – Standard Deviation (See Appendix B)

APPENDIX A

SLUG-CALORIMETER ANALYSIS

A slug calorimeter consists of two primary components: a calorimetric mass and a mass support system. The backside temperature history is usually measured with fine-wire thermocouples. Since the wires are small (0.003-in. diam) and it has been shown in recent thermal analyses at the AEDC that the effects of these wires are negligible, they will not be considered in this analysis. The thermal interaction between the calorimetric mass and the mass support is the heat-conduction problem which will be addressed in this appendix.

The equation normally used for reduction of heat-flux data from a slug calorimeter is

$$\dot{q} = \varrho \, \ell \, C_p \frac{dT}{dt} \tag{A-1}$$

and assumes one-dimensional heat conduction only. This defines ideal (no heat losses or gains except at the sensing surface) slug-calorimeter behavior. In reality, it is difficult to design and fabricate a slug calorimeter which behaves in the ideal manner. It is the degree to which the actual approaches the ideal which is of primary interest. Since it is realized that heat conduction is not truly one dimensional, an analytical technique which considers heat conduction in at least two dimensions must be used. Such a method exists and has been successfully used in Schmidt-Boelter gage design among other applications. This method is a finite-element, two-dimensional heat-conduction code designated TRAX (Ref. 15).

Analytical modeling of the slug-calorimeter system by the TRAX computer code is simple and straightforward. A block matrix of the analytical TRAX model used to represent the slug-calorimeter system is shown in Fig. A-1. This is an axisymmetric model of radius, R, and length, X, with 176 elements and 210 nodal points. Each square block in Fig. A-1 represents one element. The element designation is indicated by the large number in the center of the block. Each element block is also identified by four nodal points, designated by the small numbers at each corner of the block. The matrix is divided into two sections, separated by the heavy lines. Section 1 represents the calorimetric mass, and Section 2 represents the support system. Boundary conditions are a constant heat flux of any specified level between each of the 20 nodal points on the top surface of the analytical model. The thermal properties of the slug-calorimeter system are considered to be non-temperature dependent. The initial temperature is considered to be zero since the parameter of interest is temperature rise rather than absolute temperature. The bottom and side surfaces of the assembly are considered to be adiabatic, i.e., neither receiving nor losing heat. The material of the calorimetric mass will always be copper, but the material of the mass support will be varied to indicate changes in behavior.

The TRAX computer program calculates and prints timewise temperature data for every nodal point in the analytical model matrix at each specified print interval. Thus, for the analytical model under consideration (210 nodal points), a large volume of tabulated data is available to the user. This large amount of data permits a close examination of gage behavior and performance. The user must exercise engineering judgment to determine which data are of interest in his particular application. For the model under consideration, the temperature history at nodal point 81 is of primary interest. This represents the physical location of the temperature sensor, i.e., the center of the back surface of the calorimetric mass (disk).

Temperature histories generated by the TRAX computer program at nodal point 81 are shown on Fig. A-2 for several different mass support materials for a copper slug diameter of 0.250 in. and a thickness of 0.10 in. The outside diameter of the mass support is 1.0 in., and the inside diameter is 0.225 in. The ideal slug-calorimeter temperature history generated by application of Eq. (A-1) is shown in Fig. A-2. As expected, the temperature histories for the materials with higher thermal conductivities (stainless steel and pyroceram) are lower than the ideal slug-calorimeter temperature history. However, the temperature histories for plexiglass and nylon supports are considerably higher than the ideal, indicating a net heat gain across the boundary between the calorimetric mass and mass support.

Several similar temperature histories generated by the TRAX program at nodal point 81 for a 0.50-in.-diam slug calorimeter are shown on Fig. A-3. The outside diameter of the mass support is 1.0 in., and the inside diameter is 0.45 in. The temperature histories are closer to the ideal slug-calorimeter temperature history for the larger diameter calorimetric mass. Errors in indicated heat flux for the plexiglass mass support are 6.4 percent high at a time point of 5 sec from the beginning of heating. This is closer to the ideal, but the percentage error is unacceptable.

Because of physical size constraints of the 2- by 2-in. block which houses the slug calorimeter and transfer standards, it is best not to make the diameter of the copper disk larger than 0.50 in. Plexiglass is a commonly available and easily machinable material so there are definite practical advantages in making the mass support from this material. Therefore, the analytical model was modified in an effort to bring the temperature history of a 0.50-in.-diam by 0.10-in.-thick copper disk supported by plexiglass into good agreement with ideal slug-calorimeter behavior. These modifications were implemented by increasing the physical size of the shoulder of the calorimetric mass support and by decreasing the heat-flux input on the top surface of mass support material. The effects of these modifications are illustrated in Fig. A-4.

With reference to Fig. A-4, the relationship between ideal slug calorimeter behavior and the analytical temperature history resulting from a plexiglass mass support with a 0.025-in. shoulder (Curve A) is shown as it was in Fig. A-3. The effect of increasing the shoulder from 0.025 to 0.050 in. is shown by Curve B. A slight improvement is seen. The effect of keeping the shoulder at 0.050 in. and decreasing the heat flux on the top surface of the plexiglass support to 0.75 Btu/ft^2-sec is shown by Curve C. This change dropped the analytical temperature history slightly below the ideal slug-calorimeter curve. Curve D shows the resulting analytical temperature history generated by decreasing the plexiglass shoulder back to 0.025 in. and holding the input heat flux on the top surface of the plexiglass calorimetric mass support at 0.75 Btu/ft^2-sec. It is obvious that Curve D is effectively in perfect agreement with the curve for ideal slug-calorimeter behavior.

The actual slug calorimeters used in the experimental calibrations described in this report were fabricated with a 0.50-in.-diam by 0.10-in.-thick copper disk and a plexiglass mass support with a 0.025-in. shoulder (see Fig. 5). When the actual experimental calibrations were performed, an attempt was made to duplicate the analytical conditions of Curve D (Fig. A-4) by not painting the top surface of the plexiglass support with the high-absorptivity coating. This should reduce the heat flux absorbed at the top surface of the mass support relative to that absorbed by the calorimetric mass (with the high-absorptivity coating). The assumption that Curve D (Fig. A-4) represents actual slug-calorimeter behavior requires that the absorptivity of the unpainted plexiglass is 75 percent of the painted calorimeteric mass sensing-surface absorptivity, i.e., 0.728. Handbook values of the absorptivity of clear plexiglass vary greatly with the type of plexiglass, thickness, wavelength, and temperature. Data* show that the maximum absorptivity of a 1/8-in.-thick sheet of plexiglass is 0.92 at 1.0 μ and drops to about 0.62 at 2.0 μ. Since the absorptivity decreases logarithmically with thickness, the 0.728 value of absorptivity assumed for the 0.35-in.-thick mass support should be accurate within ± 10 percent over the transmitting wavelength of the quartz lamp. Since the accuracy of the indicated heat flux with slug calorimeters is not a strong function of mass support system absorptivity, no attempt was made to evaluate this absorptivity experimentally.

* Plastics Department of Rohm and Haas Company. "Plexiglass-Design, Fabrication, and Molding Data." Bulletin No. PL-53f, May 1964.

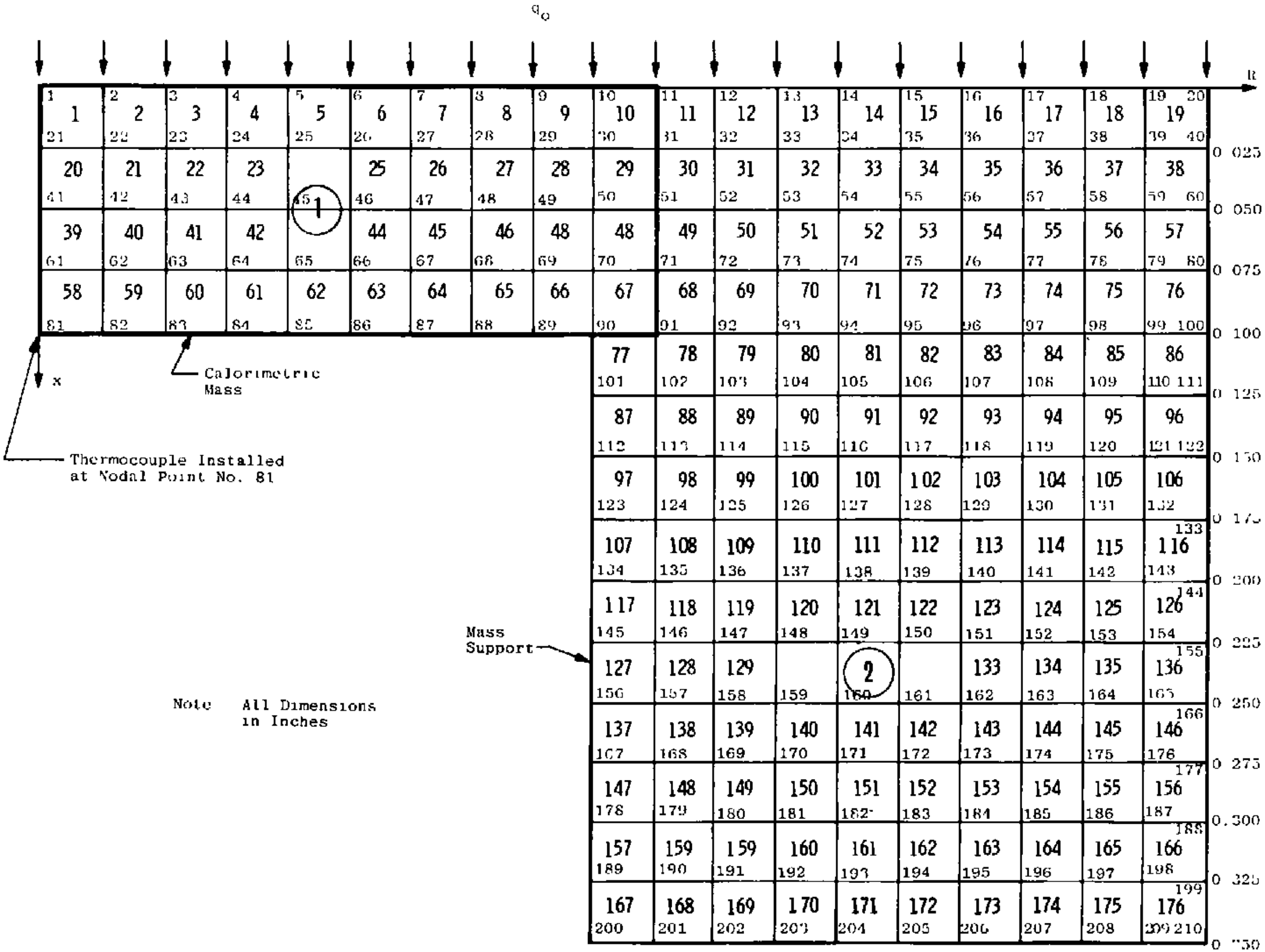


Figure A-1. Computer-generated sketch of TRAX analytical model (slug calorimeter).

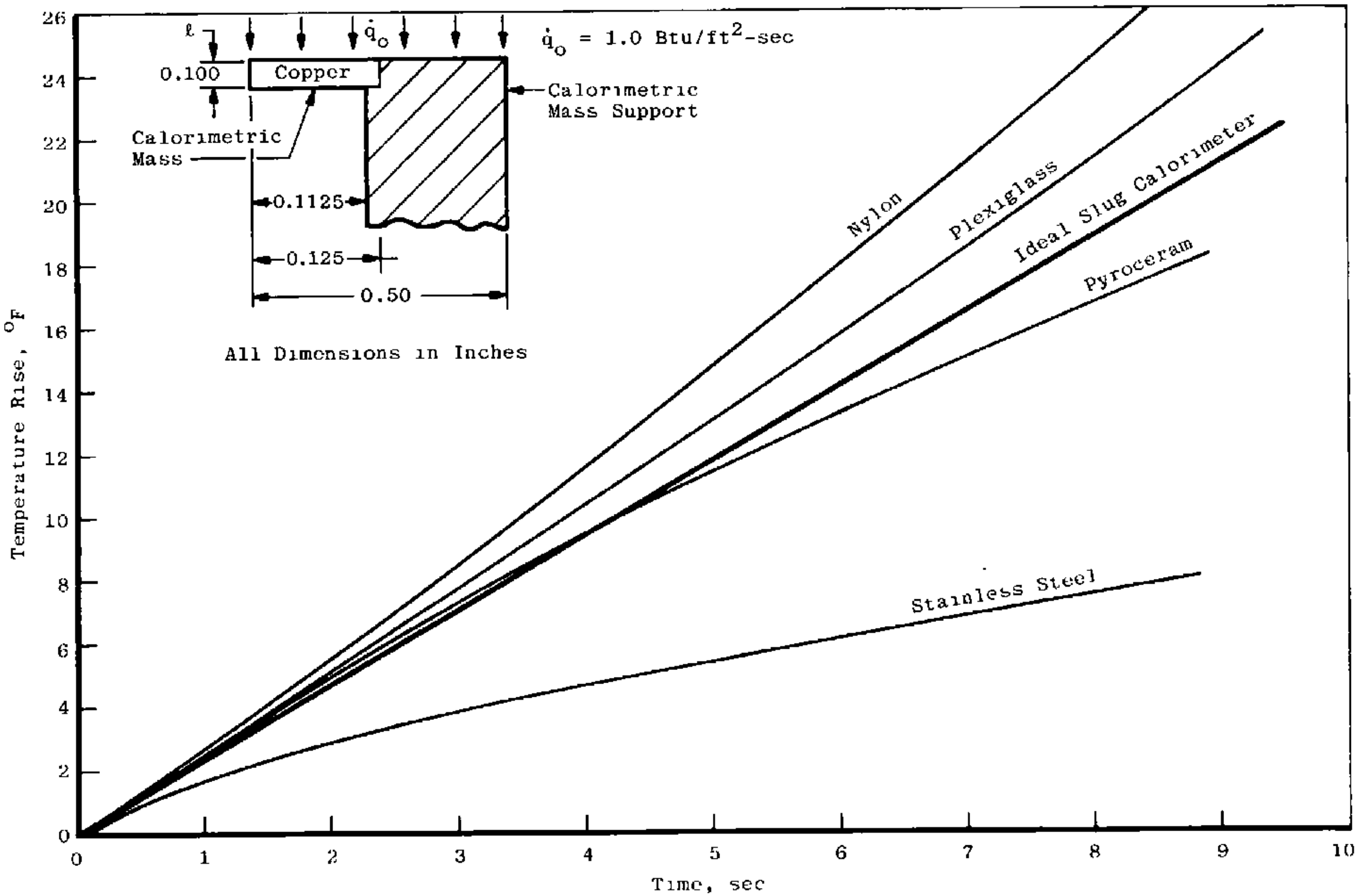


Figure A-2. TRAX analytical model back-surface temperature histories for a 0.250-in. OD by 0.10-in. copper slug supported by different materials.

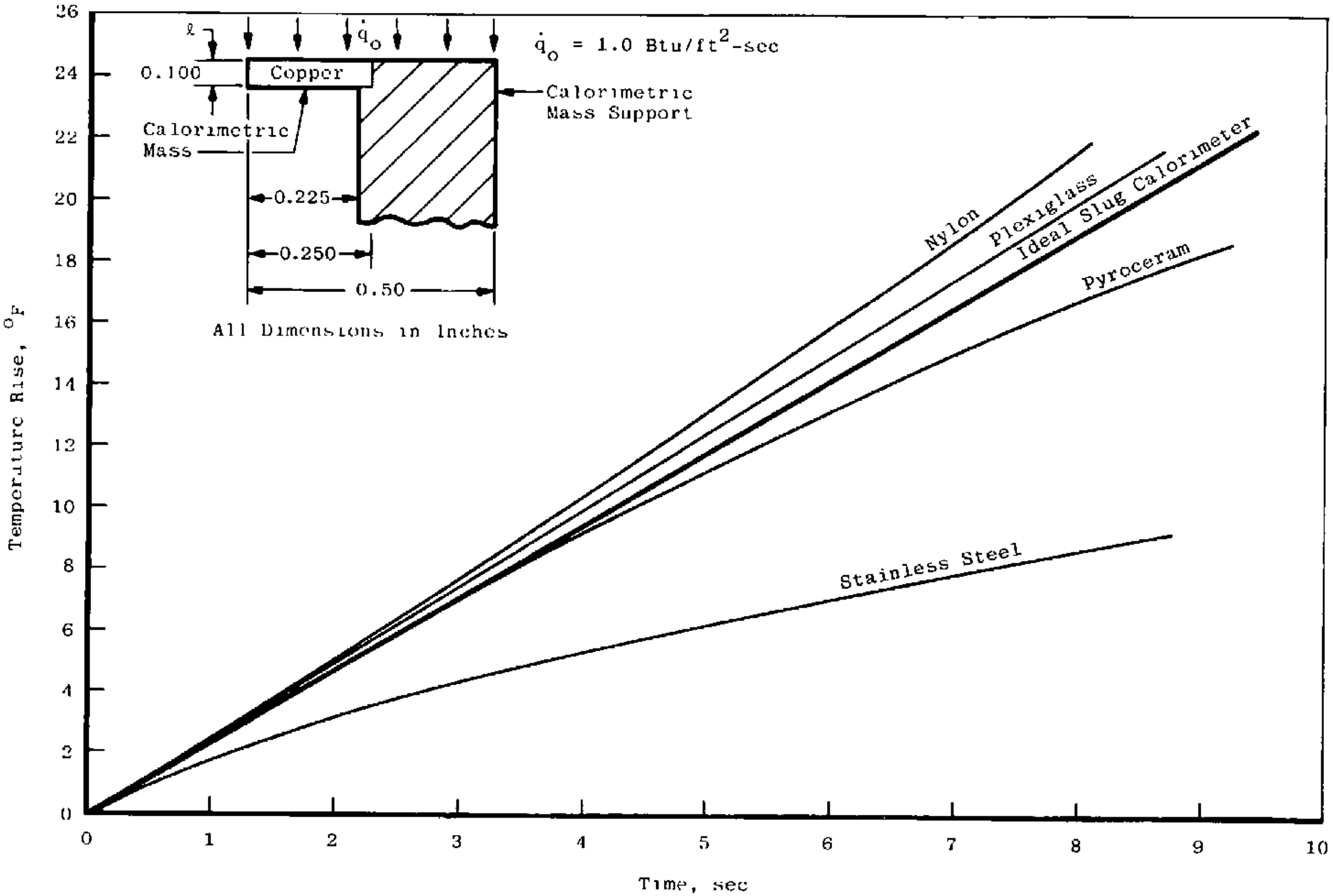


Figure A-3. TRAX analytical model back-surface temperature histories for a 0.50-in. OD by 0.10-in. copper slug supported by different materials.

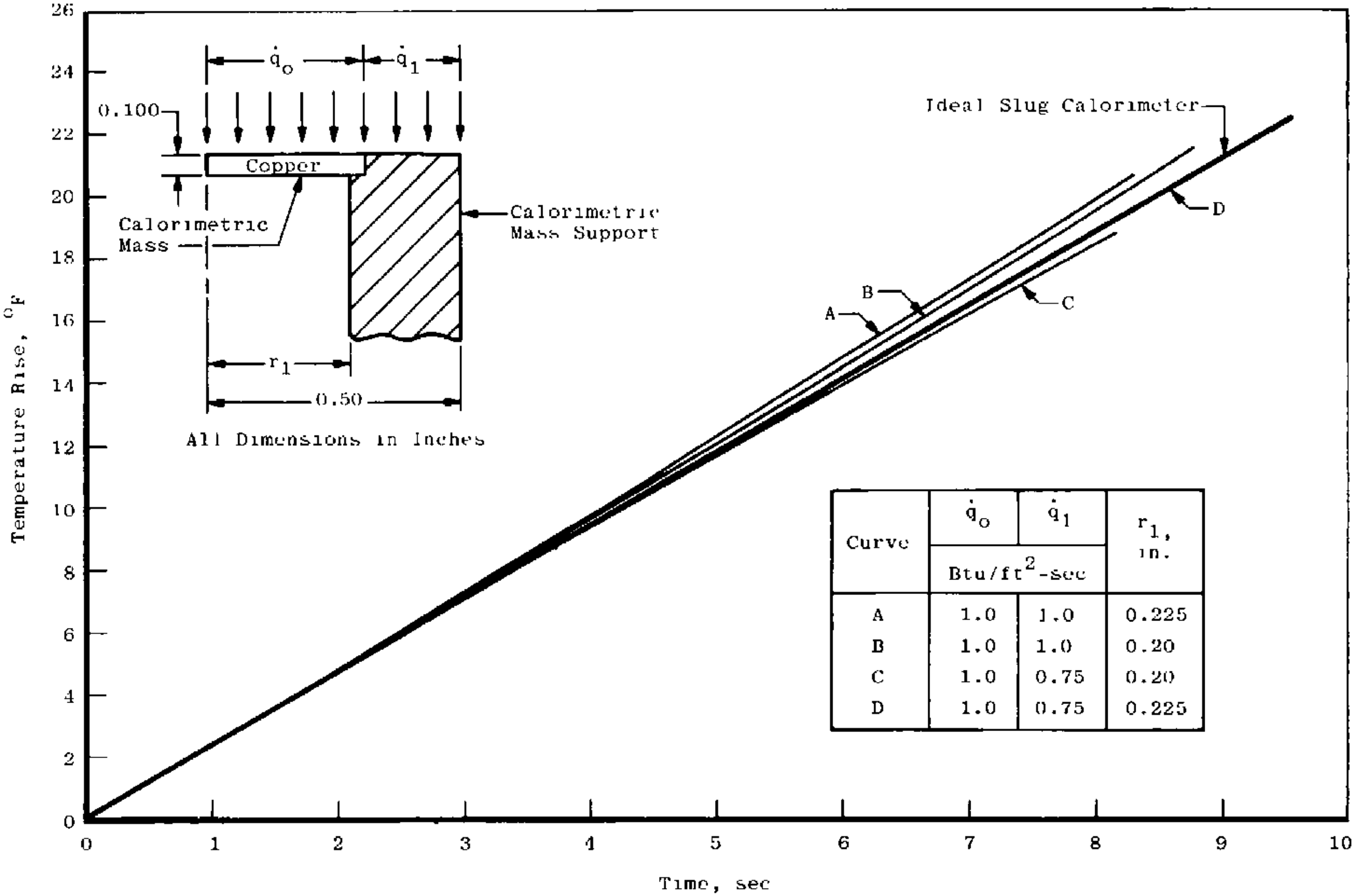


Figure A-4. TRAX analytical model back-surface temperature histories for a 0.50-in. OD by 0.10-in. copper slug in a plexiglass mass support.

APPENDIX B

DEFINITION OF UNCERTAINTY

Abernethy et al.* present a working outline detailing and illustrating the techniques for estimating the measurement uncertainty in rocket engine systems. The same terms are used in estimating uncertainty in the AEDC heat-flux calibrations. To review briefly, there are two types of measurement error: precision and bias. Precision error is the variation of repeated measurements of the same quantity. The sample standard deviation (S) is used as an index of the precision. Bias is the difference between the true value and the average of many repeated measurements. A limit (B) for the bias is estimated on judgment, experience, and testing. The formula for combining these into uncertainty (U) is

$$U = \pm (B + t_{95} S) \tag{B-1}$$

where t_{95} is the 95th percentile point for the two-tailed Student's "t" distribution. The t value is a function of the number of degrees of freedom (DOF) used in calculating S. For small samples, t will be large, and for larger samples, t will be smaller, approaching 1.96 as a lower limit. The use of the t arbitrarily inflates the limit U to reduce the risk of underestimating S when a small sample is used to calculate S. In a sample, the number of DOF is the size of the sample. Since 30 DOF yield a t of 2.04 and infinite DOF yield a t of 1.96, an arbitrary selection of t = 2 for values of DOF from 30 to infinity was made; i.e., $U = \pm (B + 2S)$, when DOF ≥ 30.

---

* Abernethy, R. B., Colbert, D. L., and Powell, B. D. "ICRPG Handbook for Estimating the Uncertainty in Measurements with Liquid Propellant Rocket Engine Systems." CPIA No. 180, April 1969.

NOMENCLATURE

a	Coefficient of n^{th} degree polynomial, °F/mv
B	Bias term (See Appendix B)
C_p	Specific heat of calorimetric mass, Btu/lb-°F
E	Thermocouple output signal, mv
ℓ	Thickness of calorimetric mass, ft
N	Number of samples in statistical analysis
$\dot{q}$	Heat flux or heat-transfer rate, Btu/ft^2-sec
$\dot{q}_o$	Constant heat flux at surface, Btu/ft^2-sec
R	Radial distance, ft
S	Standard deviation or precision index (See Appendix B)
SF	Scale factor, Btu/ft^2-sec/mv
$\overline{SF}$	Mean value of scale factor, Btu/ft^2-sec/mv
T	Temperature, °F
T_{back}	Back-surface temperature of calorimetric mass, °F
t	Time, sec
t_{95}	Ninety-fifth percentile point for two-tailed Student's "t" distribution (See Appendix B)
U	Uncertainty (See Appendix B)
x	Axial distance, ft
ρ	Density of calorimetric mass, lb/ft^3

SUBSCRIPTS

1	Degree of polynomial
2	Degree of polynomial
3	Degree of polynomial
4	Degree of polynomial
5	Degree of polynomial
i	Index