THE THERMAL CONDUCTIVITIES OF SEVERAL METALS: AN EVALUATION OF A METHOD EMPLOYED BY THE NATIONAL BUREAU OF STANDARDS

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The Thermal Conductivities of Several Metals: An Evaluation of a Method Employed by the National Bureau of Standards

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An evaluation is made of a National Bureau of Standards apparatus and absolute method for finding thermal conductivities of metals. The method, involving two experiments, gives two equations wherein thermal conductivity and heat loss are functions of measured temperatures. Simultaneous solution provides the thermal conductivity.

An Armco iron specimen of known thermal conductivity is used to calibrate the apparatus for heat losses. This calibration affords a comparative method for determining thermal conductivities in one experiment. A second absolute method is devised in which heat losses are made negligible. This method also allows thermal conductivities to be found in a single experiment.

Armco iron, 2024-T351 aluminum, AISI 303MA and AISI 316 stainless steels are tested. Comparisons show the N.B.S. absolute method is accurate within four percent; the comparative method is accurate within ten percent; and the negligible loss absolute method is accurate within two percent.

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I appreciate this opportunity to express my heartfelt thanks to those who have so generously helped me in this work.

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The enthusiastic, though non-technical, support of my wife and children has been ever present. To them I dedicate this thesis.

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LIST OF SYMBOLS

Symbol	Description	Units
A	Cross-sectional area of specimen	ft^2
E	Electrical potential	volts
f	An average heat transfer coefficient for the thermal path from specimen to guard	BTU/hr-ft-^oF
k	Thermal conductivity	BTU/hr-ft-^oF
L	Length	ft
p	Electrical power	watts
q	Heat transfer rate	BTU/hr
R	Electrical resistance	ohms
S	An approximation of the integral $\int_o^x (t_{bar} - t_{guard})\,dx$	^oF-ft
t	Temperature	^oF
x	Length	ft
Δ	An increment	

Subscripts

a	Designates run (a) of experiment
b	Designates run (b) of experiment
g	Guard
h	Heater
r	Radial
s	Specimen

I. INTRODUCTION

A. Background

The National Aeronautics and Space Administration awarded Grant NsG-711/44-07-004 to Southern Methodist University for the purpose of conducting research in the field of thermal conductance between metal surfaces in contact as influenced by the effects of transient temperature and pressure environments. Early in this research it was realized that accurate results depended upon the availability of good thermal conductivity values for the metals used in the experiments. The materials to be tested were: AISI 303MA stainless steel, Armco iron, and 2024-T351 aluminum alloy. While good values were available in the literature for Armco iron (1)[1], none were found for the particular stainless steel and the aluminum alloy. Consequently, the decision was made to obtain a precise thermal conductivity test apparatus and to perform the necessary experiments on all materials for the accurate establishment of their thermal conductivity values.

It was decided to construct, use, and evaluate a method first reported by Watson and Robinson (2) in 1960. Theirs is an

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[1] Numbers enclosed in parentheses refer to like-numbered entries in the Bibliography.

absolute method which provides thermal conductivity values, for a considerable temperature range, and obtainable from an experiment consisting of two test-runs. The specimen is a cylindrical metal bar, concentrically located within a temperature-controlled guard cylinder. A known heat transfer rate is applied to one end of the specimen while the other end is exposed to a constant-temperature heat sink. Under steady-state conditions, temperatures are measured along the specimen and at corresponding points along the guard. Two tests are performed in which the guard temperature is slightly changed from one to the next. From the results of the two tests, a simultaneous solution is obtained for the thermal conductivity of the specimen and for the radial heat loss or gain, both as functions of the temperature of the specimen.

B. Objective and Scope

The objective of this thesis is to present an evaluation of a thermal conductivity test apparatus which has been constructed here. The device is identical, in all important respects, to an apparatus used by the National Bureau of Standards (2).

The scope or extent of this evaluation is as follows:

1. Apply the Watson and Robinson (2) absolute method to determine the thermal conductivity of an AISI 316 stainless steel specimen previously tested by the

National Bureau of Standards. Results are compared with those reported by Watson and Robinson (3) in 1963.

2. This absolute method is employed to determine the thermal conductivities of samples of 303MA stainless steel, Armco iron, and 2024-T351 aluminum alloy for a temperature range of approximately 100°F to 300°F.
3. This absolute method is applied to the same metals used in Step 2 but for a temperature range of approximately 150°F to 500°F. The values obtained here are compared with those above for the overlapping temperature range.
4. The known thermal conductivities of Armco iron (1) are used in conjunction with a series of experiments for the purpose of calibrating the apparatus. Heat loss as a function of the radial temperature difference between the specimen and the guard and also as a function of the specimen temperature is obtained.
5. Thermal conductivities for the specimens of 303MA stainless steel, 2024-T351 aluminum alloy, and 316 stainless steel are obtained on a comparative basis devised from the apparatus loss calibration obtained in Step 4.
6. The feasibility of minimizing radial heat loss from the specimen to the extent of its being neglible is deter-

mined; this method is called the "no-loss" absolute method.

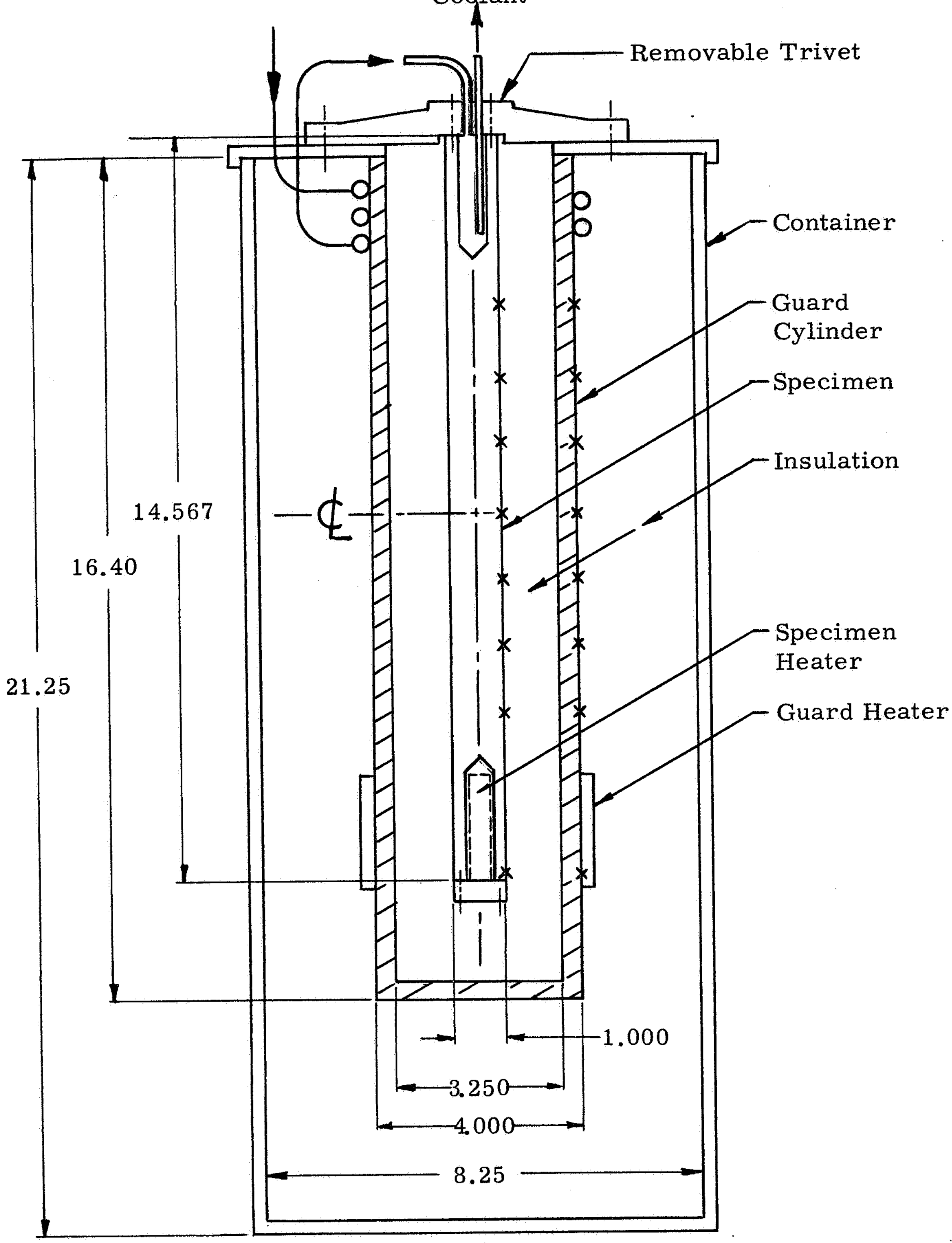
II. EXPERIMENTAL APPARATUS

The thermal conductivity test apparatus is schematically illustrated in Figure 1. The apparatus accomodates a specimen which is a cylindrical bar 1.000 inch in diameter by 14.567 inches long.

The function of the apparatus is to provide, under steady-state conditions, a desired heat transfer rate to one end of the bar while the opposite end is exposed to a constant-termperature heat sink. The bar is centered within a cylindrical guard which has an independent heat source but shares a common heat sink with the specimen. In operation, temperature gradients are established along the bar and along the guard. These gradients are determined from the readings of thermocouples which are installed at precise intervals along the bar and its guard. Eight thermocouples are located on the bar, and an equal number are located along the length of the guard. The system contains some additional thermocouples for reference purposes. The bar is vertically positioned within the guard such that a particular specimen thermocouple lies in the same transverse plane as the corresponding thermocouple on the guard.

Thermocouples are made by butt welding No. 24 AWG

Figure 1 - Apparatus for Measuring Thermal Conductivity of Metals



Notes: 1. Dimensions in inches. 2. X indicates thermocouple position.
3. Main thermocouples are spaced 1.383 inches apart.

chromel and alumel wires. These thermocouples are then calibrated for output voltage-versus-temperature. The calibration procedure is given in Appendix B.

Seven of the specimen thermocouples are symmetrically installed with respect to the length of the bar at equally-spaced intervals of 1.383 inches. The eighth specimen thermocouple is located 0.157 inch from the heated end. These thermocouples are placed in transverse slots milled into the cylindrical surface of the bar; slots are 0.022 inch wide and 0.025 inch deep. The wires are secured in the slots by peening the specimen metal over the junctions. This installation procedure is illustrated in Figure 2 for a typical thermocouple.

A 0.515 inch diameter hole is drilled in each end of the bar to a depth of 2.15 inches. One hole is provided for the insertion of an electrical heating element, and the other permits the circulation of a fluid, in this case, water, which is the heat sink. The specimen heating element contains approximately 8.5 feet of No. 24 AWG nichrome wire, which has an electrical resistance of approximately 14.5 ohms. A mullite ceramic core, 0.500 inch in diameter, 2.00 inches long, and containing forty-nine extruded holes of 0.025 inch diameter, is used to hold this wire. The wire is passed throughout forty-eight of these holes. A length of No. 24 AWG stainless steel wire is welded to each of the heater leads at a location approximately 0.12 inch from the face of the mullite

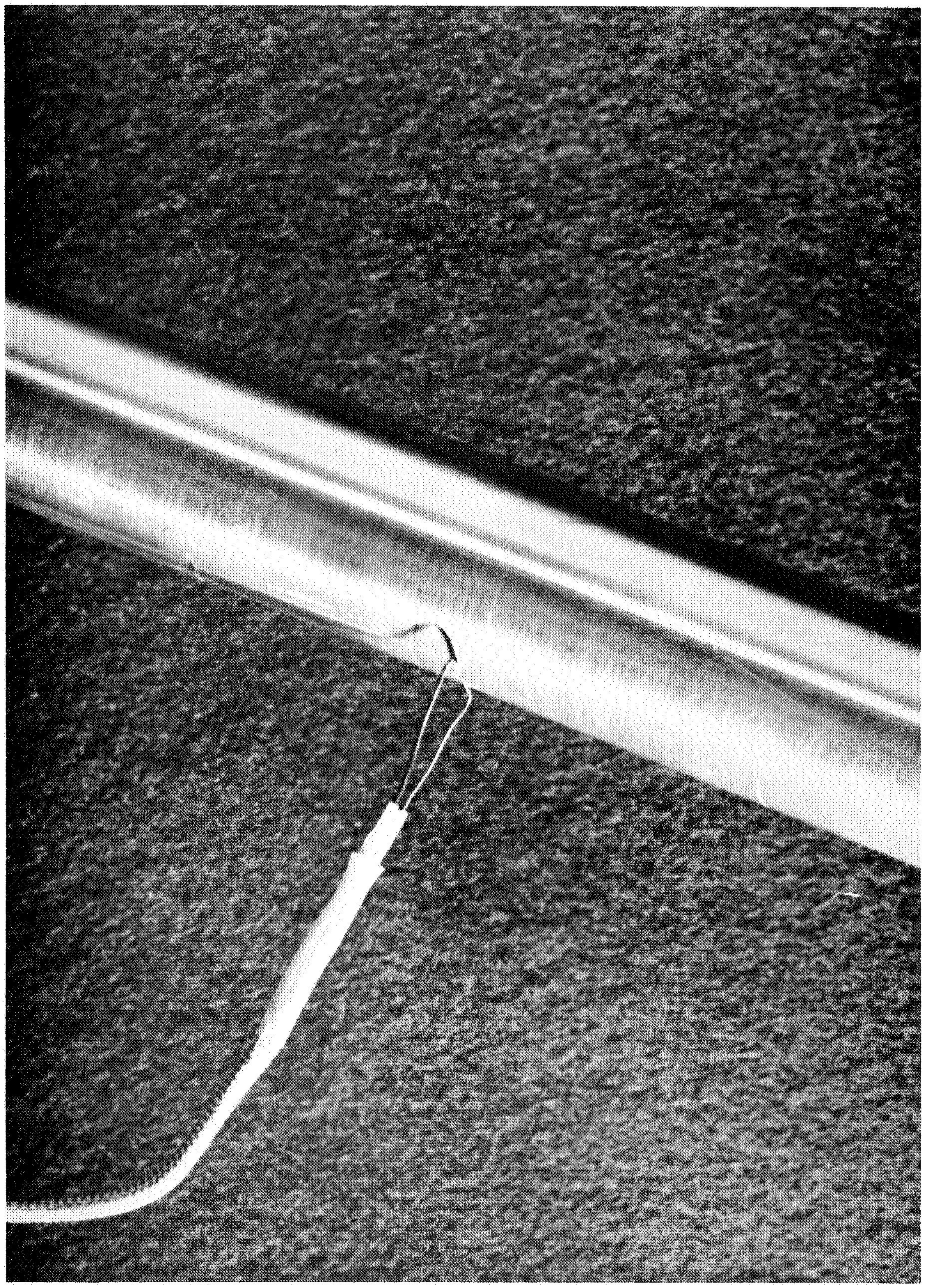


Figure 2 - Typical Thermocouple Installation

core. These leads provide connections for the subsequent voltage measurements across the heater resistance.

The specimen heating element is inserted in the end of the specimen and is retained by a cap which is screwed to the bottom end of the bar. Four short lengths of 0.125 inch diameter mullite tubing extend through the cap for electrical insulation of the four leads from the heating element. Figure 3 pictures the specimen heating element and its retaining cap.

The specimen is attached at its heat-sink end to a trivet. Assembly consists of applying a non-hardening, liquid-tight sealant to the end of the bar and then fastening the two parts together with two No. 5-40 screws. This assembly is shown in Figure 4.

The guard assembly consists of the guard cylinder, guard heating element, coolant coil and top plate. This cylinder is fabricated from AISI 321 stainless steel and has a 4.000 inch outside diameter, 3.250 inch inside diameter, and a length of 16.40 inches. A 4.000 inch diameter by 0.375 inch thick plate of the same material is welded to the bottom end of the guard cylinder.

Approximately eleven feet of No. 24 AWG nichrome wire is wound onto an externally-threaded alundum core to form the guard heating element. This core, having an inside diameter of 4.00 inches, and a length of 2.30 inches, is positioned on the lower portion of the guard cylinder. A coating of alundum cement is applied to the outer surface of the core to retain the helically

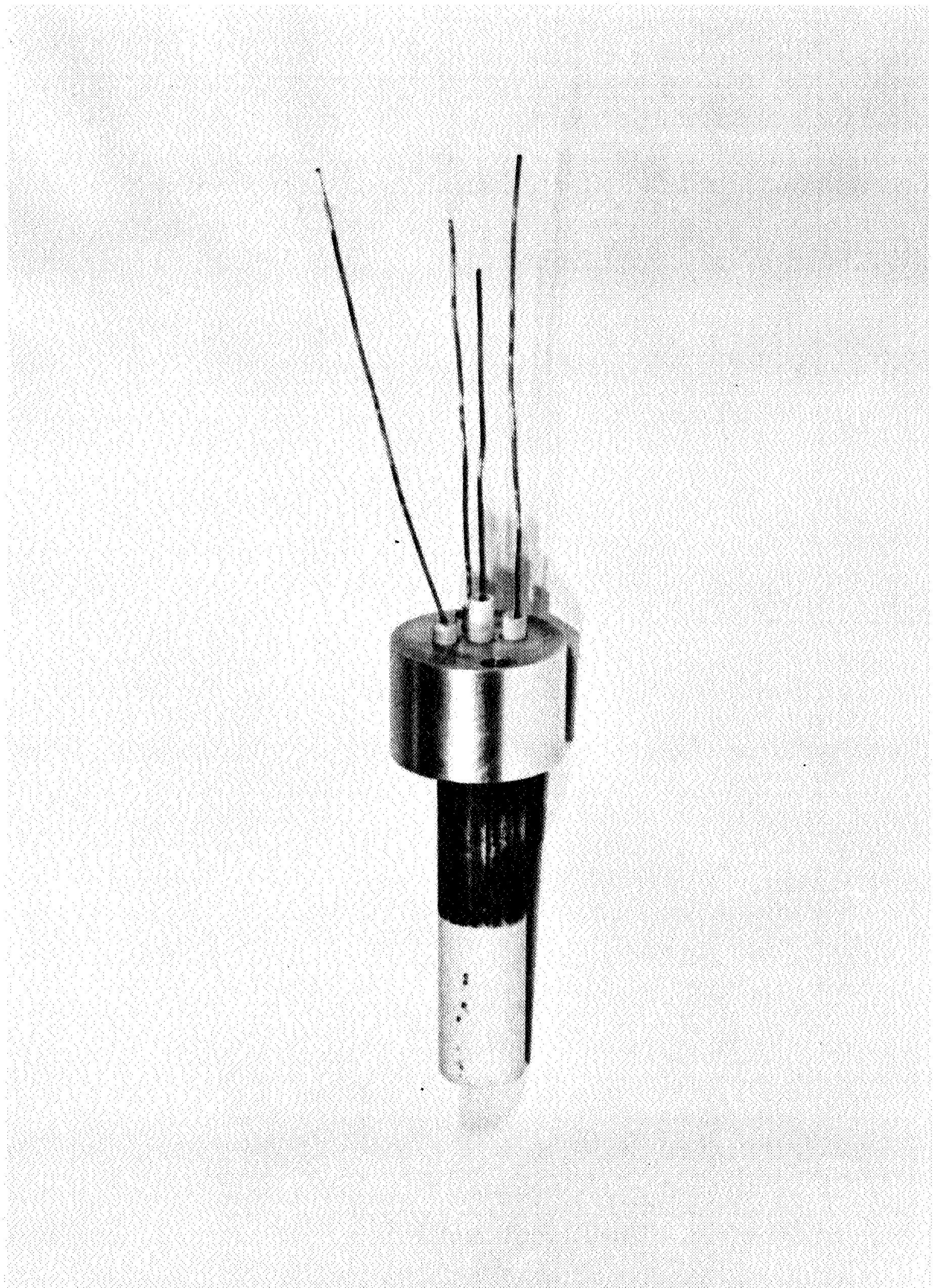


Figure 3 - Specimen Heater and Retaining Cap

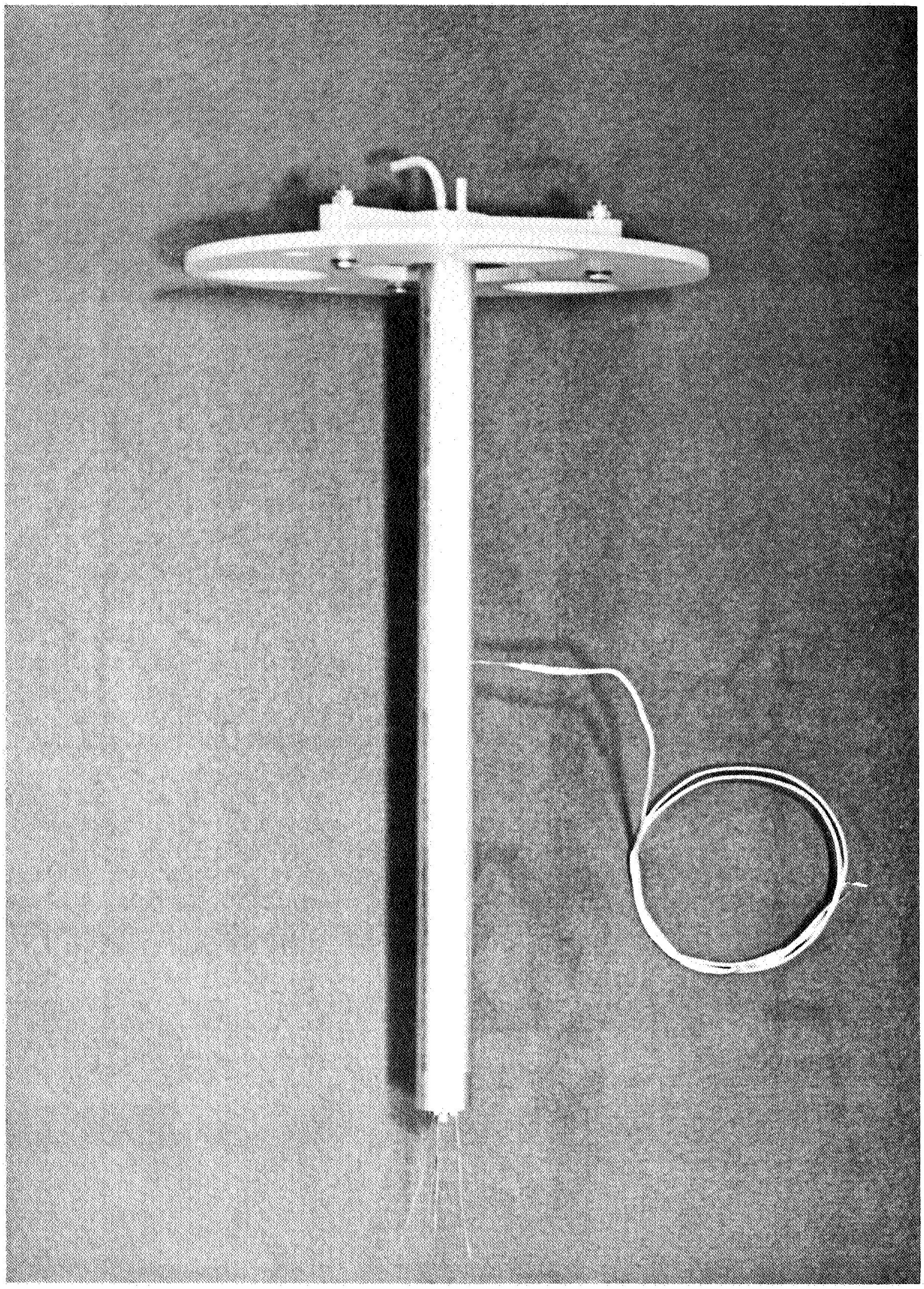


Figure 4 - Specimen and Trivet Assembly

wound heater wire. This heating element has an electrical resistance of approximately 18 ohms.

The guard coolant coil is made of 1/4 inch diameter copper tubing which is helically-wound around, and soldered to, the upper end of the guard cylinder.

Seven thermocouples are installed along the length of the guard in the same manner as previously described for the specimen. The eighth thermocouple is inserted into a drilled hole at the bottom of the cylinder. This hole extends 2.65 inches up into the side wall of the cylinder to a point adjacent to the bottom of the guard heating element.

A top plate is then bolted to the upper end of the guard cylinder. The previously assembled specimen, specimen heater, specimen thermocouples, and trivet are lowered into the guard assembly. Centering is accomplished by aligning holes in the trivet legs with matching studs projecting from the top plate. This stage of assembly is displayed in Figure 5.

The entire assembly is placed in an outer container which is constructed from a 9.00 inch diameter steel casing. This casing has a wall thickness of 1/4 inch, and it is 21.00 inches high. The bottom end of the casing is closed by welding a 1/4 inch thick, 9.00 inch diameter plate thereto. The container is completely painted with a white epoxy enamel. Figure 6 shows the apparatus assembled within the container.

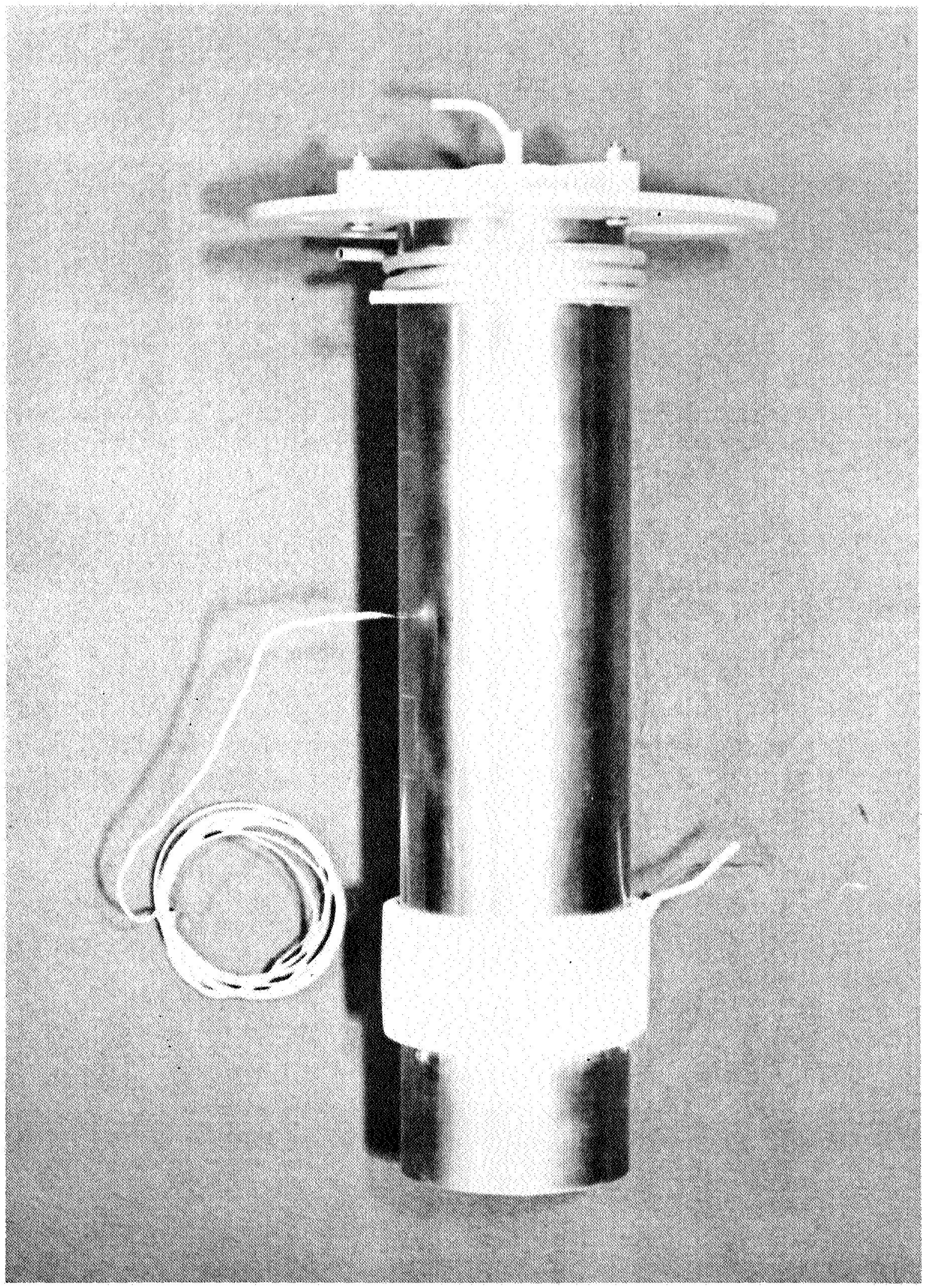


Figure 5 - Guard Assembly Containing Specimen

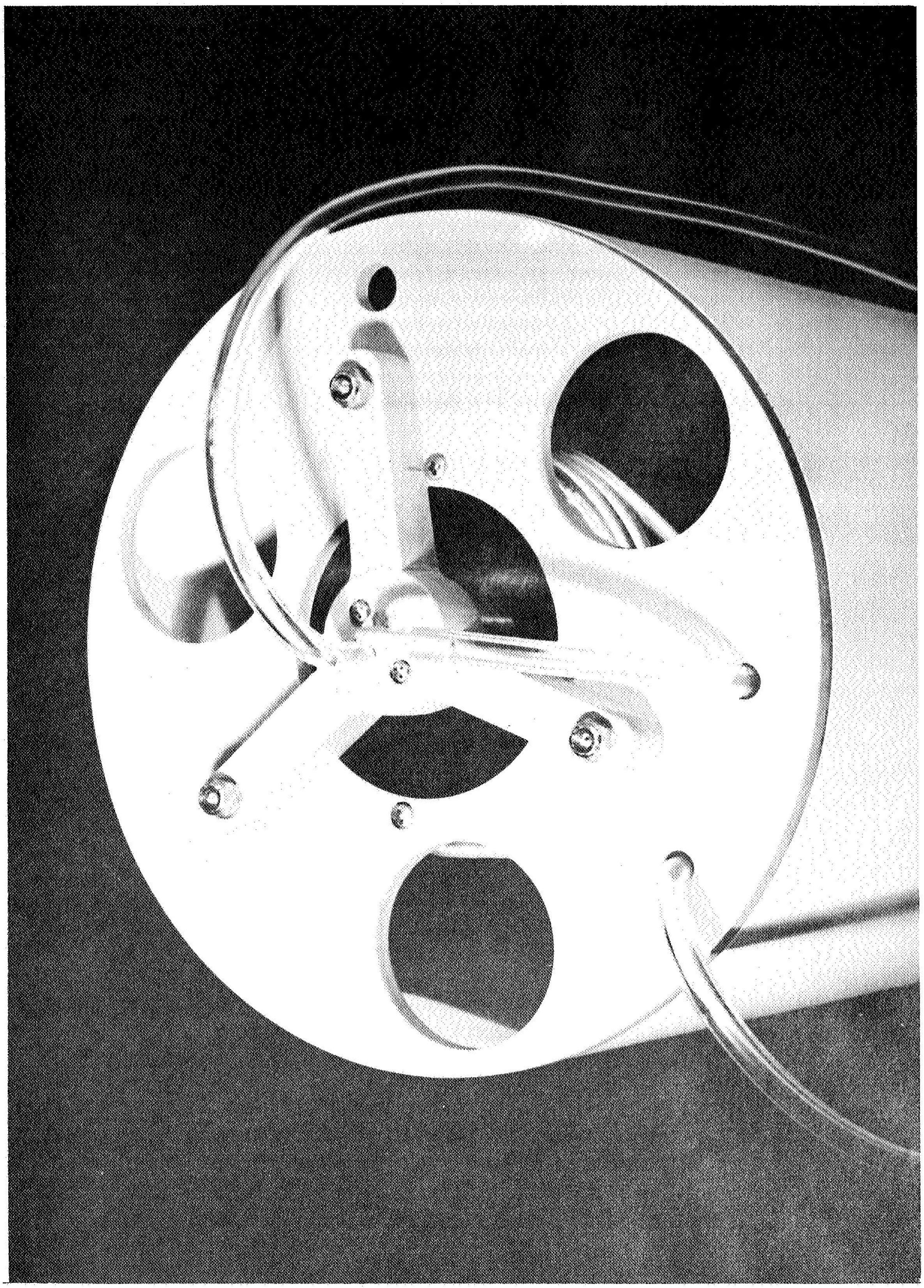


Figure 6 - Top View of Assembled Apparatus

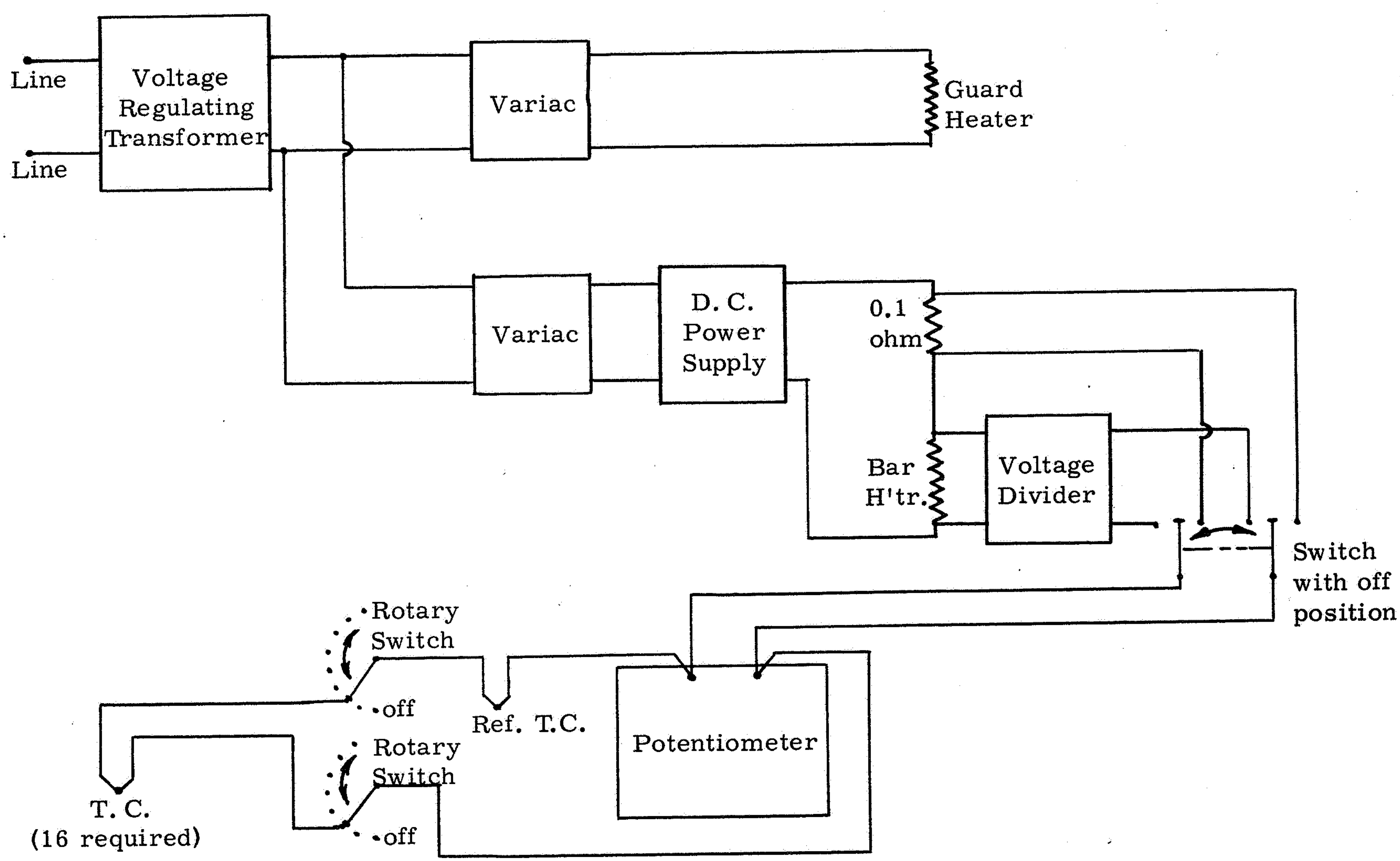
Figure 7 is a schematic diagram of the electrical power circuitry, the thermocouples, and the instrumentation circuitry.

Since the experiments are conducted under steady-state conditions, power to the specimen and guard heaters must be maintained at constant levels. The power immediately available was obtained from one of the 115 v. a. c. circuits in the building, and since this source is subject to voltage fluctuations, a voltage stabilizing transformer was used. All electrical power for these experiments was delivered from this transformer.

Accuracy of the results obtainable is directly dependent upon the accuracy which is applied to the measurement of temperatures and specimen heater power. Since greater precision is available in the measurement of d. c. power than a. c., due to the absence of power factor considerations, a d. c. power supply was used for the specimen heater. A full-wave rectified, pi-filtered power supply was constructed, and the output voltage from this source demonstrated less than 0.02% ripple under full-load operation.

All of the critical measurements in these experiments are reducible to the measurement of d. c. voltages. A precision potentiometer, Honeywell Model 2780, is used in conjunction with a Honeywell Model 3431 spot light galvonometer to obtain these readings. Thermocouple voltages are read directly with this instrumentation. The magnitude of the specimen heater voltage requires the use of a precision voltage divider to bring this voltage within

Figure 7 - Electrical Schematic



the range of the potentiometer. The current in the specimen heater circuit is determined from reading of the voltage drop across a 0.1 ohm precision resistor connected in series with the heating element. This resistor is a Honeywell Model 1162.

Since guard heater power measurements do not enter into the analysis, the guard heater is suitably supplied by an a. c. source. A variac is used to control the guard heater power level, and another variac, connected to the input of the d. c. power supply, controls the power in the specimen heater circuit.

III. EXPERIMENTAL PROCEDURE

Experiments were performed on a single specimen of each of the following metals: AISI 316 stainless steel, AISI 303 stainless steel, Armco iron, and 2024-T351 aluminum alloy.

In each experiment it was desired to determine the thermal conductivities of a particular specimen within a specified temperature range. Two types of experiments were carried out. The first type required two test-runs per specimen in each desired temperature range; results from the pair of test-runs were analyzed by the Watson and Robinson (2) absolute method to obtain thermal conductivities. The second experiment involved nine test-runs, using a specimen of known thermal conductivity. The results of these nine test-runs provided a basis for calibrating the apparatus for heat transfer between specimen and guard. With the availability of this calibration, thermal conductivities of a specimen are determinable on a relative basis from the data obtained in a single test-run on each. Accordingly, the data collected previously for the Watson and Robinson (2) experiments were reanalyzed, run-by-run, to evaluate thermal conductivities by this relative method.

The experimental procedure for setting up the apparatus, installing the specimen, and performing a test is independent of the method of analysis applied to the data obtained. Thus, an experiment is carried out in the following manner.

The potentiometer is checked for correct calibration through the use of a standard cell. The resistances of the voltage divider and the 0.1 ohm resistor are checked with a Wheatstone bridge. The thermocouples are calibrated as described in Appendix B.

Specimen thermocouples are peened into the slots provided; the heating element is installed in the end of the bar; and the specimen is attached to the trivet. Fittings on the trivet are connected to the tap water supply and the drain with 1/4 inch flexible tubing. At this stage, thermocouples are checked for continuity and output. The specimen heating element is ascertained to be operating correctly, and the specimen coolant circuit is examined for leaks.

In a similar manner, thermocouples are attached to the guard; the guard's coolant and heater circuits are connected; and all of these systems are tested and verified to be functioning properly.

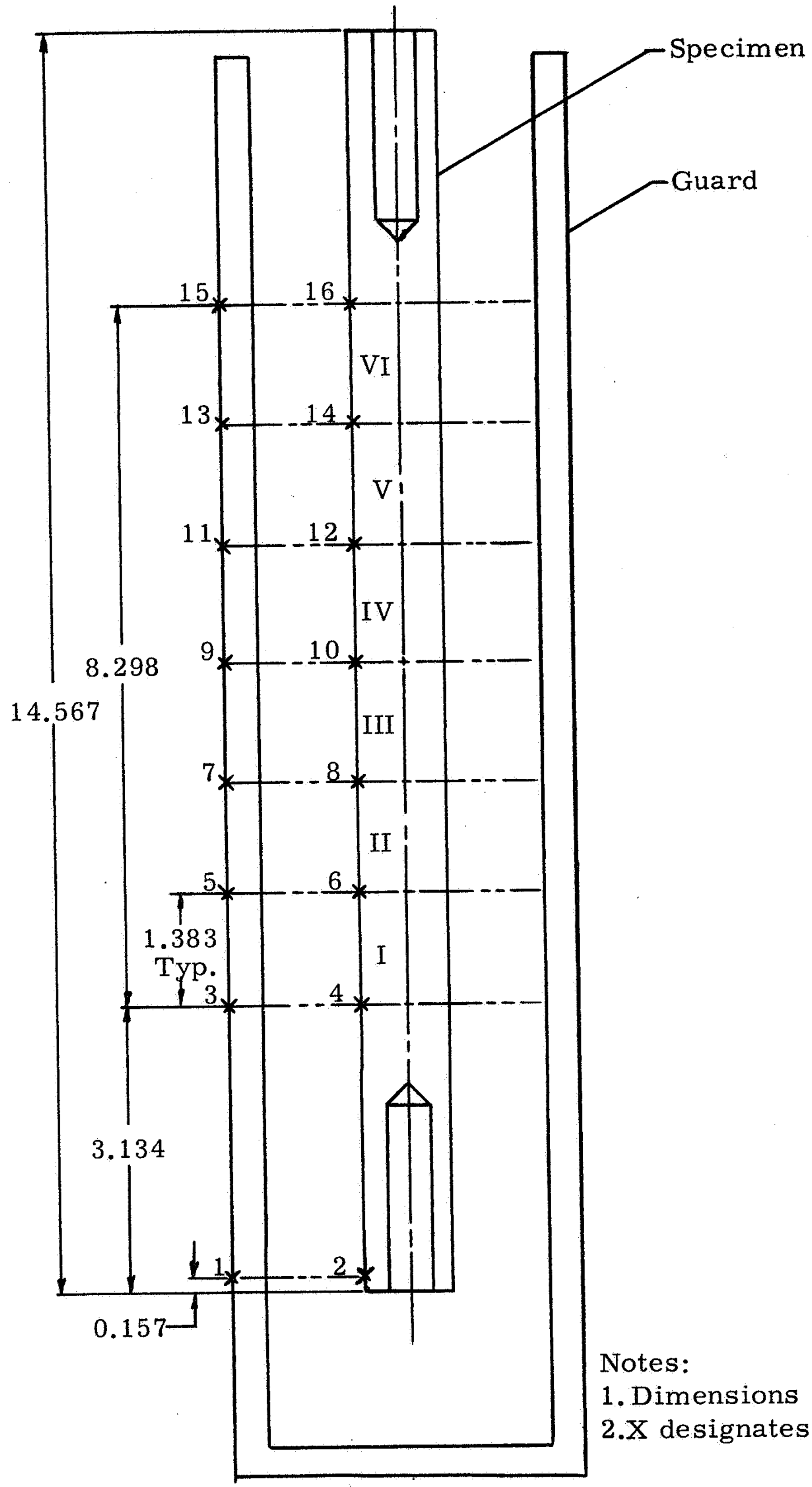
The instrumented specimen is lowered into the guard assembly, and the annular spaces between bar and guard and between guard and outer container are filled with powdered diatomaceous earth.

Thermocouples are identified by number as shown in Figure 8. Numbering begins at the heated end of the guard and the specimen. Odd-numbered thermocouples 1 through 15 are consecutively located along the length of the guard. Similarly, even-numbered thermocouples 2 through 16 are delegated to the specimen. As seen in Figure 8, thermocouples 1 and 2 lie in the same transverse plane, and succeeding numbers are paired and oriented likewise.

Starting with thermocouple number 4, the six succeeding thermocouples along the bar are precisely located at intervals of 1.383 inches. This arrangement provides six equal spans, which are identified by the Roman numerals I through VI.

In the experiment, temperatures are measured across each of the six spans; thus, a temperature gradient, $\Delta t/\Delta x$, is determinable for each. Six values of thermal conductivity are obtainable in the experiment, a value for the average temperature in each span. A particular experiment is designed to obtain thermal conductivity values over a desired temperature range. The maximum temperature for which k can be obtained, in a single experiment, is the average temperature in span I. Accordingly, the lowest temperature for which k is to be determined is that average temperature existing in span VI. Then, the first requirement in the experiment is to establish the desired temperature range between the midpoint of span I and the midpoint of span VI.

Figure 8 - Thermocouple Locations



Notes:
1. Dimensions in inches.
2. X designates t'couple.

At the outset of an experiment, there is advantage in knowing an approximate relationship for the thermal conductivity of the specimen as a function of temperature. With such preliminary information, it becomes possible to make a reasonable estimate of the specimen heater power required to establish the desired temperature gradient. This estimate is obtained from the application of Fourier's one-dimensional, steady-state, conduction equation:

$$q = -kA\frac{\Delta t}{\Delta x} \qquad \text{III-1}$$

In this equation, III-1, k is that based on the available estimate; A is the known cross-sectional area of the bar; and $\Delta t/\Delta x$ is the average temperature gradient in the six spans. The value of q so calculated is for one-dimensional heat transfer in the bar; consequently, a refinement would take into account the additional heat transfer between the bar and the guard. The advantage in having a reasonable estimate of specimen heater power is that it minimizes the amount of subsequent power adjustment necessary to attain the desired specimen temperature.

The estimated power is converted from units of BTU/hr to watts, and the resulting wattage is expressed as:

$$p = \frac{(E_h)^2}{R_h} \qquad \text{III-2}$$

where: E_h is the voltage across the specimen heater

and, R_h is specimen heater resistance of 14.5 ohms

An estimate of guard heater power can be found with the application of equations III-1 and III-2 to the guard system. The guard cylinder's thermal conductivity is known to a reasonable degree of accuracy, the k being that for AISI 321 stainless steel. The cross-sectional area of the guard cylinder is calculated from the known inside and outside diameters. Temperature gradient along the guard is the same as that established for the specimen, although the absolute temperature at a point on the guard will normally differ by a few degrees from the temperature at the corresponding point on the specimen. Radial heat loss from the guard should be included in the total estimate of guard heater power. A detailed analysis of this radial loss is not justified, considering the time required. Therefore, a radial loss of 25% is assumed, and this amount is added to the estimate for the one-dimensional heat transfer along the guard. With the total estimate of guard heater power so obtained, the corresponding voltage for the heater can be found from the known heater resistance of 18 ohms.

To initiate the experiment, first, the tap water is turned on to supply the specimen and guard heat sinks. Second, a suitable d. c. voltmeter is connected to the terminals of the voltage leads that are attached across the specimen heater. The specimen heater controlling variac is turned on, and power is increased until the desired voltage is observed on the voltmeter scale. Finally, a suitable a.c. voltmeter is connected across the guard heater resistance; its controlling variac is switched on, and power level is increased until the desired guard heater voltage is attained.

With the experiment underway, a vigil is undertaken during which the temperatures within the system are monitored to detect the approach of steady-state operation. Usually some adjustment in power to one or both heaters is necessary to achieve the desired specimen and guard temperatures.

Steady-state is considered achieved when none of the system temperatures varied more than $1^{o}F$ over the span of one hour.

When the experiment has reached steady-state, the millivolt readings are recorded for all thermocouples; and using the potentiometer, the voltages across the specimen heater and the 0.1 ohm resistor are measured and recorded. All recorded values are verified by immediately making these measurements a second time.

Another check is applied to each of the recorded millivolt readings obtained from the thermocouples. These readings are converted to temperatures, and each is plotted with respect to its location along the length of the bar or guard. Two smooth curves should result when a plot of t-versus-x for the specimen and a plot of t-versus-x for the guard are made.

IV. METHODS FOR DETERMINING THERMAL CONDUCTIVITY

Three methods of analysis are applied to the experimental data obtained in tests using the previously described apparatus. These methods are:

1. An absolute method devised by Watson and Robinson (2) which requires the data obtained from a two-run experiment. A heat balance equation is written for the specimen in each run. The heat input to the specimen is equated to the thermal conductivity and the heat loss - both expressed as functions of temperature. The two equations are solved simultaneously to yield the thermal conductivity and heat loss.

2. A comparative method, wherein by a series of experiments, using a specimen of known thermal conductivity, the apparatus is calibrated for heat transfer between specimen and guard. Thereafter, thermal conductivities for other specimens are obtainable on a relative basis from the results of a one-run experiment.

3. A "no-loss" absolute method for which the temperature differences between specimen and guard are reduced to the extent that heat transfer between the two becomes

negligible. On this basis, thermal conductivites are determinable on an absolute basis from the results of a one-run experiment.

A. The Watson and Robinson (2) Absolute Method

Reference is made to Figure 8, which is a schematic representation of the bar specimen installed within its guard. Ideally, if the bottom end and the cylindrical surface of the specimen were adiabatic, then the measured power input to the specimen heater would be manifest in a simple, one-dimensional heat flux, constant at each cross-section along the uniform bar. To achieve such adiabatic boundaries would allow the calculation of thermal conductivities to be made directly through the application of the Fourier, one-dimensional, steady-state conduction equation. A value of k would be obtained for the average temperature in each of the six equal-lengthed spans on the specimen.

The function of the guard is to minimize the heat transfer across the cylindrical surface of the specimen contained, thus creating an environment in which an adiabatic boundary is approached for this particular surface.

The method of Watson and Robinson (2) provides a means of calculating thermal conductivities corresponding to the temperatures at the midpoints of each of the six spans. Their method makes corrections for the heat exchange between bar and guard and requires the performance of a pair of steady-state test runs. In each of these runs, the specimen temperature is maintained essentially constant by adjustment of power to the specimen heater. In one run, the guard temperature at thermocouple number 3 is kept a few degrees higher than the corresponding bar temperature at thermocouple number 4. In the second run, the guard temperature is adjusted a few degrees lower than the adjacent specimen temperature.

In each test of the pair, and at the mid-point of a given span of the bar, the sum of the heat flow in the bar at that point and the total net heat loss from the bottom of the bar up to that point must equal the measured power input to the specimen heater. It is thus possible to write two equations (one for each test-run) of the form:

$$q = -kA \frac{\Delta t}{\Delta x} + fS \qquad \text{IV-1}$$

where: q is the measured power input to the specimen heater.

k is the thermal conductivity of the specimen at the mean temperature in the span.

Δt is the measured temperature drop from end to end of the span.

fS represents the total net heat loss from the specimen from its bottom end at the heater to the mid-point, x, of the given span, expressed as the product of S, which is the integral $\int_0^x (t_{bar} - t_{guard})dx$, and the average heat transfer coefficient, f, for the thermal path from bar to guard.

The two equations written for each of the six spans of the specimen can be solved simultaneously to determine k and f. For this to be strictly valid, k and f must have equal values in the two equations. Since the mean temperature of the span in the two test-runs will, in general, differ slightly, a small adjustment is made to the observed values of Δt so that k corresponds to the mean of the span mean temperatures in the two runs.

The computation of k and f values is accomplished by the Control Data Corporation's 3400 digital computer, programmed to accept the observed experimental data. An operations plan for this computer program is given in Appendix C.

Designating the two test-runs as (a) and (b), the resulting simultaneous equations are written for each span, i (i = 1, 2, ... , 6) as:

$$q_a = k_i A \left[\frac{\Delta t}{\Delta x}\right]_{a_i} + f_i S_{a_i} \qquad \text{IV-2}$$

$$q_b = k_i A \left[\frac{\Delta t}{\Delta x}\right]_{b_i} + f_i S_{b_i} \qquad \text{IV-3}$$

In accordance with these equations, the following input data are provided with the computer program.

1. Specimen heater powers, q_a and q_b
2. Cross-sectional area, A, of the specimen
3. Millivolt readings for all thermocouples
4. The location, x, for all thermocouples, measured from the heated end of the specimen

5. The calibration coefficients, C_1, C_2, and C_3, for millivolt-to-temperature conversion for each thermocouple

The computer is programmed to accomplish the following:

1. Calculate, by the method of least-squares, the specimen temperature for each run and the guard temperature for each run as respective functions of the distance, x, from the heated end of the specimen.
2. Using the above four equations of t-versus-x, perform numerical integrations to obtain S_{a_i} and S_{b_i} $(i = 1, 2, \ldots, 6)$.
3. Solve equations IV-2 and IV-3 simultaneously to find k_i and f_i $(i = 1, 2, \ldots, 6)$.
4. Applying the method of least-squares to the six values of k_i, determine k as a linear function and also as a quadratic function of temperature.

B. A Comparative Method

One of the specimen materials used in these experiments is Armco iron for which thermal conductivity values have been well established by many investigators. A least-squares curve fit applied to the values of k obtained from thirteen sources (1) yielded the following equation for the thermal conductivity of Armco iron in the range of temperature from 0^{o} to 1000^{o}F.

$$k = 43.6\ (1 - 0.0004587t) \qquad \text{IV-4}$$

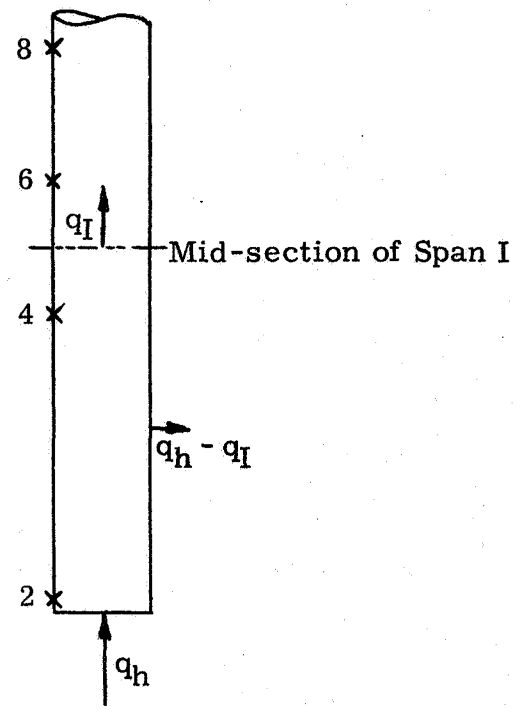
where: k is thermal conductivity, BTU/hr-ft-^{o}F

and, t is temperature, ^{o}F

Knowing the thermal conductivity of Armco iron affords a means for determining heat transfer between specimen and guard. Accordingly, a series of experiments is performed with the Armco iron specimen installed in the apparatus. From these experiments, a correlation is established between radial heat transfer and temperatures within the apparatus.

From this calibration, thermal conductivity of another metal can be found on a comparative basis from measured temperatures and specimen heater power in a single experiment with the metal.

In each of the apparatus calibration experiments using Armco iron, there is a known power input to the specimen; temperatures are measured for both specimen and guard, and thermal conductivity is available from equation IV-4. The determination of net heat loss from the Armco iron specimen is made by the application of equation IV-1 to successive spans of the specimen, starting at the heated end. This succession of heat balances is illustrated in the diagram which follows.



The heat input to the specimen is q_h, applied at the bottom end of the bar. Considering that portion of the specimen from the bottom end. to the mid-point of span I, q_I is the heat flux leaving the mid-section of span I. Now, q_I can be calculated directly from the Fourier conduction equation for the known temperature drop $(t_4 - t_6)$, the known k corresponding to the mid-span temperature, and the known geometry A and Δx for the span:

$$q_I = \frac{k_I A (t_4 - t_6)}{\Delta x} \qquad \text{IV-5}$$

Thus, the heat loss, positive or negative, in this first increment of the bar is: $q_h - q_I$.

The second heat balance is made for that portion of the specimen between the mid-point of span I and the mid-point of span II. The process is repeated for the remainder of the bar to the mid-point of span VI.

Nine calibration test-runs were made using the Armco iron specimen. The purpose of this series of runs was to determine the effects of radial temperature difference and absolute temperature upon the heat transfer between specimen and guard.

The nine test-runs were divided into subsets of three runs each and were performed in this manner: In the first subset, the specimen temperature at thermocouple 4 was held at approximately $275^{\circ}F$. The guard temperature was changed from one run to the next to produce a distinct radial temperature difference for each of the three runs with respect to the fixed specimen temperature. In a like manner, another subset of three runs was conducted with a fixed specimen temperature of approximately $450^{\circ}F$, and different radial temperature differences were created for each of these three runs. In the last subset of three runs, the specimen temperature was maintained at approximately $650^{\circ}F$ at thermocouple number 4; and a different radial temperature difference was established in each of these runs.

A heat balance was performed, increment-by-increment, on the data from each run to determine radial heat transfer in each case. The average radial temperature difference and the average specimen temperature were also calculated for every run. Table 1 shows the application of this analytic technique to the data obtained from the first calibration test-run.

Table 2 is a tabulation of the results from the nine runs.

Table 1 - Apparatus Calibration Run with Armco Iron Specimen

Calibration Run No. 1 $\qquad q_h$ = 56.533 BTU/hr

Span	Specimen Temp. (°F)	Avg. Spec. Temp. in Span (°F)	k @ Avg. Spec. Temp. in Span BTU/hr-ft-°F	Spec. Δt in Span (°F)	q in Span BTU/hr	Guard Temp. (°F)	Avg. Grd. Temp. in Span (°F)
0	t_2 = 330.4 t_4 = 275.6					t_1 = 307.6 t_3 = 266.7	

$q_h - q_I$ = 1.663 BTU/hr; $(\Delta t)_r = (t_2 - t_1 + t_{I_s} - t_{I_g})/2$ = 16.4 °F; t_{avg} = 295.4 °F

Span	Specimen Temp. (°F)	Avg. Spec. Temp. in Span (°F)	k @ Avg. Spec. Temp. in Span BTU/hr-ft-°F	Spec. Δt in Span (°F)	q in Span BTU/hr	Guard Temp. (°F)	Avg. Grd. Temp. in Span (°F)
I	t_4 = 275.6 t_6 = 245.4	t_{I_s} 260.4	38.392	30.2	q_I 54.870	t_3 = 266.7 t_5 = 234.3	t_{I_g} 250.5

$q_I - q_{II}$ = 0.440 BTU/hr; $(\Delta t)_r = t_6 - t_5$ = 11.1 °F; $t_{avg} = t_6$ = 245.4 °F

Span	Specimen Temp. (°F)	Avg. Spec. Temp. in Span (°F)	k @ Avg. Spec. Temp. in Span BTU/hr-ft-°F	Spec. Δt in Span (°F)	q in Span BTU/hr	Guard Temp. (°F)	Avg. Grd. Temp. in Span (°F)
II	t_6 = 245.4 t_8 = 215.9	t_{II_s} 230.6	38.988	29.5	q_{II} 54.430	t_5 = 234.3 t_7 = 204.0	t_{II_g} 219.2

$q_{II} - q_{III}$ = 0.875 BTU/hr; $(\Delta t)_r = t_8 - t_7$ = 11.9 °F; $t_{avg} = t_8$ = 215.9 °F

Span	Specimen Temp. (°F)	Avg. Spec. Temp. in Span (°F)	k @ Avg. Spec. Temp. in Span BTU/hr-ft-°F	Spec. Δt in Span (°F)	q in Span BTU/hr	Guard Temp. (°F)	Avg. Grd. Temp. in Span (°F)
III	t_8 = 215.9 t_{10} = 187.3	t_{III_s} 201.6	39.568	28.6	q_{III} 53.555	t_7 = 204.0 t_9 = 176.1	t_{III_g} 190.1

$q_{III} - q_{IV}$ = 0.564 BTU/hr; $(\Delta t)_r = t_{10} - t_9$ = 11.2 °F; $t_{avg} = t_{10}$ = 187.3 °F

Span	Specimen Temp. (°F)	Avg. Spec. Temp. in Span (°F)	k @ Avg. Spec. Temp. in Span BTU/hr-ft-°F	Spec. Δt in Span (°F)	q in Span BTU/hr	Guard Temp. (°F)	Avg. Grd. Temp. in Span (°F)
IV	t_{10} = 187.3 t_{12} = 159.4	t_{IV_s} 173.3	40.134	27.9	q_{IV} 52.991	t_9 = 176.1 t_{11} = 149.9	t_{IV_g} 163.0

$q_{IV} - q_V$ = 0.039 BTU/hr; $(\Delta t)_r = t_{12} - t_{11}$ = 9.5 °F; $t_{avg} = t_{12}$ = 159.4 °F

Span	Specimen Temp. (°F)	Avg. Spec. Temp. in Span (°F)	k @ Avg. Spec. Temp. in Span BTU/hr-ft-°F	Spec. Δt in Span (°F)	q in Span BTU/hr	Guard Temp. (°F)	Avg. Grd. Temp. in Span (°F)
V	t_{12} = 159.4 t_{14} = 131.9	t_{V_s} 145.6	40.688	27.5	q_V 52.952	t_{11} = 149.9 t_{13} = 125.0	t_{V_g} 137.5

$q_V - q_{VI}$ = 1.445 BTU/hr; $(\Delta t)_r = t_{14} - t_{13}$ = 6.9 °F; $t_{avg} = t_{14}$ = 131.9 °F

Span	Specimen Temp. (°F)	Avg. Spec. Temp. in Span (°F)	k @ Avg. Spec. Temp. in Span BTU/hr-ft-°F	Spec. Δt in Span (°F)	q in Span BTU/hr	Guard Temp. (°F)	Avg. Grd. Temp. in Span (°F)
VI	t_{14} = 131.9 t_{16} = 105.5	t_{VI_s} 118.7	41.226	26.4	q_{VI} 51.507	t_{13} = 125.0 t_{15} = 100.5	t_{VI_g} 112.8

$\sum q_{loss} = q_h - q_{VI}$ = 56.533 - 51.507 = 5.026 BTU/hr

$(\overline{\Delta t})_r$ = 11.17°F

$q' = q_{loss} / (\overline{\Delta t})_r$ = 5.026/11.17 = 0.450 BTU/hr-°F

Table 2

Summary of Results from Apparatus Calibration Runs

Calibration Run No.	1 q_h (BTU/hr)	2 q_{loss} (BTU/hr)	3 Avg. $(\Delta t)_r$ (^oF)	4 q' (BTU/hr-^oF)	5 Specimen Mean Temp (^oF)
1	56.333	5.026	11.2	0.450	205.9
2	57.529	6.250	14.7	0.426	205.1
3	55.387	2.728	5.6	0.485	207.9
				$\bar{q}'$ = 0.454	$\bar{t}$ = 206.3
4	96.578	1.377	-0.02	-----	315.4
5	97.950	4.325	5.52	0.784	314.2
6	98.629	5.694	9.10	0.626	311.5
				$\bar{q}'$ = 0.705	$\bar{t}$ = 312.9
7	145.443	5.756	-0.47	-----	442.3
8	146.490	10.868	10.78	1.008	430.8
9	148.389	17.169	23.35	0.735	421.1
				$\bar{q}'$ = 0.872	$\bar{t}$ = 426.0

A term identified as "specific heat loss" is introduced in Table 2. It is defined as the net radial heat transfer, divided by the average radial temperature difference, and is represented by q', having units of BTU/hr-^{o}F.

The correlation utilizes the mean value of q' obtained from each subset of three runs, and this mean value is symbolized by $\bar{q}'$. The mean value of the average specimen temperatures in each subset is employed in correlating radial heat transfer with temperature. Figure 9 is a plot of $\bar{q}'$ with respect to the mean specimen temperature. Thus, a radial heat transfer calibration of the apparatus and specimen combination is afforded by the relationship plotted in Figure 9.

With the availability of this calibration, the comparative method can be employed to determine thermal conductivities. The performance of a one-run experiment provides the required data for the application of this method.

The comparative method is exemplified by its application to the data obtained from the test of the AISI 316 stainless steel specimen; these results are shown in Table 3. Referring to the notation in Table 3, the procedure is as follows:

1. Enter the temperatures corresponding to the eight specimen thermocouples and eight guard thermocouples.
2. Calculate and enter the mid-span temperatures for the six spans.

Figure 9

Specific Heat Loss, $\bar{q}'$, from Specimen

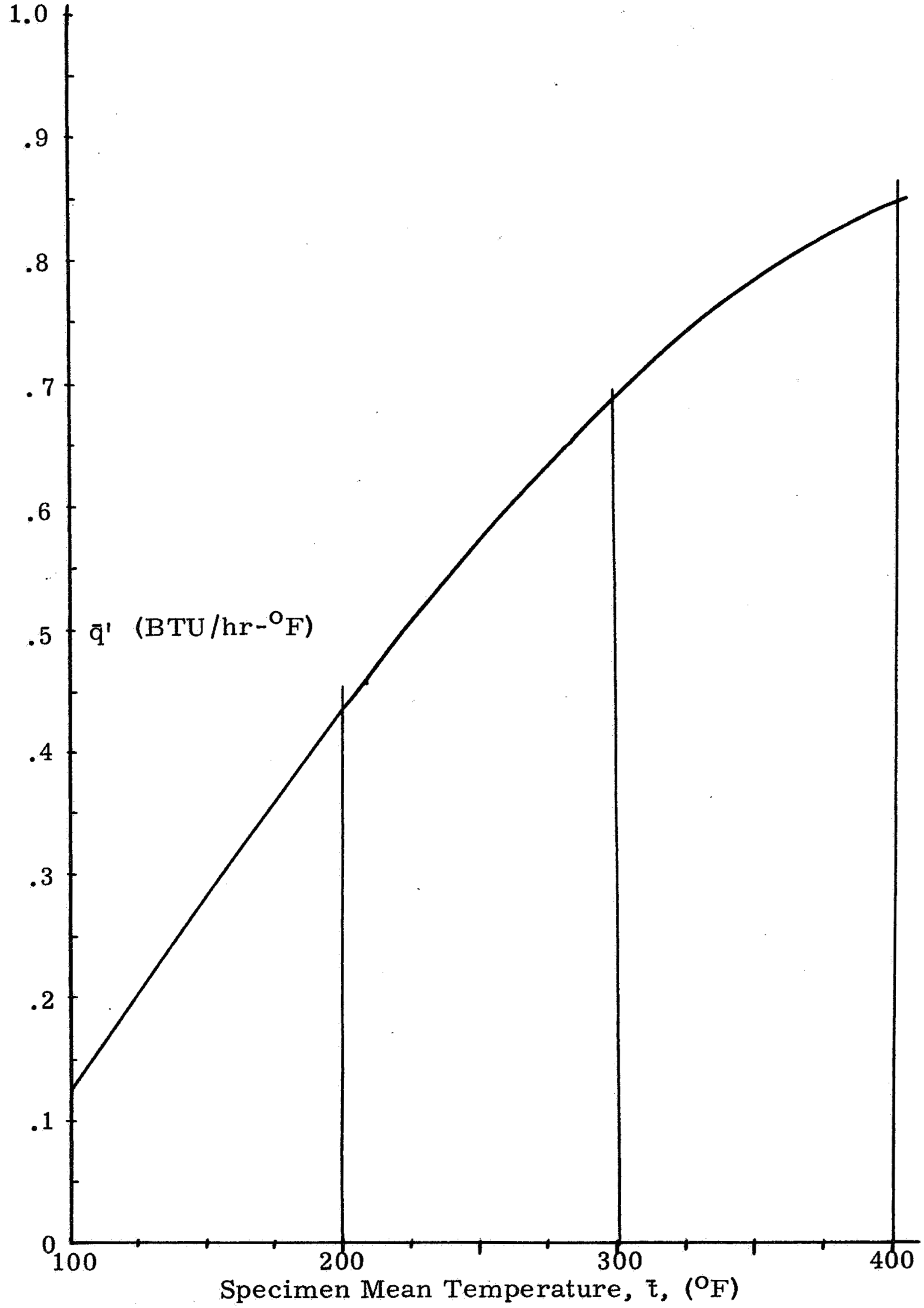


Table 3 - The Comparative Method

Specimen: AISI 316 Experiment 1, Run (a) q_h = 24.986 BTU/hr

Span	Specimen Temp. ($^\circ$F)	Avg. Spec. Temp. in Span ($^\circ$F)	k @ Avg. Spec. Temp. in Span BTU/hr-ft-$^\circ$F	Spec. Δt in Span ($^\circ$F)	q in Span BTU/hr	Guard Temp. ($^\circ$F)	Avg. Grd. Temp. in Span ($^\circ$F)
0	t_2 = 568.7 t_4 = 474.9					t_1 = 572.1 t_3 = 485. 7	

$q_h - q_I$ = -1.086 BTU/hr; $(\Delta t)_r = (t_2 - t_1 + t_{I_s} - t_{I_g})/2 = -4.0\ ^\circ$F; $t_{avg} = 508.5\ ^\circ$F

I	t_4 = 474.9 t_6 = 421.3	t_{I_s} 448.3	10.278	53.6	q_I 26.072	t_3 = 485.7 t_5 = 419.9	t_{I_g} 452.8

$q_I - q_{II}$ = 0.137 BTU/hr; $(\Delta t)_r = t_6 - t_5 = 1.4^\circ$F; $t_{avg} = t_6 = 421.3^\circ$F

II	t_6 = 421.3 t_8 = 366.4	t_{II_s} 395.0	9.982	54.9	q_{II} 25.935	t_5 = 419.9 t_7 = 359.3	t_{II_g}

$q_{II} - q_{III}$ = 0.697 BTU/hr; $(\Delta t)_r = t_8 - t_7 = 7.1^\circ$F; $t_{avg} = t_8 = 366.4^\circ$F

III	t_8 = 366.4 t_{10} = 311.4	t_{III_s} 339.6	9.696	55.0	q_{III} 25.238	t_7 = 359.3 t_9 = 302.2	t_{III_g}

$q_{III} - q_{IV}$ = 0.903 BTU/hr; $(\Delta t)_r = t_{10} - t_9 = 9.2^\circ$F; $t_{avg} - t_{10} = 311.4^\circ$F

IV	t_{10} = 311.4 t_{12} = 253.7	t_{IV_s} 282.1	8.912	57.7	q_{IV} 24.335	t_9 = 302.2 t_{11} = 246.7	t_{IV_g}

$q_{IV} - q_V$ = 0.687 BTU/hr; $(\Delta t)_r = t_{12} - t_{11} = 7.0^\circ$F; $t_{avg} = t_{12} = 253.7^\circ$F

V	t_{12} = 253.7 t_{14} = 192.1	t_{V_s} 222.5	8.112	61.6	q_V 23.648	t_{11} = 246.7 t_{13} = 192.0	t_{V_g}

$q_V - q_{VI}$ = 0.010 BTU/hr; $(\Delta t)_r = t_{14} - t_{13} = 0.1^\circ$F; $t_{avg} = t_{14} = 192.1^\circ$F

VI	t_{14} = 192.1 t_{16} = 128.7	t_{VI_s} 160.8	7.878	63.4	q_{VI} 23.638	t_{13} = 192.0 t_{15} = 137.0	t_{VI_g}

$\bar{t} = 342.6^\circ$F

From Figure 9, $\bar{q}' = 0.762$ BTU/hr-$^\circ$F

3. Calculate and enter the temperature difference from end-to-end of each span, $(\Delta t)_s$.

4. Calculate and enter the average radial temperature difference, $(\Delta t)_r$, for each of the six increments as indicated.

5. Enter the average specimen temperature for each of the six increments, denoted as t_{avg}.

6. Calculate the specimen overall mean temperature from the six specimen temperatures in step 5. Using the overall specimen mean temperature, obtain the value of specific heat loss, $\bar{q}'$, from Figure 9.

7. Calculate the radial heat transfer in the first increment of the specimen, i.e., from the heated end to the mid-point of span I in this manner:

$$q_h - q_I = q'(\Delta t)_r \frac{x}{L} \qquad \text{IV-6}$$

where: $(\Delta t)_r$ is the average radial temperature difference from the heated end to the mid-point of span I.

x is the distance from the heated end to the mid-point of span I.

L is the distance from the heated end to the mid-point of span VI.

8. Solve equation IV-6 for q_I, knowing the value of q_h.

9. Apply and rearrange equation IV-1 to solve for k_I, the

thermal conductivity for the mid-span temperature of span I:

$$k_I = q_I \frac{\Delta x}{A(t_4 - t_6)} \qquad \text{IV-1a}$$

10. Repeat steps 7, 8, and 9 to determine succeeding values of k for the remaining five spans.

C. A "No-Loss" Absolute Method

A more precise wording in describing this method would be to call it: the "negligible-loss" absolute method. However, it simply identifies an experiment and analysis wherein heat transfer between specimen and guard is made sufficiently small to permit its being neglected for all practical purposes. Referring to equation IV-1,

$$q = -kA\frac{\Delta t}{\Delta x} + fS \qquad \text{IV-1 (repeated)}$$

the product fS is very small relative to the first term on the right-hand side of the equation. Hence, this equation is reduced to the familiar Fourier, steady-state, one-dimensional, conduction equation:

$$q = -kA\frac{\Delta t}{\Delta x} \qquad \text{III-1 (repeated)}$$

Thus, to apply equation III-1 to the determination of k values with this apparatus necessitates the performance of a one-run experiment in which the temperature differences between bar and guard are made negligibly small.

In Section V, this "no-loss" absolute method is applied to the data from several experiments. Results are compared with the values of thermal conductivity determined by the other methods described in this section.

V. PRESENTATION AND DISCUSSION OF RESULTS

In this investigation, the first seven experiments included two runs each, identified respectively as run (a) and run (b). As explained previously, the data obtained from a run (a) and a run (b) are required for the solution of k values by the absolute method of Watson and Robinson (2).

These seven experiments are the following:

Experiment No.	Specimen Material	Average Specimen Temperatures Span VI	Average Specimen Temperatures Span I	Remarks
1	AISI 316	161	448	Tested By N.B.S.
2	AISI 303MA	122	279	
3	AISI 303MA	164	453	
4	Armco iron	131	296	
5	Armco iron	170	473	
6	2024-T351	131	291	
7	2024-T351	173	421	

In this tabulation, span VI and span I refer to segments of the specimen as shown in Figure 8. The average specimen temperature in each span designates the arithmetic average of the temperatures in that span from runs (a) and (b).

Further experiments consisted of nine individual runs using the Armco iron specimen. As explained in Section IV-B, the object of these nine runs was to calibrate the apparatus for heat transfer between specimen and guard as a basis for determining k values by a comparative method.

These nine calibration runs were divided into three subsets of three runs each. In each subset, the specimen temperature was maintained essentially constant, and the guard temperature was changed for each of the three runs.

Each subset of three runs provided bonus results in that any two runs of a subset can be paired and analyzed by the Watson and Robinson (2) absolute method. This pairing of runs was, in fact, done to the extent that six additional analyses were made on Armco iron by this absolute method. For consistency with the above table, these six pairs of runs are identified as six additional two-run experiments, numbered 8 through 13 in the continuing tabulation below:

Experiment No.	Specimen Material	Average Specimen Temperatures Span VI	Average Specimen Temperatures Span I	Calibration Runs
8	Armco iron	119	261	1 and 2
9	Armco iron	119	262	2 and 3
10	Armco iron	152	414	4 and 5
11	Armco iron	152	412	5 and 6
12	Armco iron	189	592	7 and 8
13	Armco iron	186	576	8 and 9

The data collected in these thirteen experiments are tabulated in Appendix A.

In this section, thermal conductivity values are presented for each of the four metals tested. Specifically, thermal conductivities have been calculated by each of the three methods described in Section IV. To reiterate these methods are:

1. The Watson and Robinson Absolute Method
2. A Comparative Method
3. A "No-Loss" Absolute Method

Thermal Conductivities of AISI 316 Stainless Steel

The particular AISI 316 specimen used in Experiment 1 was earlier tested by the National Bureau of Standards, and the results were reported by Watson and Robinson (3). These investigators determined thermal conductivities of AISI 316, in the range from 90°C to 840°C, to be:

$$k = 0.1333 + 0.1727 \frac{T}{1000} - 0.04334\left[\frac{T}{1000}\right]^2 + 0.0332\left[\frac{T}{1000}\right]^3 \qquad \text{V-1}$$

where: k is thermal conductivity, watts/cm-°C

and, T is temperature, °C

The data from Experiment 1 performed here were analyzed by the Watson and Robinson (2) method, and the relationship of k and temperature was found by the least-squares method for a temperature range from 161°F to 448°F to be:

$$k = 7.704 + 0.0024t + 0.00001t^2 \qquad \text{V-2}$$

where: k is thermal conductivity, BTU/hr-ft-°F

and, t is temperature, °F

Values of k obtained from equations V-1 and V-2 are compared in Table 4. Further comparisons are made in Table 4; namely, values of k computed by the comparative method and the "no-loss" absolute method are also presented for the AISI 316 specimen.

The comparison of k values in Table 4 is acknowledged to involve a slight error. This is explained by considering the k values for span I in this table: the Watson and Robinson (2) absolute method yields a k value of 10.56 corresponding to the average temperature in this span from runs (a) and (b). This average temperature in span I is $(448.3 + 447.2)/2 = 447.75^{o}F$. However, both the "no-loss" method and the comparative method employ the temperature in this span from only one of the runs. Arbitrarily, run (a) is used; and the k values are determined by these latter methods corresponding to the span I temperature of $448.3^{o}F$. Thus, the error is small.

In Table 4, the N.B.S. value of k in each span is used as a reference, and comparison of other values is made in terms of percent of difference from the reference value.

The AISI 316 thermal conductivity values presented here for the comparative method are those previously calculated in Table 3 wherein this method was demonstrated.

The application of the "no-loss" method to the data obtained in run (a) of Experiment 1 proves to be valid by the close

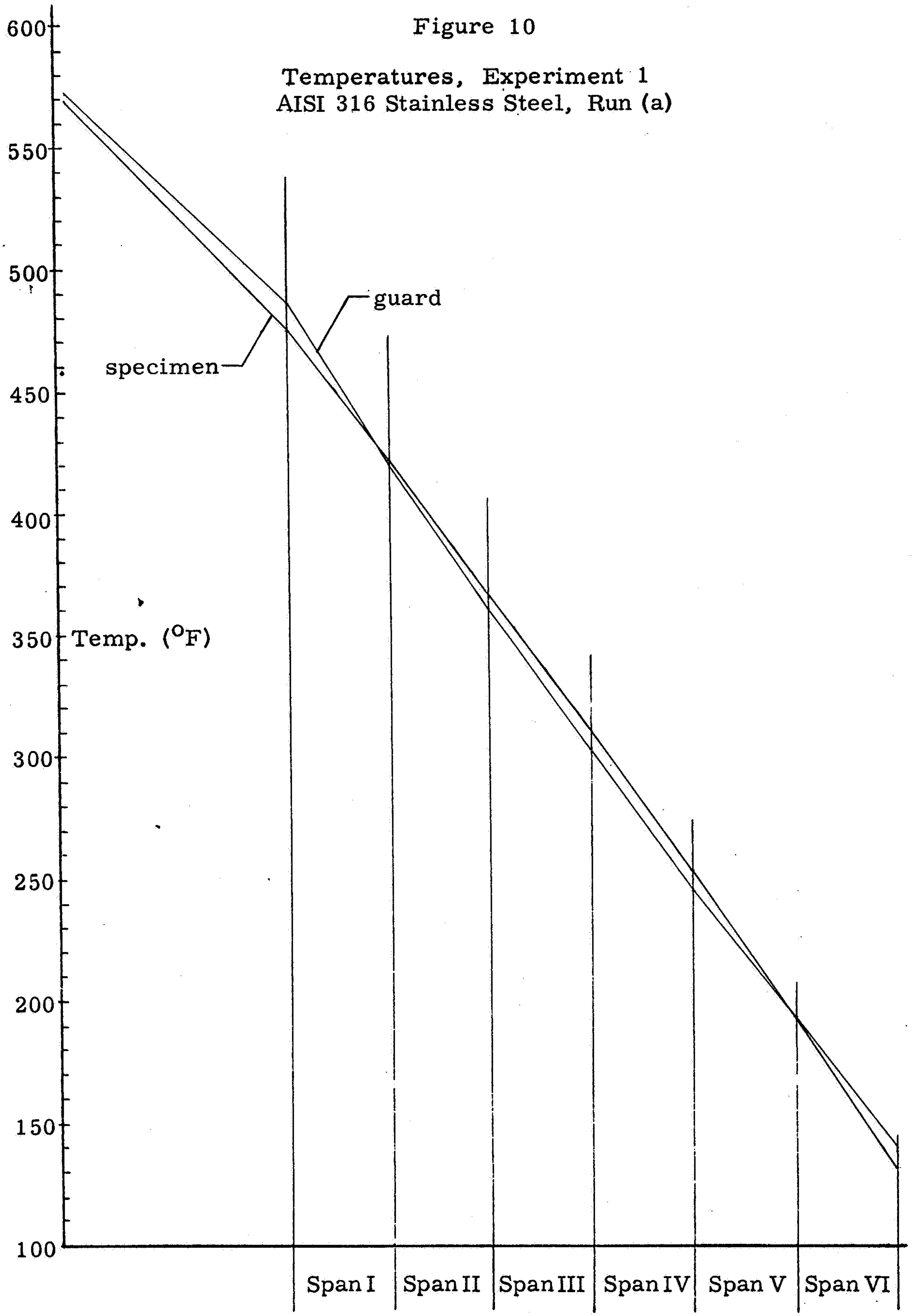
Table 4

Thermal Conductivity Values of AISI 316 Stainless Steel

Span No.	Specimen Mid-Span Temperature (^oF)		Thermal Conductivities (BTU/hr-ft-^oF)						
	Run (a)	Run (b)	N. B. S.	W. & R. Method	% Diff.	Comparative Method	% Diff.	"No-Loss" Method	% Diff.
I	448.3	447.2	9.90	10.56	+6.7	10.28	+3.8	9.85	-0.5
II	395.0	393.8	9.63	10.10	+4.9	9.98	+3.6	9.62	-0.1
III	339.6	338.5	9.34	9.58	+2.6	9.70	+3.9	9.60	+2.8
IV	282.1	281.2	9.05	9.08	+0.3	8.91	-1.5	9.15	+1.1
V	222.5	222.1	8.73	8.65	-0.9	8.11	-7.1	8.57	-1.8
VI	160.8	161.1	8.41	8.35	-0.7	7.88	-6.3	8.33	-0.9

Figure 10

Temperatures, Experiment 1
AISI 316 Stainless Steel, Run (a)



agreement of values obtained with the N.B.S. values. A better appreciation of the "no-loss" method is had by considering the plot of specimen and guard temperatures for run (a) which is shown in Figure 10. It is seen thereon that the temperature difference between bar and guard is small over the entire length.

Thermal Conductivities of AISI 303MA Stainless Steel

Experiments 2 and 3 were performed with the AISI 303MA specimen. From the data in Experiment 2, thermal conductivities were determined for a temperature range from 122°F to 279°F; from Experiment 3, k values were found in the temperature range from 164°F to 453°F.

Application of the Watson and Robinson (2) absolute method to Experiment 2 data yields the following relationship for thermal conductivity:

$$k = 7.410 + 0.0079t \quad (122 < t < 279) \qquad \text{V-3}$$

where: k is thermal conductivity, BTU/hr-ft-°F

and, t is temperature, °F

For Experiment 3, the Watson and Robinson absolute method provides the following equation for k as a function of temperature:

$$k = 7.997 + 0.0064t \quad (164 < t < 453) \qquad \text{V-4}$$

where: k is thermal conductivity, BTU/hr-ft-°F

and, t is temperature, °F

In the overlapping temperature range, the values of k determined by equations (V-3) and (V-4) agree within approximately three percent.

As stated in Section I, published values of thermal conductivity could not be found for this particular stainless steel. The alloying elements and percentages thereof in AISI 303MA and AISI 303 are identical with two exceptions: AISI 303MA contains 0.60% molybdenum, maximum, and 0.50/0.90% aluminum; whereas, AISI 303 does not contain these elements. The influence which these added elements might have on thermal conductivity can only be surmised to be small.

For information only, Table 5 includes thermal conductivities for AISI 303 as given by McAdams (4).

In Table 5, values of thermal conductivity of AISI 303MA are presented for the Watson and Robinson (2) method applied to Experiment 2 data; in addition, values are given for the comparative and "no-loss" methods as applied to run (a) of Experiment 2.

Arbitrarily, the values of k obtained by the "no-loss" method are used as a basis for comparison of the values derived by the other methods. Comparison is expressed in percent of difference from the "no-loss" value in each span.

Figure 11 is a plot of specimen and guard temperatures for run (a) of Experiment 2, performed on the AISI 303MA specimen. The nominal temperature difference between bar and guard

Table 5

Thermal Conductivities of AISI 303MA Stainless Steel

Span No.	Specimen Mid-Span Temperature (^oF)		Thermal Conductivities (BTU/hr-ft-^oF)					
	Run (a)	Run (b)	"No-Loss" Method	W. & R. Method	% Diff.	Comparative Method	% Diff.	AISI 303 (Information) (Only)
I	277.9	280.1	9.61	9.61	0	9. 42	-2. 0	9. 68
II	247.3	249.4	9.39	9.41	+0.1	9.07	-3.4	9. 55
III	216.4	218.2	9.49	9.13	-3.8	8.91	-6.1	9. 42
IV	185.2	186.6	9.36	8.84	-5.6	8.53	-9.0	9. 29
V	153.6	154.7	9.19	8.58	-6.6	8.18	-10.9	9. 16
VI	121.6	122.3	8.99	8.43	-6.2	7.98	-11.1	9. 02

Figure 11

Temperatures, Experiment 2
AISI 303MA Stainless Steel, Run (a)

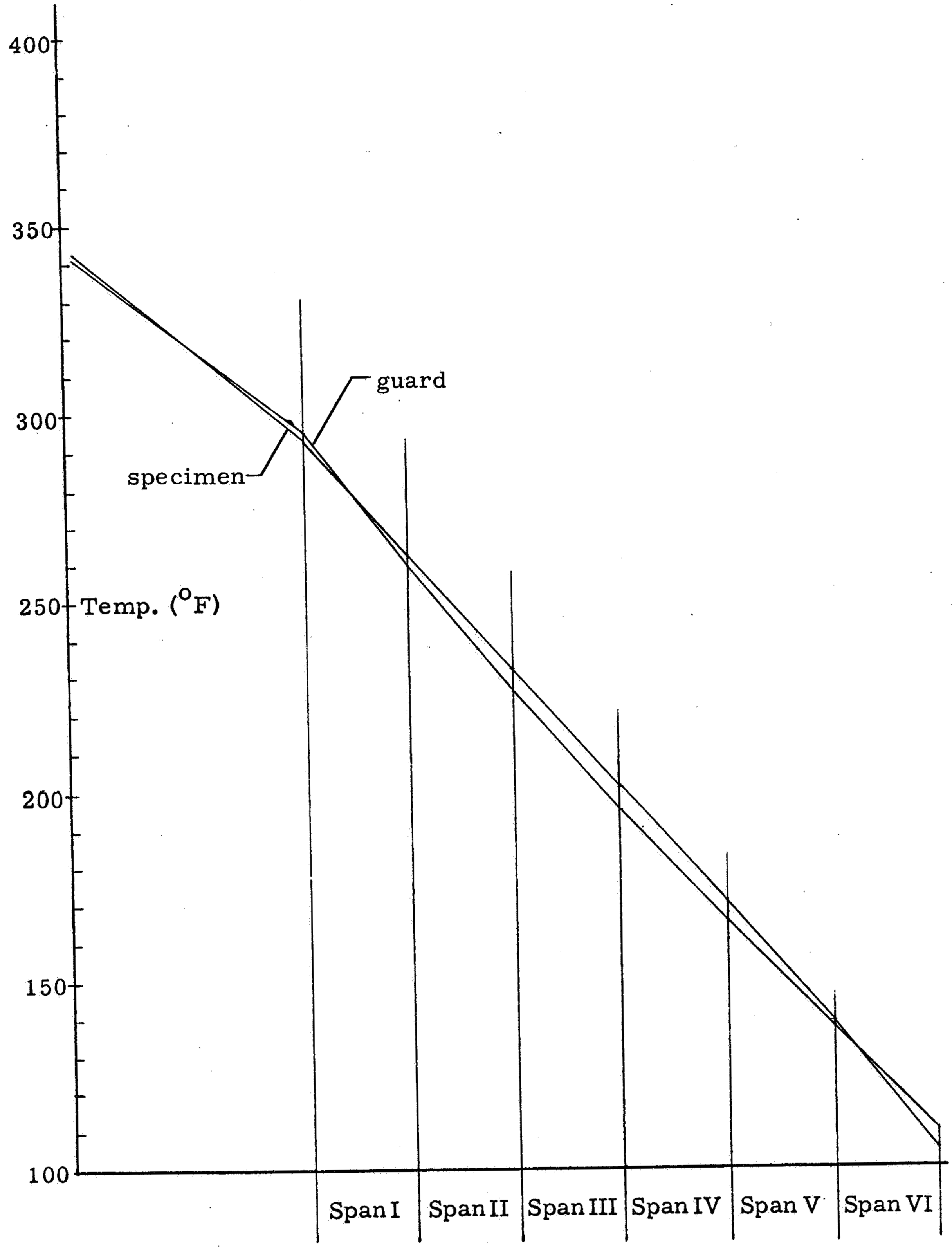
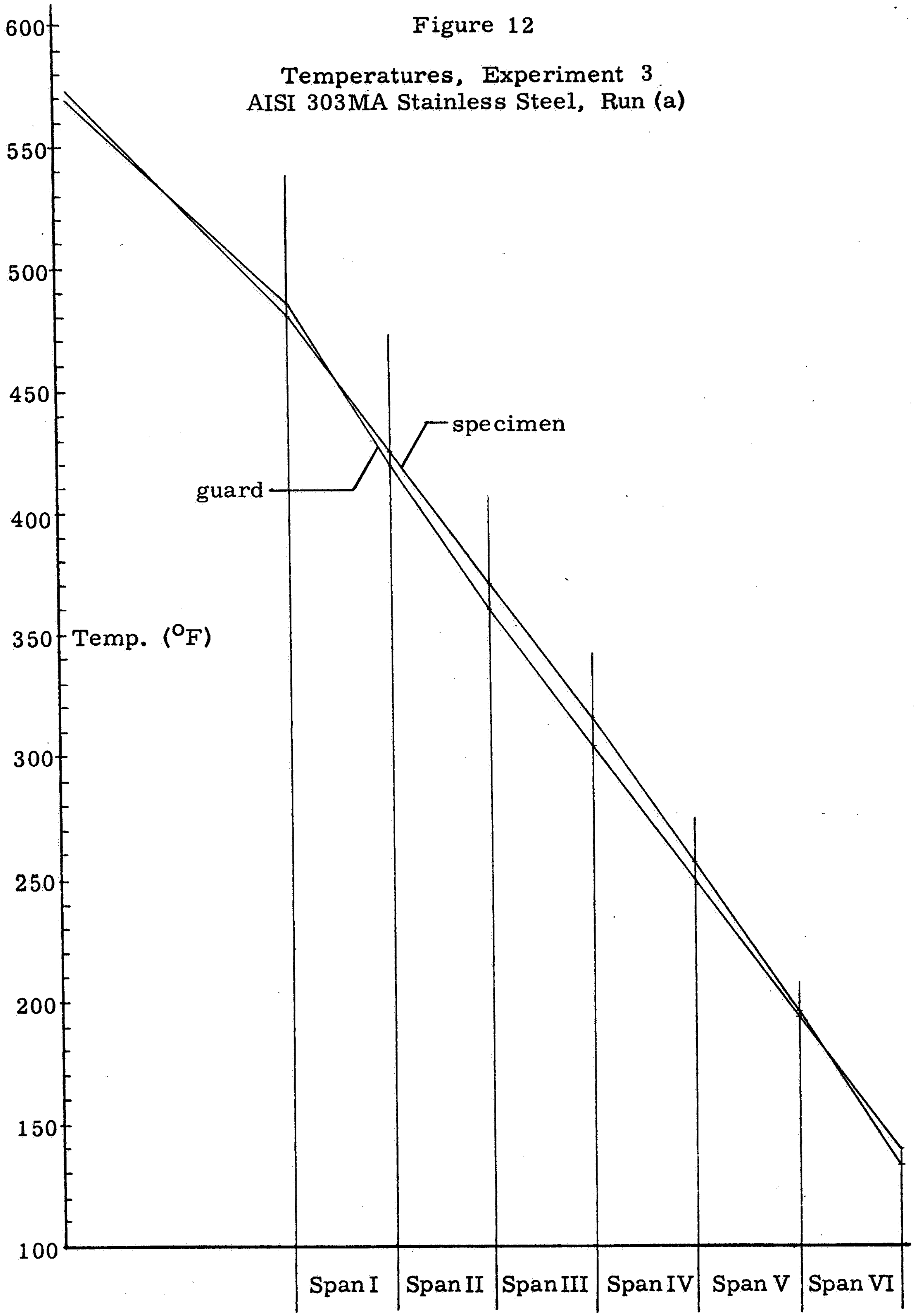


Figure 12

Temperatures, Experiment 3
AISI 303MA Stainless Steel, Run (a)



is 3.6°F over the entire length, and the maximum temperature difference is 6.3°F.

Under these conditions, the "no-loss" method is reasoned to have considerable validity. Admittedly, this is conjecture, with the author's reasoning being influenced by comparing the "no-loss" values with the corresponding values for AISI 303.

Figure 12 is a plot of specimen and guard temperatures from run (a) of experiment 3 and is submitted for reference purposes only.

Thermal Conductivities of Armco Iron

As previously stated in Section IV-B, the thermal conductivities of Armco iron have been found by many investigators. Equation IV-4 represents the application of the method of least-squares to the values reported by thirteen investigators (1) of Armco iron and is valid over a temperature range from 0° to 1000°F.

$$k = 43.6 \ (1 - 0.0004587t) \qquad \text{IV-4 (repeated)}$$

Consequently, knowing the thermal conductivity for Armco iron permits further evaluation of the apparatus and the method of Watson and Robinson (2). Also, it provides the basis for the comparative method and a means of evaluating the proposed "no-loss" method.

To this end, eight experiments were performed using the Armco iron specimen. These experiments are numbers 4, 5, 8, 9, 10, 11, 12, and 13. The eight experiments were analyzed by the Watson and Robinson (2) method and by the "no-loss" method. In addition, the comparative method was applied to run (a) of experiment 4 and run (a) of experiment 5.

Thermal conductivities are presented for each of the eight experiments in the tables which follow. In addition, a plot of specimen and guard temperature is included for run (a) of each experiment. A plot of run (b) for each experiment is not included because superimposing the run (b) on the same graph with run (a) results in a set of four curves which practically coincide, and reading becomes difficult.

Where the comparative method or "no-loss" method are used, each is applied to the experimental results from a run (a).

The values of thermal conductivity determined in each experiment are compared with values at the corresponding temperatures from equation IV-4.

The application of the Watson and Robinson (2) absolute method produced poor results for experiments 4 and 5. The reason is not known. In each case the "no-loss" method provided very favorable results for the same data.

However, in the six additional experiments with Armco iron, the Watson and Robinson (2) analysis technique provided overall results within 1.5% of the reference values from equation IV-4.

Validity of the "no-loss" method is seen to be related to the specimen-to-guard temperature difference. For example, in experiment 9, the specimen temperature is higher than guard temperature by approximately 10^{o}F over the length of the bar. Thus, the cumulative loss of heat from the specimen results in progressively poorer results from span I to span VI for the "no-loss" method.

In experiment 10, the "no-loss" method affords very favorable values for k. In Figure 17 it is shown that the average radial temperature difference between specimen and guard is approximately 4^{o}F.

Another aspect in comparing the "no-loss" results in experiments 9 and 10 concerns the specimen heater power applied in each case. Referring to Appendix A, the specimen heater powers for runs (a) of experiments 9 and 10 are 57.529 BTU/hr and 96.578 BTU/hr, respectively. The reasoning used here is simply that for a fixed radial temperature difference, increasing the heat input results in proportionately smaller radial heat loss from the specimen.

Thermal Conductivities of 2024-T351 Aluminum Alloy

Two experiments, numbers 6 and 7, were performed using the 2024-T351 aluminum specimen. The temperature range in each of these experiments overlapped to permit a comparison of k values in the common temperature range.

As previously stated, no reference was found for the thermal conductivity of this particular aluminum. Consequently, this portion of the investigation is limited to the comparison of k values which have been determined by the several methods.

Table 14 summarizes the results from experiment 6, and Figure 21 shows the specimen and guard temperatures for this experiment.

As seen in Table 14, the three methods of analysis provide generally comparable values for k. Values calculated by the "no-loss" method are higher than the mean and are progressively departing therefrom in the successive spans on the specimen. In considering Figure 21, the heat transfer from specimen to guard is cumulative from the heated end to the mid-point of span VI. Nominally, an 8°F radial temperature difference existed over all the spans. Therefore, the departure of k values by the "no-loss" method is reasonable.

In the overlapping temperature range of experiments 6 and 7, the application of the Watson and Robinson (2) method to each experiment gives values of k which agree within three percent.

Table 6

Thermal Conductivity Values of Armco Iron from Experiment 4

Span No.	Specimen Mid-Span Temperature (^oF)		Thermal Conductivities (BTU/hr-ft-^oF)						
	Run (a)	Run (b)	Ref. (1)	W. & R. Method	% Diff.	Comparative Method	% Diff.	"No-Loss" Method	% Diff.
I	296.8	295.1	37.67	36.07	-4.3	36.32	-3.9	36.59	-2.9
II	262.6	261.1	38.35	36.81	-4.0	36.09	-5.9	36.38	-5.2
III	229.0	227.6	39.02	36.95	-5.3	37.27	-4.5	37.69	-3.4
IV	195.9	194.7	39.68	36.87	-7.1	37.30	-6.0	37.92	-4.4
V	163.4	162.4	40.33	36.76	-8.9	37.70	-6.5	38.51	-4.5
VI	131.5	130.6	40.97	36.75	-10.4	38.71	-5.5	39.74	-3.0

Figure 13

Temperatures, Experiment 4
Armco Iron Run (a)

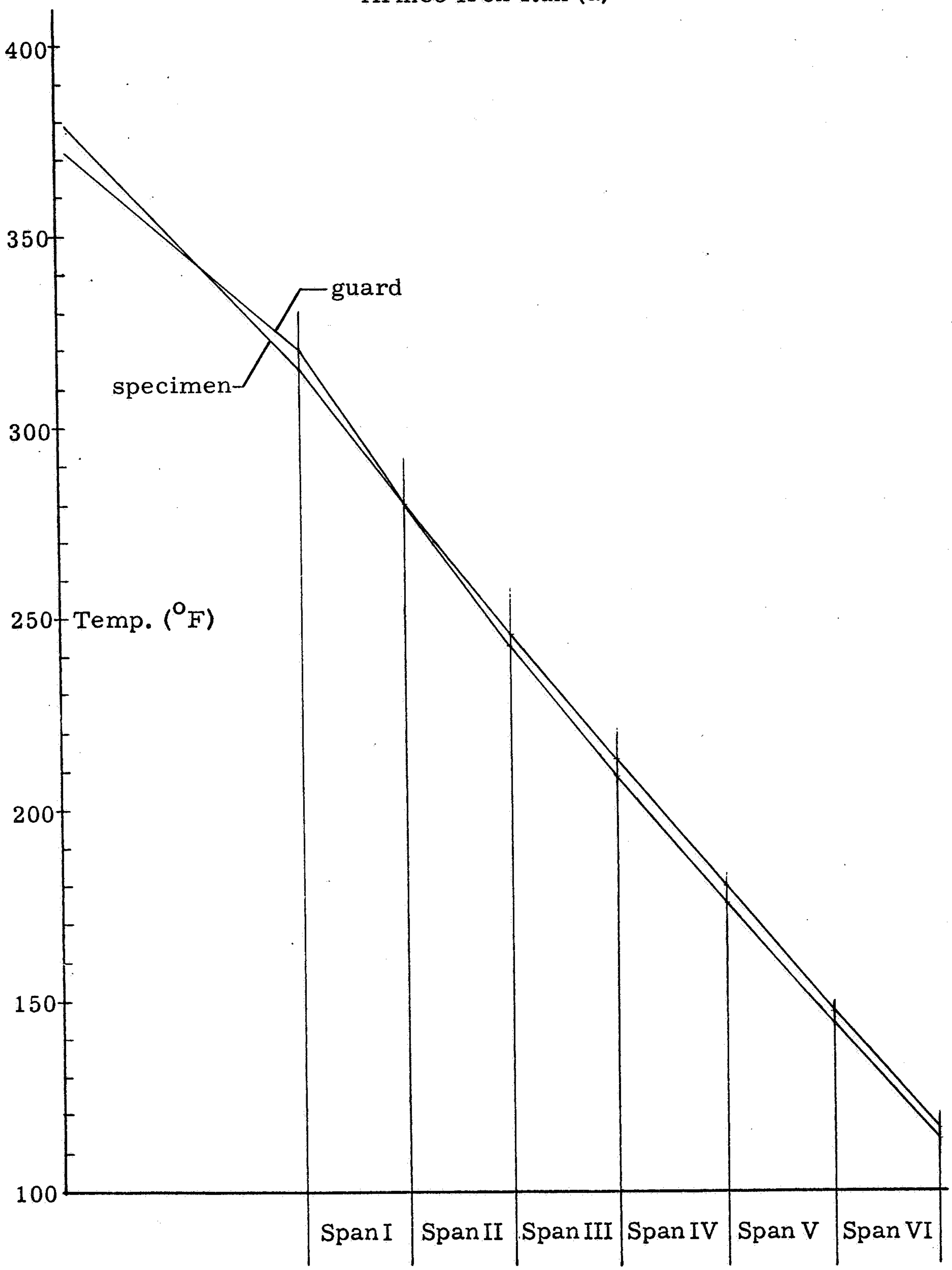


Table 7

Thermal Conductivity Values of Armco Iron from Experiment 5

Span No.	Specimen Mid-Span Temperature (^{o}F)		Thermal Conductivities (BTU/hr-ft-^{o}F)						
	Run (a)	Run (b)	Ref. (1)	W. & R. Method	% Diff.	Comparative Method	% Diff.	"No-Loss" Method	% Diff.
I	472.6	474.6	34.15	25.85	-24.0	32.69	-4.3	34.63	+0.1
II	408.8	410.2	35.43	23.19	-34.6	34.18	-3.5	36.27	+2.4
III	346.6	347.5	36.67	22.65	-38.1	36.23	-0.1	38.52	+5.0
IV	286.1	286.6	37.88	25.15	-33.6	36.40	-3.9	38.78	+2.4
V	227.3	227.4	39.05	28.79	-21.0	36.49	-6.5	38.91	-0.3
VI	170.0	169.9	40.20	32.15	-20.0	37.81	-5.9	40.28	+0.2

Figure 14

Temperatures, Experiment 5
Armco Iron, Run (a)

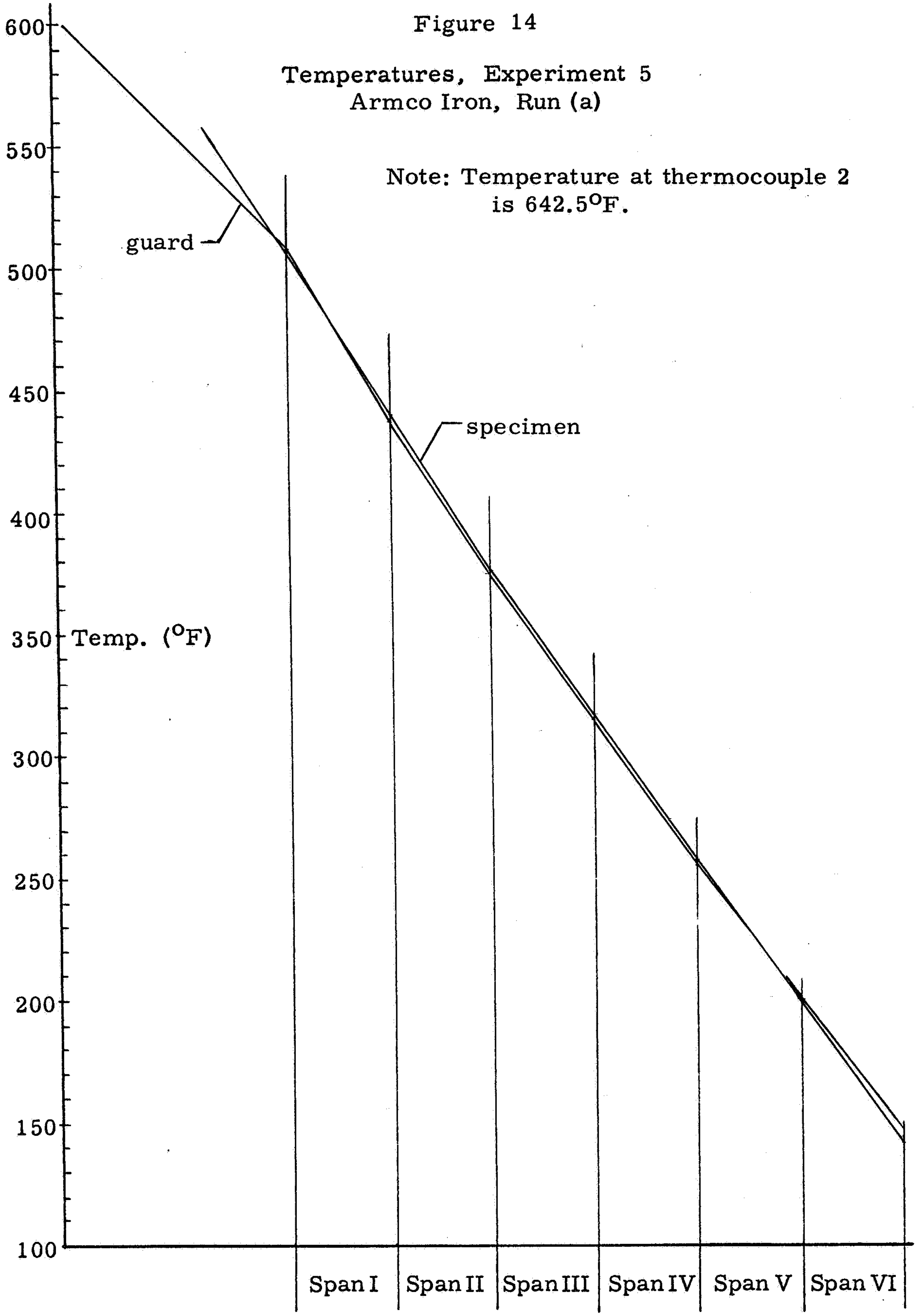


Table 8

Thermal Conductivity Values of Armco Iron from Experiment 8

Span No.	Specimen Mid-Span Temperature (^oF)		Thermal Conductivities (BTU/hr-ft-^oF)						
	Run (a)	Run (b)	Ref. (1)	W. & R. Method	% Diff.	Comparative Method	% Diff.	"No-Loss" Method	% Diff.
I	260.4	261.4	38.39	37.91	-1.2	Not Used		39.56	+3.0
II	230.6	231.7	38.99	38.79	-0.5			40.49	+3.8
III	201.6	202.7	39.57	39.62	+0.5			41.77	+5.6
IV	173.2	174.4	40.14	40.45	+0.8			42.82	+6.7
V	145.6	146.8	40.69	41.31	+1.5			43.44	+6.8
VI	118.6	120.0	41.23	42.24	+2.4			45.25	+9.7

Figure 15

Temperatures, Experiment 8
Armco Iron, Run (a)

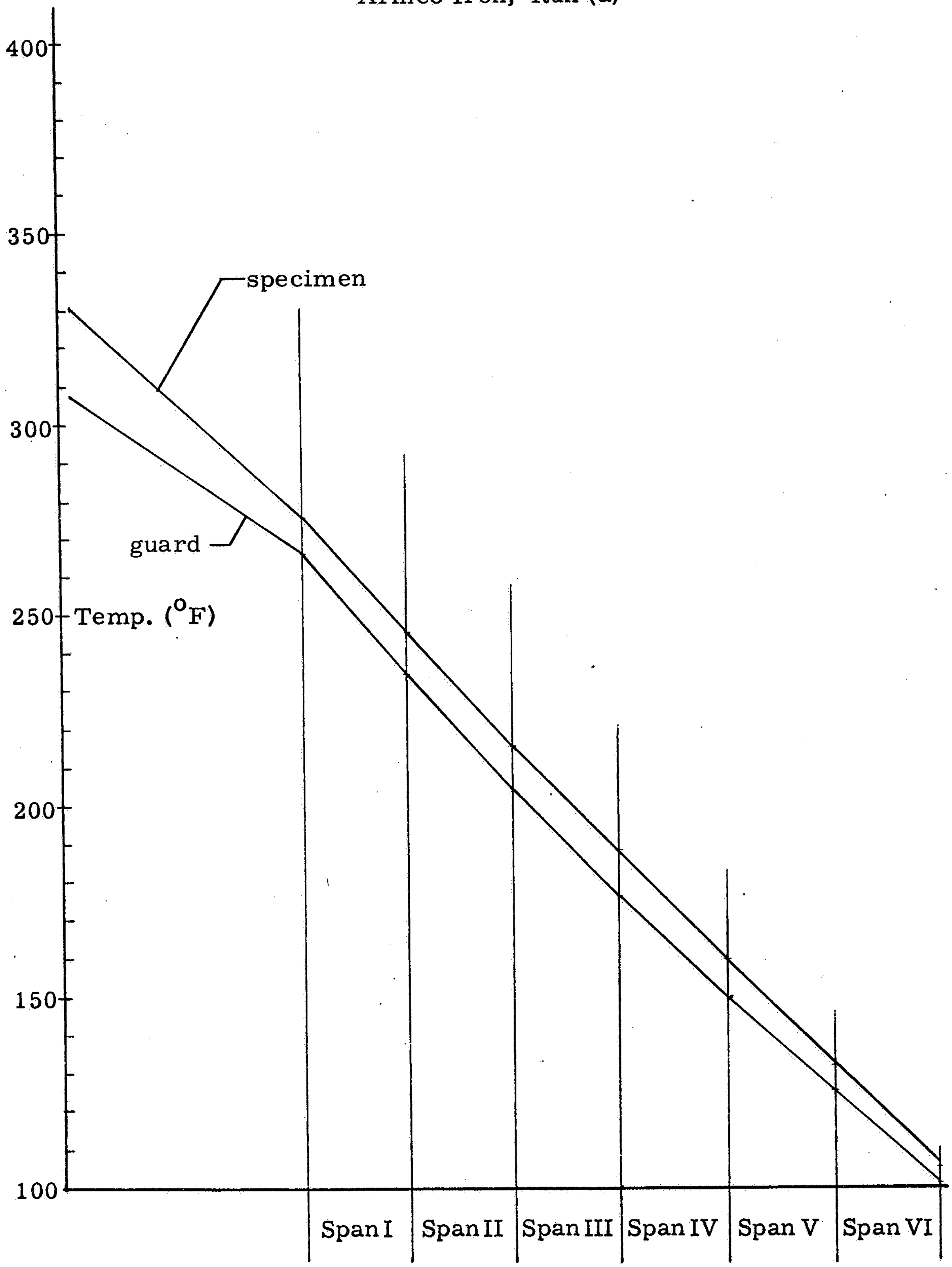


Table 9

Thermal Conductivity Values of Armco Iron from Experiment 9

Span No.	Specimen Mid-Span Temperature (^oF)		Thermal Conductivities (BTU/hr-ft-^oF)						
	Run (a)	Run (b)	Ref. (1)	W. & R. Method	% Diff.	Comparative Method	% Diff.	"No-Loss" Method	% Diff.
I	261.4	262.8	38.37	38.18	-0.5	Not Used		40.38	+7.8
II	231.7	232.9	38.97	38.91	-0.2			41.07	+5.4
III	202.7	203.7	39.55	39.58	+0.1			42.80	+8.2
IV	174.4	175.0	40.11	40.24	+0.3			43.57	+8.6
V	146.8	146.9	40.66	40.92	+0.6			44.37	+9.1
VI	120.0	119.4	41.20	41.65	+1.1			46.22	+12.0

Figure 16

Temperatures, Experiment 9
Armco Iron, Run (a)

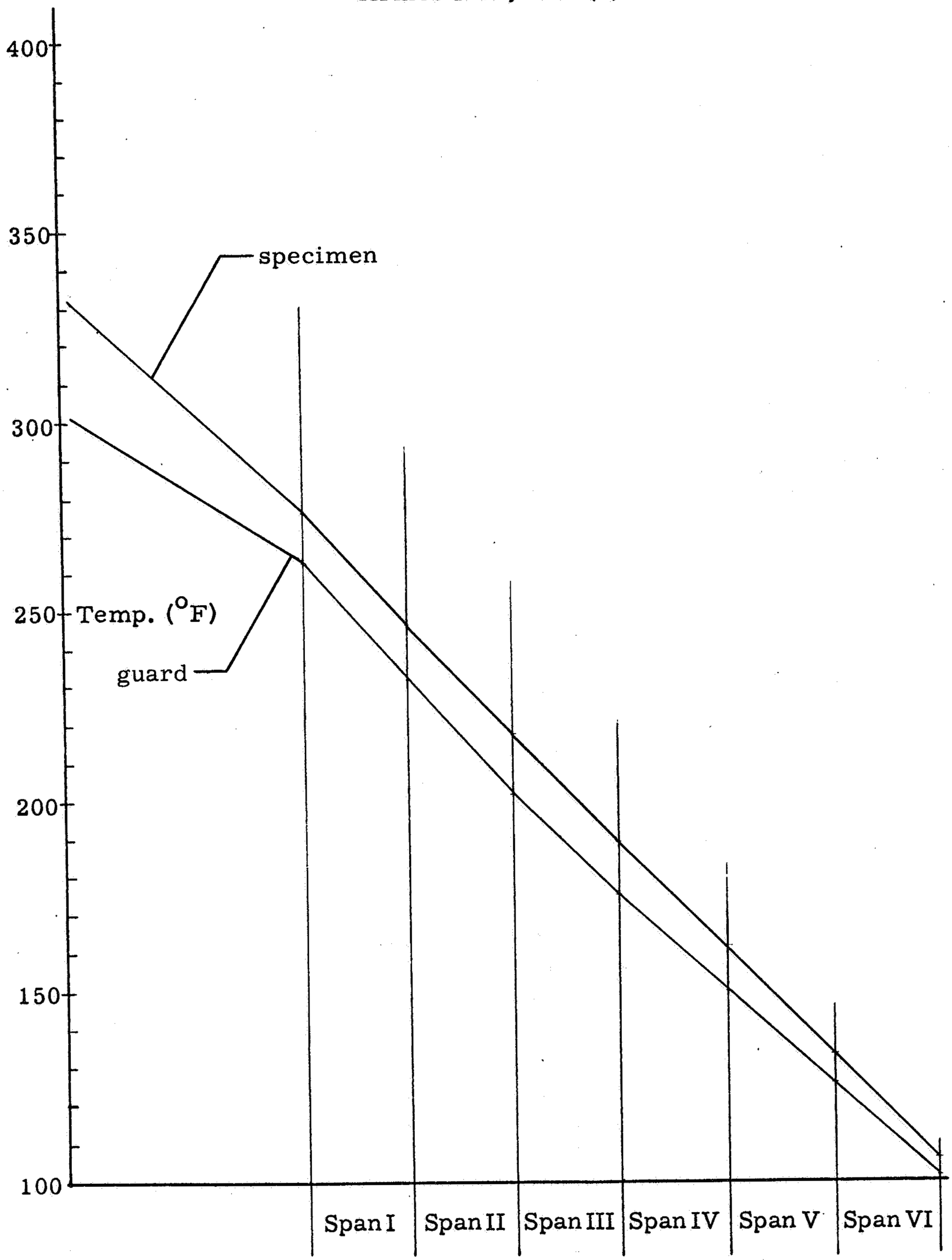


Table 10

Thermal Conductivity Values of Armco Iron from Experiment 10

Span No.	Specimen Mid-Span Temperature (^oF)		Thermal Conductivities (BTU/hr-ft-^oF)						
	Run (a)	Run (b)	Ref. (1)	W. & R. Method	% Diff.	Comparative Method	% Diff.	"No-Loss" Method	% Diff.
I	415.9	413.4	35.28	36.50	+3.5	Not Used		36.18	+2.5
II	361.0	359.0	36.38	37.40	+2.8			37.65	+3.5
III	307.1	305.8	37.46	38.23	+2.1			38.87	+3.8
IV	254.3	253.8	38.51	39.03	+1.4			38.95	+1.1
V	202.7	202.8	39.55	39.86	+0.8			39.32	-0.6
VI	152.1	153.0	40.56	40.73	+0.4			41.14	+1.4

Figure 17

Temperatures, Experiment 10
Armco Iron, Run (a)

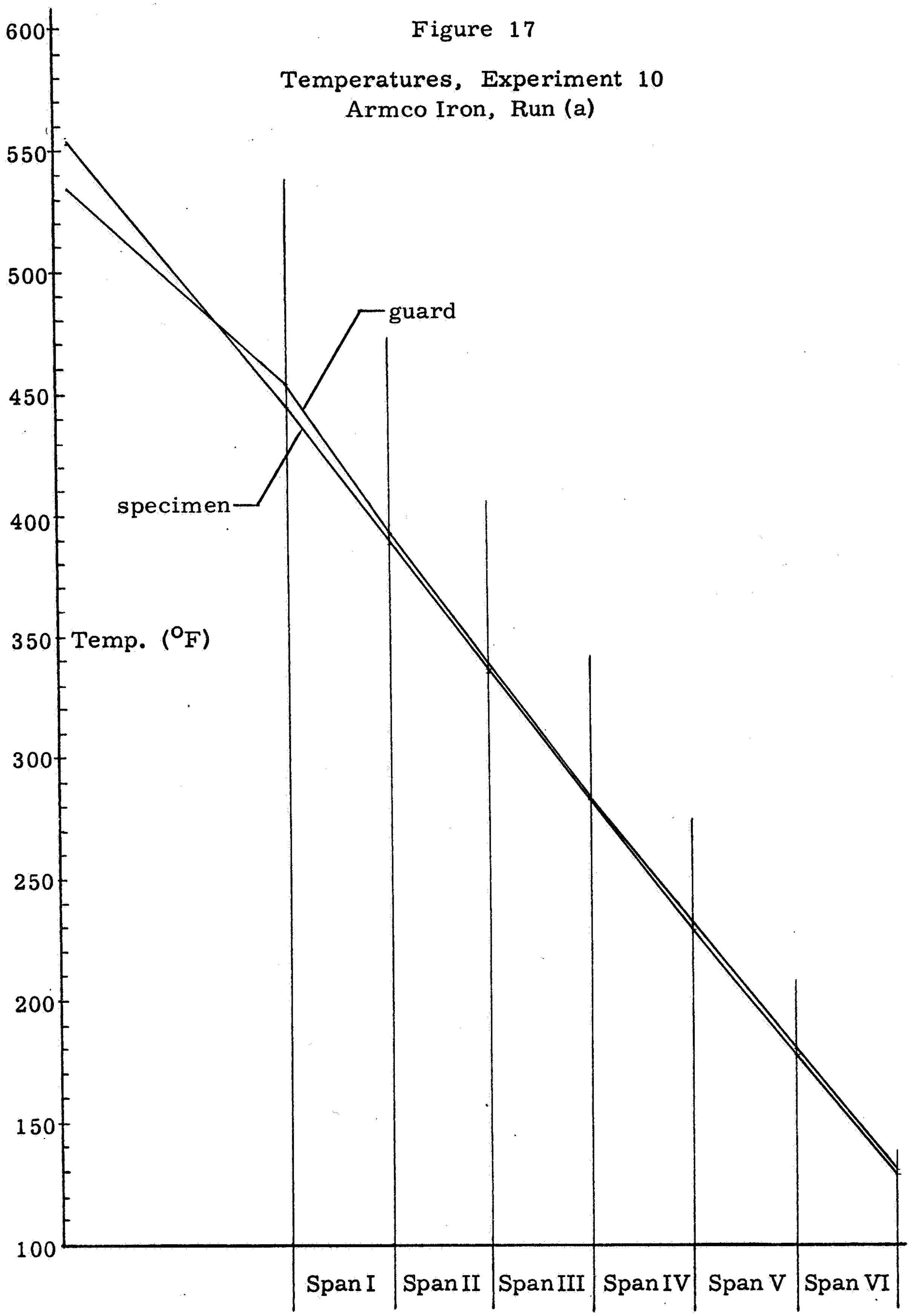


Table 11

Thermal Conductivity Values of Armco Iron from Experiment 11

Span No.	Specimen Mid-Span Temperature (^{o}F)		Thermal Conductivities (BTU/hr-ft-^{o}F)						
	Run (a)	Run (b)	Ref. (1)	W. & R. Method	% Diff.	Comparative Method	% Diff.	"No-Loss" Method	% Diff.
I	413.4	410.1	35.33	36.89	+4.4	Not Used		37.03	+4.8
II	359.0	356.0	36.42	37.74	+3.6			38.69	+6.2
III	305.8	303.1	37.48	38.54	+2.8			39.88	+6.4
IV	253.8	251.3	38.52	39.34	+2.1			40.11	+4.1
V	202.8	200.7	39.54	40.17	+1.3			40.50	+2.4
VI	153.0	151.3	40.54	41.04	+1.2			42.41	+4.6

Figure 18

Temperatures, Experiment 11
Armco Iron, Run (a)

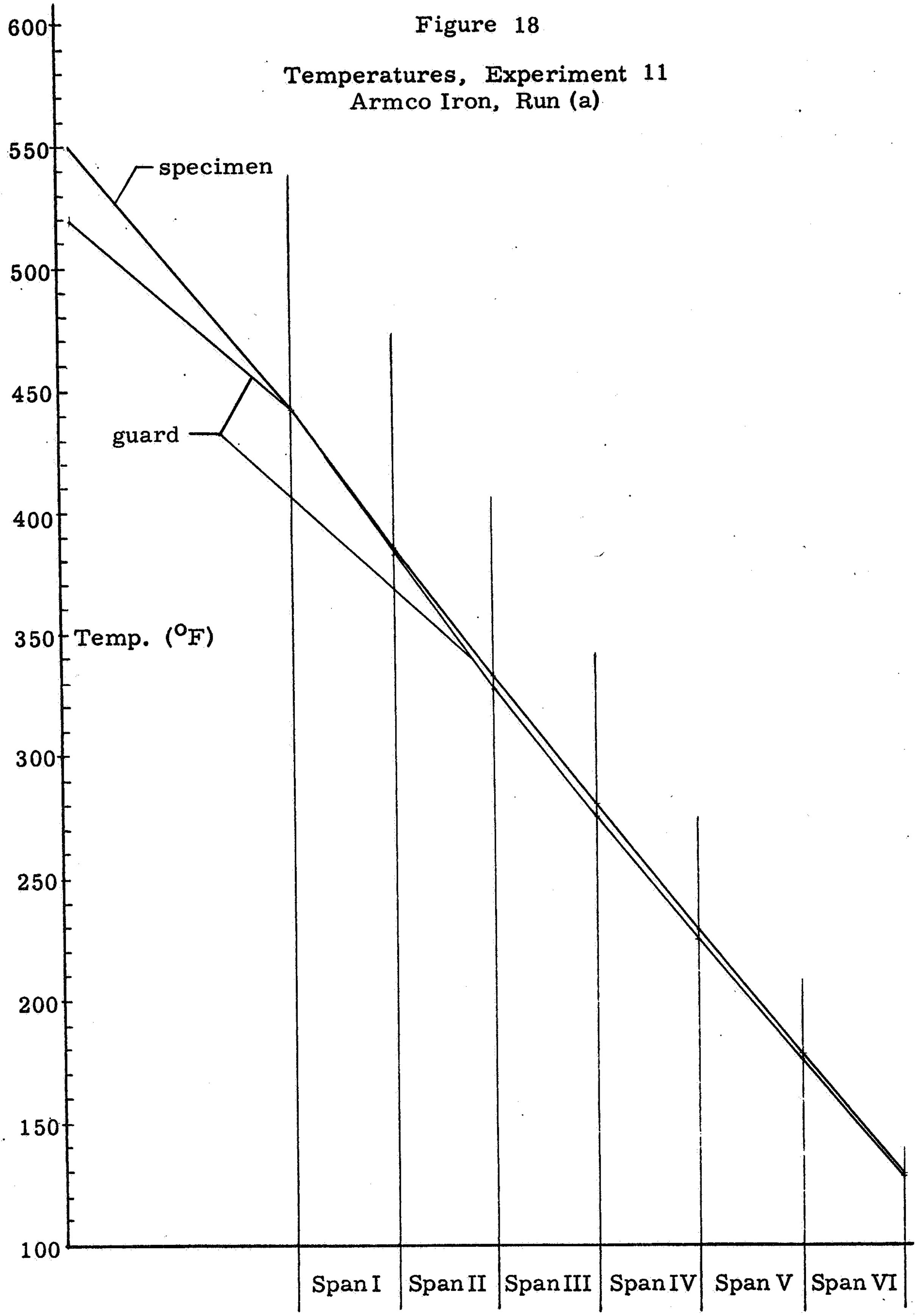


Table 12

Thermal Conductivity Values of Armco Iron from Experiment 12

Span No.	Specimen Mid-Span Temperature (°F)		Thermal Conductivities (BTU/hr-ft-°F)						
	Run (a)	Run (b)	Ref. (1)	W. & R. Method	% Diff.	Comparative Method	% Diff.	"No-Loss" Method	% Diff.
I	600.1	583.7	31.60	31.84	+0.8	Not Used		32.45	+2.7
II	510.3	496.6	33.39	33.70	+0.9			34.80	+4.2
III	424.5	413.4	35.11	35.59	+1.4			37.48	+6.8
IV	342.7	334.1	36.75	37.60	+2.3			39.71	+8.0
V	264.9	258.6	38.30	39.77	+3.8			39.81	+3.9
VI	191.0	187.1	39.78	42.13	+5.9			41.42	+4.1

Figure 19

Temperatures, Experiment 12
Armco Iron, Run (a)

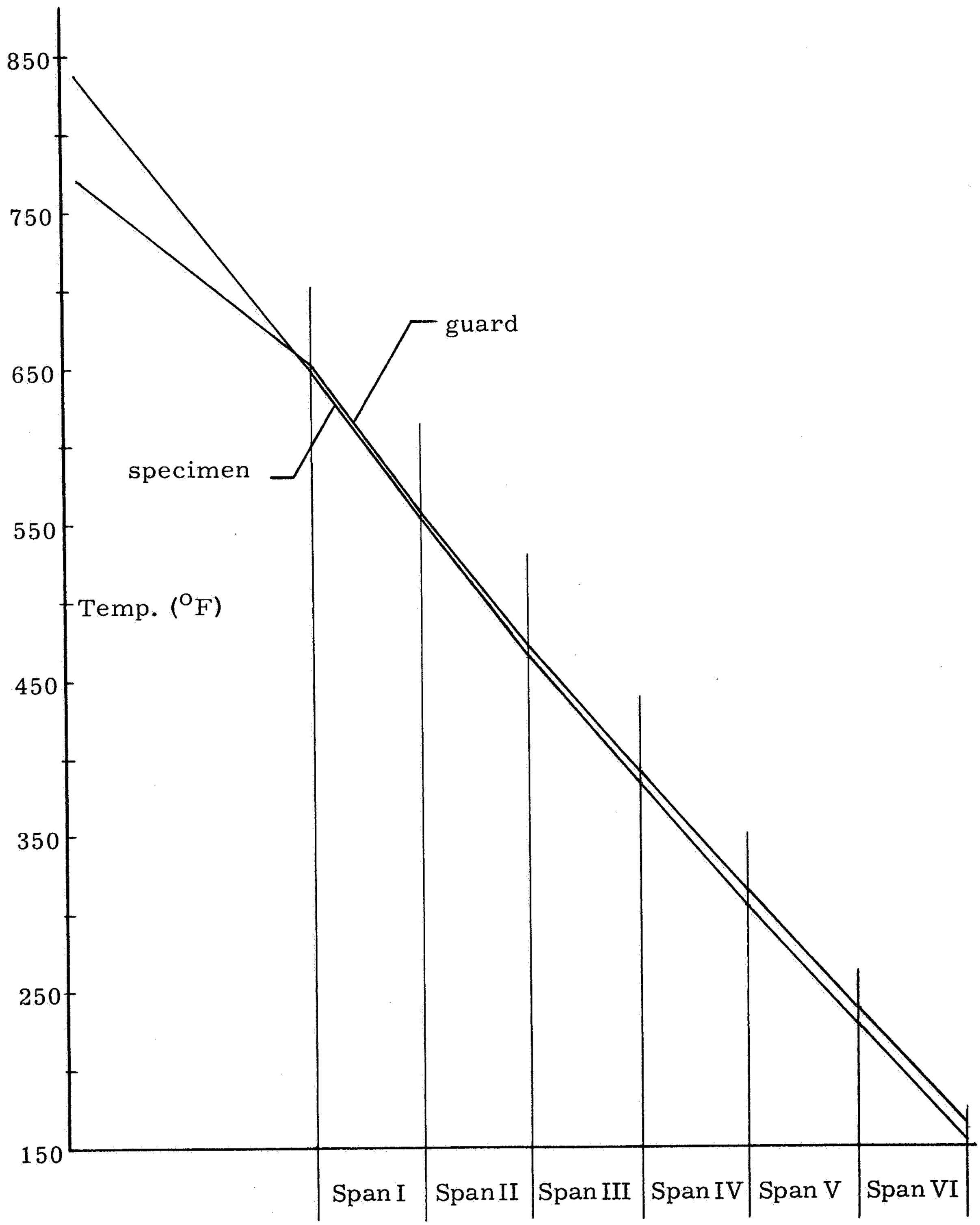


Table 13

Thermal Conductivity Values of Armco Iron from Experiment 13

Span No.	Specimen Mid-Span Temperature (^{o}F)		Thermal Conductivities (BTU/hr-ft-^{o}F)						
	Run (a)	Run (b)	Ref. (1)	W. & R. Method	% Diff.	Comparative Method	% Diff.	"No-Loss" Method	% Diff.
I	583.7	569.1	31.93	31.74	-0.6	Not Used		33.57	+5.1
II	496.6	484.7	33.67	33.60	-0.7			36.16	+7.4
III	413.4	404.1	35.33	35.49	+0.5			39.03	+10.0
IV	334.1	327.3	36.92	37.50	+1.6			41.27	+11.8
V	258.6	254.4	38.43	39.66	+3.2			41.33	+7.5
VI	187.1	185.2	39.86	42.02	+5.4			43.05	+8.0

Figure 20

Temperatures, Experiment 13
Armco Iron, Run (a)

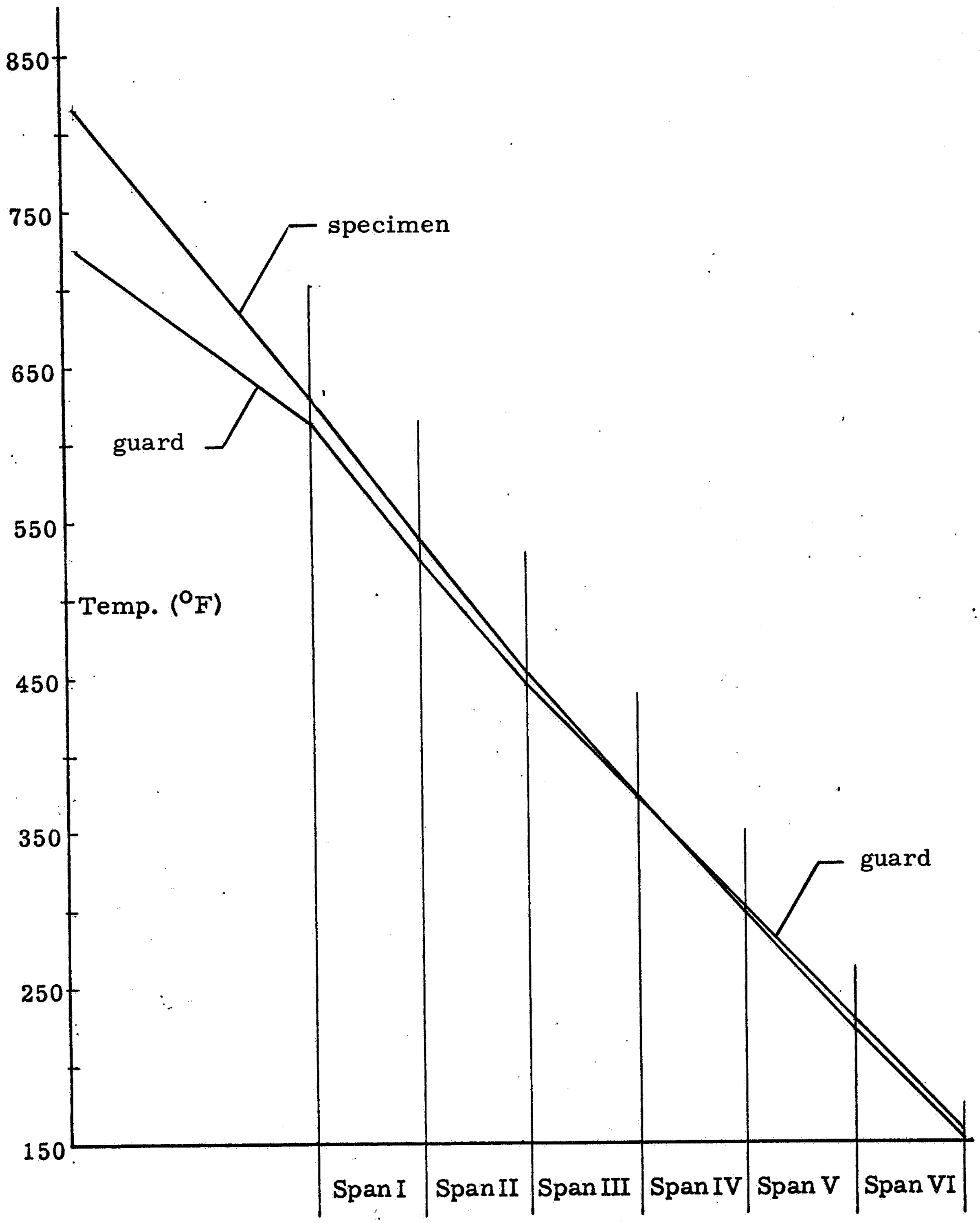


Table 14

Thermal Conductivity Values of 2024-T351 Aluminum from Experiment 6

Span No.	Specimen Mid-Span Temperature (^{o}F)		Thermal Conductivities (BTU/hr-ft-^{o}F)				
	Run (a)	Run (b)	W. & R. Method	Comparative Method	% Diff.	"No-Loss" Method	% Diff.
I	291.1	290.3	80.29	80.71	+0.5	82.31	+2.5
II	260.5	260.0	78.30	77.22	-1.4	79.39	+1.4
III	229.3	229.0	76.28	74.77	-2.0	77.65	+1.8
IV	197.4	197.4	74.30	73.56	-1.0	77.16	+3.8
V	164.8	165.0	72.41	70.69	-2.4	74.82	+3.3
VI	131.6	131.9	70.66	69.41	-1.8	73.93	+4.6

Figure 21

Temperatures, Experiment 6
2024-T351 Aluminum, Run (a)

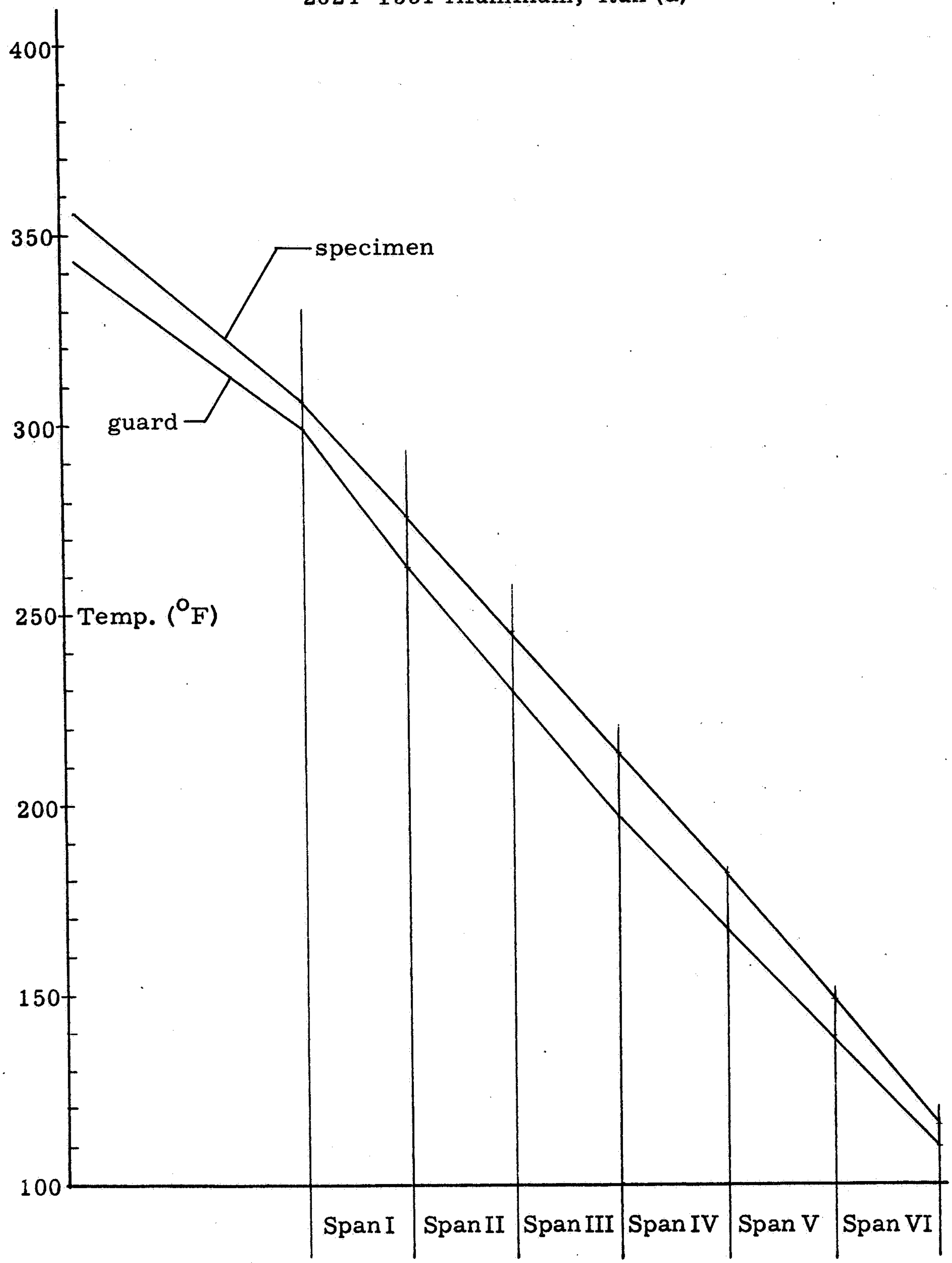


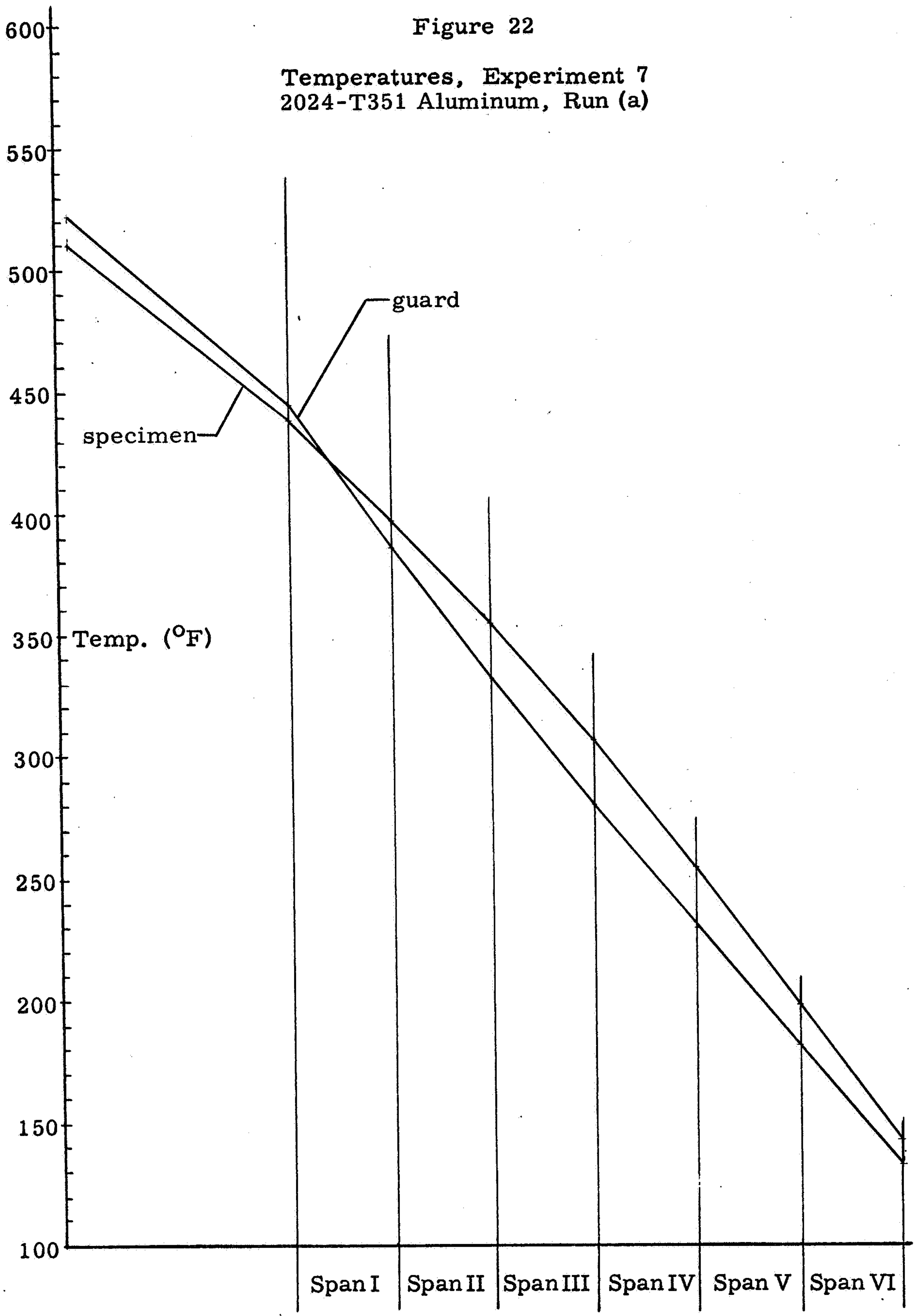
Table 15

Thermal Conductivity Values of 2024-T351 Aluminum from Experiment 7

Span No.	Specimen Mid-Span Temperature (^{O}F)		Thermal Conductivities (BTU/hr-ft-^{O}F)				
	Run (a)	Run (b)	W. & R. Method	Comparative Method	% Diff.	"No-Loss" Method	% Diff.
I	418.2	424.0	105.14	Not Used		103.47	-1.6
II	376.1	382.4	96.86			101.26	+4.5
III	330.2	336.8	89.45			89.56	+0.7
IV	280.8	287.1	82.73			80.43	-2.8
V	227.6	233.5	76.66			76.53	-0.2
VI	170.8	175.8	71.28			75.58	+6.0

Figure 22

Temperatures, Experiment 7
2024-T351 Aluminum, Run (a)



VI. CONCLUSIONS AND RECOMMENDATIONS

An evaluation has been conducted on the Watson and Robinson (2) apparatus and absolute method for determining thermal conductivities of metals.

In this investigation, specimen metals have been tested within a temperature range from 100°F to 650°F. The metals employed have nominal thermal conductivities ranging from 9 to 70 BTU/hr-ft-°F.

At least to the extent of these limits, the author concludes that the Watson and Robinson (2) method and apparatus can be applied to yield thermal conductivities accurate within four percent.

A comparative method for obtaining thermal conductivities was devised for this apparatus. The basis of this method is the calibration of the apparatus for heat losses. From the relatively few results obtained by this method, the predictable accuracy is within ten percent. It is believed that further experimentation would result in a more precise calibration and thus improve the accuracy obtainable by this method.

Another absolute method was applied to the experiments with generally favorable results. It has been conveniently named herein the "no-loss" method. The simple basis for this method is precise adjustment of specimen and guard heater power to minimize the temperature difference between specimen and guard; therefore, heat transfer at the cylindrical surface of the specimen becomes negligible. The application of this method to some chosen experiments proves its validity under properly controlled conditions. The author concludes that the "no-loss" method, in conjunction with the Watson and Robinson (2) apparatus, can be used to obtain k values accurate within two percent.

There is prospect that the basic apparatus could be employed in experiments to determine the thermal conductivity of granular or powdered materials. These would be substituted for the normal insulation in the annular space between the specimen and guard cylinder. Such experiments would require the use of a bar of known thermal conductivity and would also require that the apparatus be operated in a vacuum to eliminate convective heat transfer between the bar and guard.

APPENDIX A

Experimental Data

Experiment No. 1 Specimen material: AISI 316

Run (a)			Run (b)		
Date: September 18, 1966 Specimen htr. voltage = 10.4122 Specimen htr. amperage = 0.70311 Specimen htr. q = 24.986 BTU/hr Guard htr. voltage = 52.8 Water discharge temp. = 80.0°F			Date: September 19, 1966 Specimen htr. voltage = 10.6660 Specimen htr. amperage = 0.72022 Specimen htr. q = 26.218 BTU/hr Guard htr. voltage = 52.0 Water discharge temp. = 80.0°F		
T'couple	Millivolts	Temp. (°F) from tables	T'couple	Millivolts	Temp. (°F) from tables
1	12.3896	579.5	1	12.1950	571.2
2	12.2880	575.4	2	12.2922	575.6
3	10.3740	491.7	3	10.2171	484.9
4	10.1275	481.0	4	10.1074	480.0
5	8.8680	425.0	5	8.7385	419.0
6	8.9015	426.5	6	8.8738	425.2
7	7.4770	362.6	7	7.3739	357.7
8	7.6439	370.1	8	7.6148	368.7
9	6.1754	303.7	9	6.0934	300.2
10	6.3795	313.0	10	6.3574	311.9
11	4.8977	247.0	11	4.8365	244.2
12	5.0535	253.6	12	5.0393	253.0
13	3.6409	192.3	13	3.6047	190.7
14	3.6416	192.3	14	3.6401	192.3
15	2.3753	137.5	15	2.3685	137.2
16	2.1827	129.1	16	2.1985	130.0
17	11.4455	538.7	17	11.2672	530.8

Experiment No. 2 Specimen material: AISI 303MA

Run (a)			Run (b)		
Date: September 4, 1966 Specimen htr. voltage = 7.7500 Specimen htr. amperage = 0.52270 Specimen htr. q = 13.826 BTU/hr Guard htr. voltage = 33.2 Water discharge temp. = 80.7^{O}F			Date: September 4, 1966 Specimen htr. voltage = 7.7350 Specimen htr. amperage = 0.52080 Specimen htr. q = 13.820 BTU/hr Guard htr. voltage = 33.4 Water discharge temp. = 81.2^{O}F		
T'couple	Millivolts	Temp. (^{O}F) from tables	T'couple	Millivolts	Temp. (^{O}F) from tables
1	7.0566	343.5	1	7.1296	347.0
2	7.1025	345.5	2	7.1590	349.3
3	6.0050	296.0	3	6.0725	299.0
4	5.9550	294.0	4	6.0085	296.4
5	5.1846	259.5	5	5.2460	262.3
6	5.2606	263.0	6	5.3101	265.0
7	4.4163	225.7	7	4.4701	228.0
8	4.5510	231.5	8	4.5945	233.3
9	3.6995	195.0	9	3.7438	196.5
10	3.8390	201.0	10	3.8755	202.2
11	3.0212	165.5	11	3.0563	167.0
12	3.1221	170.0	12	3.1513	171.0
13	2.3774	137.6	13	2.4000	138.5
14	2.3932	138.0	14	2.4132	139.0
15	1.7395	110.0	15	1.7521	110.3
16	1.6452	105.7	16	1.6560	106.0
17	6.5650	321.2	17	6.6389	324.6

Experiment No. 3 Specimen material: AISI 303MA

Run (a)			Run (b)		
Date: September 6, 1966 Specimen htr. voltage = 11.1674 Specimen htr. amperage = 0.72000 Specimen htr. q = 27.442 BTU/hr Guard htr. voltage = 51.5 Water discharge temp. = 82.6^{o}F			Date: September 6, 1966 Specimen htr. voltage = 11.1045 Specimen htr. amperage = 0.71970 Specimen htr. q = 27.276 BTU/hr Guard htr. voltage = 52.7 Water discharge temp. = 82.8^{o}F		
T'couple	Millivolts	Temp. (^{o}F) from tables	T'couple	Millivolts	Temp. (^{o}F) from tables
1	12.3302	577.0	1	12.4860	583.8
2	12.4029	580.0	2	12.4434	582.1
3	10.3440	490.0	3	10.4494	582.3
4	10.2503	486.0	4	10.2538	486.2
5	8.8524	424.0	5	8.9291	427.6
6	8.9957	430.7	6	9.0010	431.0
7	7.4777	326.6	7	7.5310	365.0
8	7.7285	374.0	8	7.7298	374.0
9	6.1900	304.5	9	6.2270	306.2
10	6.4595	316.5	10	6.4575	316.4
11	4.9223	248.0	11	4.9464	248.9
12	5.1391	257.4	12	5.1351	257.3
13	3.6783	194.0	13	3.6887	194.4
14	3.7419	196.5	14	3.7321	196.1
15	2.4245	139.7	15	2.4190	139.4
16	2.2678	133.0	16	2.2495	132.0
17	11.3817	535.6	17	11.5138	541.7

Experiment No. 4

Specimen material: Armco iron

Run (a)			Run (b)		
Date: August 29, 1966 Specimen htr. voltage = 15.6000 Specimen htr. amperage = 1.1090 Specimen htr. q = 59.046 BTU/hr Guard htr. voltage = 35.8 Water discharge temp. = 81.0°F			Date: August 30, 1966 Specimen htr. voltage = 15.3456 Specimen htr. amperage = 1.0881 Specimen htr. q = 56.989 BTU/hr Guard htr. voltage = 35.1 Water discharge temp. = 81.0°F		
T'couple	Millivolts	Temp (°F) from tables	T'couple	Millivolts	Temp. (°F) from tables
1	7.7641	375.0	1	7.7230	373.5
2	7.9205	382.5	2	7.8367	379.0
3	6.5591	321.0	3	6.5432	320.3
4	6.4355	315.0	4	6.3920	313.5
5	5.6520	280.0	5	5.6401	279.6
6	5.6545	280.0	6	5.6164	278.7
7	4.7987	242.0	7	4.7870	242.0
8	4.8725	246.0	8	4.8395	244.3
9	4.0040	208.0	9	3.9890	207.3
10	4.1069	212.0	10	4.0766	211.0
11	3.2495	175.5	11	3.2336	174.6
12	3.3519	180.0	12	3.3266	178.8
13	2.5331	144.0	13	2.5160	143.8
14	2.6091	147.5	14	2.5866	146.8
15	1.8290	114.0	15	1.8082	113.0
16	1.8865	116.0	16	1.8665	115.3
17	7.2044	350.0	17	7.1726	348.6

Experiment No. 5 Specimen material: Armco iron

Run (a)			Run (b)		
Date: August 31, 1966 Specimen htr. Voltage = 21.6570 Specimen htr. amperage = 1.4700 Specimen htr. q = 108.656 BTU/hr Guard heater voltage = 54.0 Water discharge temp. = 81.5°F			Date: August 31, 1966 Specimen htr. voltage = 21.6000 Specimen htr. amperage =1.4650 Specimen htr. q = 108.001 BTU/hr Guard heater voltage = 54.5 Water discharge temp. = 81.7°F		
T'couple	Millivolts	Temp. (°F) from tables	T'couple	Millivolts	Temp. (°F) from tables
1	13.0080	606.0	1	13.0364	607.8
2	13.9851	648.7	2	13.9155	645.7
3	10.8637	513.0	3	10.8836	514.1
4	10.8383	512.0	4	10.8945	514.5
5	9.2804	443.3	5	9.3016	444.0
6	9.3217	445.0	6	9.3595	447.0
7	7.8198	378.0	7	7.8406	379.0
8	7.8721	380.0	8	7.8976	381.4
9	6.4585	316.4	9	6.4785	317.4
10	6.4997	318.5	10	6.5143	319.2
11	5.1250	256.7	11	5.1418	257.5
12	5.1418	257.5	12	5.1496	258.0
13	3.8135	199.7	13	3.8216	200.0
14	3.7899	198.6	14	3.7915	198.6
15	2.4876	142.4	15	2.4865	142.3
16	2.4768	141.8	16	2.4692	141.5
17	12.0119	563.0	17	12.0434	564.7

Experiment No. 6 Specimen material: 2024-T351 aluminum

Run (a)			Run (b)		
Date: September 11, 1966 Specimen htr. voltage = 22.6425 Specimen htr. amperage = 1.5121 Specimen htr. q = 116.853 BTU/hr Guard htr. Voltage = 35.3 Water discharge temp. = 81.2°F			Date: September 12, 1966 Specimen htr. voltage = 22.2495 Specimen htr. amperage = 1.4868 Specimen htr. q = 112.904 BTU/hr Guard htr. voltage = 36.2 Water discharge temp. = 81.3°F		
T'couple	Millivolts	Temp. (°F) from tables	T'couple	Millivolts	Temp. (°F) from tables
1	7.1145	346.0	1	7.4825	362.6
2	7.4014	359.0	2	7.3262	356.0
3	6.0590	298.5	3	6.3520	311.6
4	6.2530	307.0	4	6.2280	306.3
5	5.2414	262.0	5	5.4777	272.5
6	5.5675	276.0	6	5.5538	275.6
7	4.4685	228.0	7	4.6529	236.0
8	4.8595	245.0	8	4.8520	244.6
9	3.7420	196.5	9	3.8791	202.5
10	4.1248	213.0	10	4.1231	213.0
11	3.0501	167.0	11	3.1457	170.7
12	3.3891	181.5	12	3.3896	181.5
13	2.3968	138.3	13	2.4524	140.7
14	2.6306	148.5	14	2.6345	148.7
15	1.7526	110.6	15	1.7744	111.2
16	1.8625	115.0	16	1.8743	115.7
17	6.6323	324.3	17	6.9565	338.8

Experiment No. 7 Specimen material: 2024-T351 aluminum

Run (a)			Run (b)		
Date: September 14, 1966 Specimen htr. voltage = 29.7753 Specimen htr. amperage = 1.9852 Specimen htr. q = 201.742 BTU/hr Guard htr. voltage = 49.0 Water discharge temp. = 82.3°F			Date: September 15, 1966 Specimen htr. voltage = 29.7435 Specimen htr. Amperage = 1.9831 Specimen htr. q = 201.314 BTU/hr Guard htr. voltage = 51.0 Water discharge temp. = 82.3°F		
T'couple	Millivolts	Temp. (°F) from tables	T'couple	Millivolts	Temp. (°F) from tables
1	11.2142	528.5	1	11.8372	556.0
2	10.9460	516.7	2	11.0974	523.3
3	9.4258	449.7	3	9.9316	472.0
4	9.2789	443.3	4	9.4169	449.3
5	8.0855	389.7	5	8.5059	408.7
6	8.3357	401.0	6	8.4682	407.0
7	6.8479	334.2	7	7.1948	349.7
8	7.3734	357.6	8	7.4991	363.4
9	5.6738	281.0	9	5.9623	294.0
10	6.2775	308.2	10	6.4272	315.2
11	4.5186	230.2	11	4.7484	240.2
12	5.0602	254.0	12	5.2200	261.0
13	3.3893	181.5	13	3.5592	189.0
14	3.7836	198.4	14	3.9246	204.5
15	2.2520	132.0	15	2.3605	137.0
16	2.4870	142.3	16	2.5735	146.1
17	10.3679	491.3	17	10.9380	516.3

Experiment No. 8 Specimen material: Armco iron

Run (a)			Run (b)		
Date: October 2, 1966 Specimen htr. voltage = 15.6783 Specimen htr. amperage = 1.0565 Specimen htr. q = 56.533 BTU/hr Guard htr. voltage = 33.6 Water discharge temp. = 76.0°F			Date: October 3, 1966 Specimen htr. voltage = 15.8151 Specimen htr. amperage = 1.0658 Specimen htr. q = 57.529 BTU/hr Guard htr. voltage = 32.9 Water discharge temp. = 76.5°F		
T'couple	Millivolts	Temp. (°F) from tables	T'couple	Millivolts	Temp. (°F) from tables
1	6.3018	309.5	1	6.1645	303.2
2	6.8116	332.5	2	6.8416	334.0
3	5.3468	266.8	3	5.2379	261.9
4	5.5532	275.7	4	5.5757	276.7
5	4.6070	233.9	5	4.5219	230.3
6	4.8631	245.1	6	4.8875	246.3
7	3.9145	204.1	7	3.8539	201.4
8	4.1899	216.0	8	4.2141	217.1
9	3.2744	176.5	9	3.2333	174.7
10	3.5300	187.5	10	3.5556	188.7
11	2.6705	150.3	11	2.6491	149.4
12	2.8872	159.8	12	2.9155	160.8
13	2.0975	125.3	13	2.0951	125.2
14	2.2558	132.3	14	2.2862	133.8
15	1.5349	100.7	15	1.5500	101.5
16	1.6483	105.9	16	1.6808	107.0
17	5.8571	289.3	17	5.7395	284.3

Experiment No. 9

Specimen material: Armco iron

Run (a)			Run (b)		
Date: October 3, 1966 Specimen htr. voltage = 15.8151 Specimen htr. amperage = 1.0658 Specimen htr. q = 57.529 BTU/hr Guard htr. voltage = 32.9 Water discharge temp. = 76.5°F			Date: October 4, 1966 Specimen htr. voltage = 15.5205 Specimen htr. amperage = 1.0456 Specimen htr. q = 55.387 BTU/hr Guard htr. voltage = 34.4 Water discharge temp. = 76.2°F		
T'couple	Millivolts	Temp. (°F) from tables	T'couple	Millivolts	Temp. (°F) from tables
1	6.1645	303.2	1	6.5886	322.4
2	6.8416	334.0	2	6.8654	334.8
3	5.2379	261.9	3	5.5919	277.6
4	5.5757	276.7	4	5.6073	278.3
5	4.5219	230.3	5	4.8185	243.4
6	4.8875	246.3	6	4.9198	248.0
7	3.8539	201.4	7	4.0979	211.9
8	4.2141	217.1	8	4.2419	218.1
9	3.2333	174.7	9	3.4285	183.0
10	3.5556	188.7	10	3.5744	189.5
11	2.6491	149.4	11	2.7965	155.8
12	2.9155	160.8	12	2.9227	161.1
13	2.0951	125.2	13	2.1976	129.9
14	2.2862	133.8	14	2.2805	133.3
15	1.5500	101.5	15	1.6071	103.9
16	1.6808	107.0	16	1.6602	106.3
17	5.7395	284.3	17	6.1365	303.2

Experiment No. 10 Specimen material: Armco iron

Run (a)			Run (b)		
Date: October 4, 1966 Specimen htr. voltage = 20.5677 Specimen htr. amperage = 1.3758 Specimen htr. q = 96.578 BTU/hr Guard htr. voltage = 50.3 Water discharge temp. = 76.4°F			Date: October 5, 1966 Specimen htr. voltage = 20.7183 Specimen htr. amperage = 1.3852 Specimen htr. q = 97.950 BTU/hr Guard htr. voltage = 49.1 Water discharge temp. = 76.5°F		
T'couple	Millivolts	Temp. (°F) from tables	T'couple	Millivolts	Temp. (°F) from tables
1	11.5082	541.4	1	11.1668	526.3
2	11.9248	559.5	2	11.8505	556.3
3	9.6216	458.6	3	9.3535	446.7
4	9.4224	449.6	4	9.3580	446.9
5	8.2131	395.6	5	7.9988	386.0
6	8.1311	392.0	6	8.0782	389.4
7	6.9151	337.2	7	6.7489	329.6
8	6.8929	336.1	8	6.8559	334.5
9	5.6892	282.0	9	5.5612	276.0
10	5.6825	281.6	10	5.6604	280.5
11	4.4896	229.0	11	4.4030	225.0
12	4.4808	228.5	12	4.4760	228.3
13	3.3234	178.7	13	3.2785	176.6
14	3.2892	177.0	14	3.3041	177.7
15	2.1594	128.0	15	2.1575	127.9
16	2.1492	127.6	16	2.1795	129.0
17	10.6252	502.7	17	10.3297	489.6

Experiment No. 11 Specimen material: Armco iron

Run (a)			Run (b)		
Date: October 5, 1966 Specimen htr. voltage = 20.7183 Specimen htr. amperage = 1.3852 Specimen htr. q = 97.950 BTU/hr Guard htr. voltage = 49.1 Water discharge temp. = 76.5 ^{O}F			Date: October 6, 1966 Specimen htr. voltage = 20.7930 Specimen htr. amperage = 1.3898 Specimen htr. q = 98.629 BTU/hr Guard htr. voltage = 48.0 Water discharge temp. = 76.2 ^{O}F		
T'couple	Millivolts	Temp. (^{O}F) from tables	T'couple	Millivolts	Temp. (^{O}F) from tables
1	11.1668	526.3	1	10.9086	515.0
2	11.8505	556.3	2	11.7648	552.5
3	9.3535	446.7	3	9.1415	437.1
4	9.3580	446.9	4	9.2802	443.3
5	7.9988	386.0	5	7.8216	378.1
6	8.0782	389.4	6	8.0066	386.3
7	6.7489	329.6	7	6.5992	323.0
8	6.8559	334.5	8	6.7890	331.4
9	5.5612	276.0	9	5.4332	270.7
10	5.6604	280.5	10	5.6011	278.0
11	4.4030	225.0	11	4.2965	220.5
12	4.4760	228.3	12	4.4228	226.1
13	3.2785	176.6	13	3.1963	173.2
14	3.3041	177.7	14	3.2595	176.0
15	2.1575	127.9	15	2.0984	125.4
16	2.1795	129.0	16	2.1450	127.5
17	10.3297	489.6	17	10.0865	478.9

Experiment 12

Specimen material; Armco iron

Run (a)			Run (b)		
Date: October 7, 1966 Specimen htr. voltage = 25.1235 Specimen htr. amperage = 1.6962 Specimen htr. q = 145.443 BTU/hr Guard htr. voltage = 65.0 Water discharge temp. = 76.2°F			Date: October 8, 1966 Specimen htr. voltage = 25.2300 Specimen htr. amperage = 1.7012 Specimen htr. q = 146.490 BTU/hr Guard htr. voltage = 62.5 Water discharge temp. = 76.2°F		
T'couple	Millivolts	Temp. (°F) from tables	T'couple	Millivolts	Temp. (°F) from tables
1	16.9440	775.2	1	15.9336	732.2
2	18.4620	839.6	2	17.9450	817.7
3	14.1202	654.5	3	13.2965	618.9
4	14.0980	653.4	4	13.6925	636.1
5	11.9916	562.3	5	11.3100	532.6
6	11.9290	559.6	6	11.5818	544.6
7	10.0250	476.2	7	9.4714	451.6
8	9.9015	470.6	8	9.6164	458.3
9	8.1975	394.9	9	7.7580	375.2
10	8.0192	387.0	10	7.7955	376.7
11	6.4565	316.3	11	6.1188	301.4
12	6.2460	306.9	12	6.0765	299.3
13	4.7171	238.8	13	4.4716	228.1
14	4.4771	228.3	14	4.3585	223.3
15	2.9084	160.6	15	2.7705	154.6
16	2.7687	154.6	16	2.7039	151.7
17	15.6456	719.8	17	14.7230	680.4

Experiment No. 13 Specimen material: Armco iron

Run (a)			Run (b)		
Date: October 8, 1966 Specimen htr. voltage = 25.2300 Specimen htr. amperage = 1.7012 Specimen htr. q = 146.490 BTU/hr Guard htr. voltage = 62.5 Water discharge temp. = 76.2^{o}F			Date: October 9, 1966 Specimen htr. voltage = 25.4106 Specimen htr. amperage = 1.7110 Specimen htr. q = 148.389 BTU/hr Guard heater voltage = 60.0 Water discharge temp. = 76.8^{o}F		
T'couple	Millivolts	Temp. (^{o}F) from tables	T'couple	Millivolts	Temp. (^{o}F) from tables
1	15.9336	732.2	1	14.9038	688.2
2	17.9450	817.7	2	17.4810	798.0
3	13.2965	618.9	3	12.4645	582.8
4	13.6925	636.1	4	13.3278	620.4
5	11.3100	532.6	5	10.6289	502.9
6	11.5818	544.6	6	11.2756	531.3
7	9.4714	451.6	7	8.9294	427.6
8	9.6164	458.3	8	9.3755	447.5
9	7.7580	375.2	9	7.3410	356.5
10	7.7955	376.7	10	7.6165	368.8
11	6.1188	301.4	11	5.8049	287.2
12	6.0765	299.3	12	5.9486	293.6
13	4.4716	228.1	13	4.2609	219.0
14	4.3585	223.3	14	4.2865	220.2
15	2.7705	154.6	15	2.6795	150.6
16	2.7039	151.7	16	2.6875	150.9
17	14.7230	680.4	17	13.7915	640.3

APPENDIX B

Thermocouple Calibration

The thermocouples used in this apparatus are made by butt welding number 24 AWG chromel and alumel wires.

A reference thermocouple was obtained which had been calibrated against a secondary standard maintained at the Minneapolis-Honeywell Laboratory.

The apparatus thermocouples and the calibrated reference thermocouple were assembled onto a 3/16 inch threaded rod. Each thermocouple was held between a pair of 3/16 inch flat washers by means of locknuts. This assembly was then placed in a temperature-controlled oven.

The oven temperature was stabilized at temperatures of 200°, 300°, 400°, 500°, and $700^{\circ}F$. After each stabilization, the millivolt output was recorded for each thermocouple, including the reference thermocouple.

For each of these five settings, the true temperature was regarded as that corresponding to the reference thermocouple millivolt reading, after applying a correction to the reference based upon its own calibration curve. Thus, each apparatus thermocouple registers its particular millivolt output corresponding to the reference thermocouple temperature.

The method of least-squares was applied to the millivolt readings and temperatures of the reference. The same method was then applied to each apparatus thermocouple to fit its millivolt readings to the reference thermocouple curve. Thus, a relationship was obtained for each thermocouple of the form:

$$t = C_1 + C_2 (mv) + C_3 (mv)^2$$

These coefficients are provided as data for the computer solution of thermal conductivity by the Watson and Robinson (2) method.

APPENDIX C

Operations Plan For Computer Calculation Of Thermal Conductivity Using Method Of Watson and Robinson (2)

1 Read and store thermocouple data (millivolts) and locations (inches) for specimen and guard in run (a) and run (b).

2 Read specimen number, experiment number, date, and heater power for run (a) and heater power for run (b).

3 Read calibration coefficients of temperature-versus-millivolts for each thermocouple.

4 Calculate temperatures from:

$$t = C_1 + C_2\,(mv) + C_3\,(mv)^2$$

for specimen and guard, runs (a) and (b).

5 Print specimen number, experiment number, date, and heater power for runs (a) and (b).

6 Print temperature for each thermocouple.

7 Call least-square sub-routine to develop constants for:

$$t = A + Bx + Cx^2$$

for specimen and guard for runs (a) and (b).

8 Calculate S for each run for heater segment of specimen.

9 Find temperature at mid-span of each segment from Step 7.

10 Calculate temperatue gradient from the t-versus-x equation at mid-span of each segment.

11 Calculate S for both runs at each span.

12 Calculate k and f for each span.

13 Use least-square sub-routine to find constants for:

$$k = f\,(t)$$

for linear and quadratic relationships.

14 Print Equations.

APPENDIX D

Cost of Apparatus

The costs of the basic thermal conductivity measuring apparatus, the required supporting equipment, and the recurring costs are as follows:

Thermal Conductivity Apparatus

Quantity	Description	Amount
1	Outer Container	$38.00
1	Guard Cylinder	390.00
1	Trivet	20.00
1	Top Plate	18.00
1	Guard Heater	42.00
1	Specimen Heater	25.00
-	Miscellaneous Hardware	10.00
-	Thermocouples	18.00
		$561.00

Support Equipment

Quantity	Description	Amount
1	D. C. Power Supply	$50.00
1	Potentiometer, Honeywell Model 2780	648.00
1	Galvonometer, Honeywell Model 3431	190.00
1	Constant-Current Power Supply for Potentiometer, Honeywell Model 2798-1	190.00
1	Constant-Voltage Transformer, 2 kva	300.00
2	Variacs, 1 kva @ $26.00	52.00
1	Resistor, 0.1 Ohm, Honeywell Model 1162	65.00
1	Voltage Divider, Honeywell Model 2795	239.00
		$1734.00

Recurring Items per Experiment

Quantity	Description	Amount
1	Thermal Conductivity Specimen	$20.00
-	Thermocouple Replacements	2.00
-	Insulation	1.00
		$23.00

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