Evaluation of the

AN INVESTIGATION OF A PARTICULAR COMPARATIVE METHOD OF SPECIFIC HEAT DETERMINATION IN THE TEMPERATURE RANGE OF 1500°F to 2600°F

By

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AN INVESTIGATION OF A PARTICULAR COMPARATIVE METHOD OF SPECIFIC HEAT DETERMINATION IN THE TEMPERATURE RANGE OF 1500°F to 2600°F

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CHAPTER I

INTRODUCTION

Contemporary technology demands physical property information for many new materials. These materials are frequently metallic or non-metallic solids. When these materials are to be used in any instance in which temperature distribution or energy balances are important, the thermophysical properties are required. One of these required properties is the heat capacity or specific heat capacity.

The users of newly developed metallic or non-metallic solids must often wait for months or years before values of the heat capacity can be obtained from laboratory measurements. Such precise laboratory measurements require highly skilled technicians and considerable time. This investigation was directed towards evaluation and improvement of a particular comparative method of measuring specific heat which is less precise but adequate for most engineering use.

Presently, the most widely accepted method of measuring the heat capacity of solids in the high temperature region is the so-called "drop method." (1). This procedure involves the measurement of the internal energy of a small sample of the solid. The sample is heated to some temperature above an arbitrary datum temperature (usually 32°F) in a furnace and then dropped into an adiabatic calorimetric enclosure. The energy is then determined by measurement of the energy increase of

the calorimeter. One of the most reliable calorimeters in present use is the Bunsen ice calorimeter. (2). This calorimeter is widely accepted as the most precise of the present-day calorimetric apparatus. Other calorimeters used are the copper block type and various mixing types. The difficulty involved in the operation of these types of apparatus is the measurement of the energy that is lost to the surroundings or absorbed by the calorimetric apparatus. In every case, the operation of the calorimeter and the evaluation of the results require highly skilled operators. Another inherent difficulty in the normal calorimetric methods is the time involved. In order to obtain the heat capacity of a sample over a range of temperatures, the apparatus must be used at numerous temperature levels. Each time a measurement is to be obtained, the sample must be brought to some well established temperature in a furnace and the entire system must be brought to thermal equilibrium. Such experimental procedures necessarily involve considerable time.

In this report the method of comparative calorimetry was examined as follows:

1. Previous work in the general field (to bring the reader up to date on the method)
2. A discussion of the theory upon which this investigation was based
3. Discussion of the experimental apparatus developed
4. Discussion of the experimental technique
5. Presentation of the results

6. Discussion of the results and conclusions with recommendations to those who would use the method

CHAPTER II

PREVIOUS INVESTIGATIONS OF FURNACE CALORIMETRY

Comparative calorimetry or furnace calorimetry has been of interest during the past century. The interest is a result of the rapidity with which the heat capacity of a substance can be obtained using comparative calorimetric methods. The original attempts to use furnace calorimetry were directed toward the use of two identical calorimeters. (1). The difficulty of constructing two identical calorimeters prompted the development of the comparative method using a single calorimeter. The most promising approach to furnace calorimetry was described by C. S. Smith. (3). It is Smith's basic method which was used in this investigation. Smith describes his new method as follows:

> "Briefly, the new method consists in placing the specimen with its thermocouple in a refractory container of low thermal conductivity and placing this in a furnace, the temperature of which is maintained a constant amount above or below the specimen temperature."

A little further in his report he says:

> "Alternately a differential couple may be used, independent of the specimen couple, with one junction inside and another outside the container."

Figure 1 represents the crucible and thermocouple arrangement described by Smith. Differential thermocouples located in the wall of the crucible were used to control the temperature of the furnace.

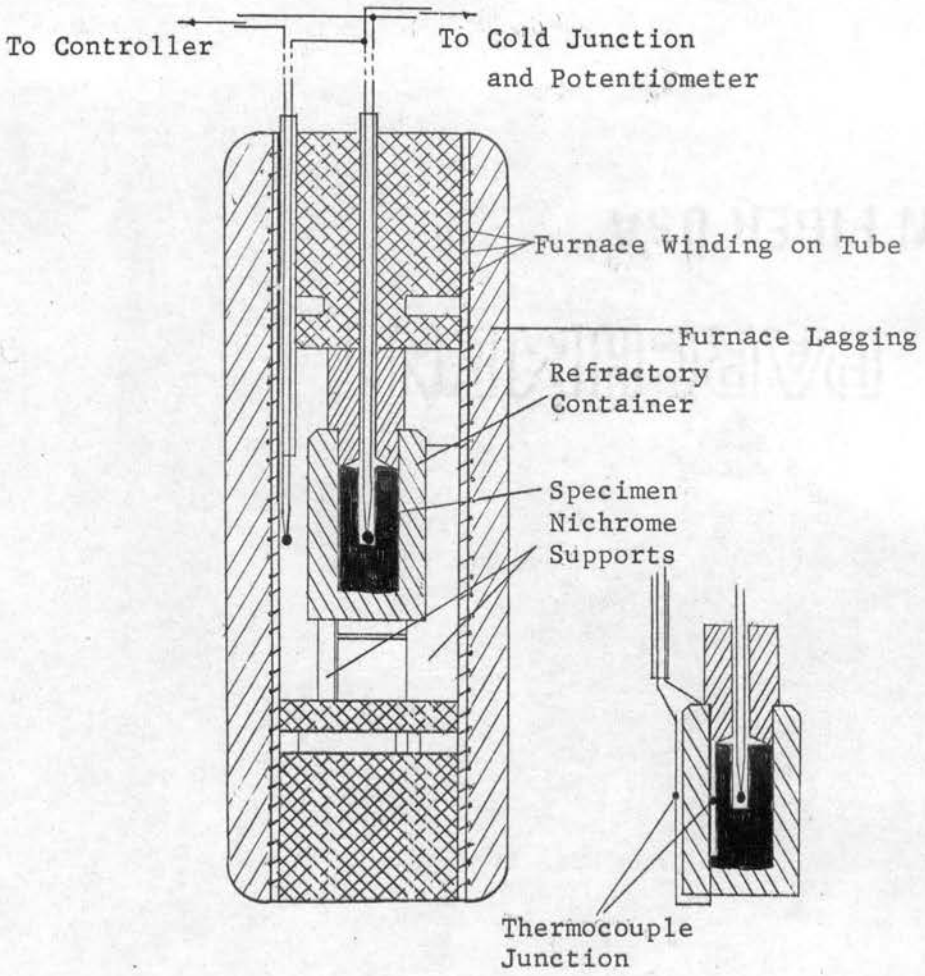
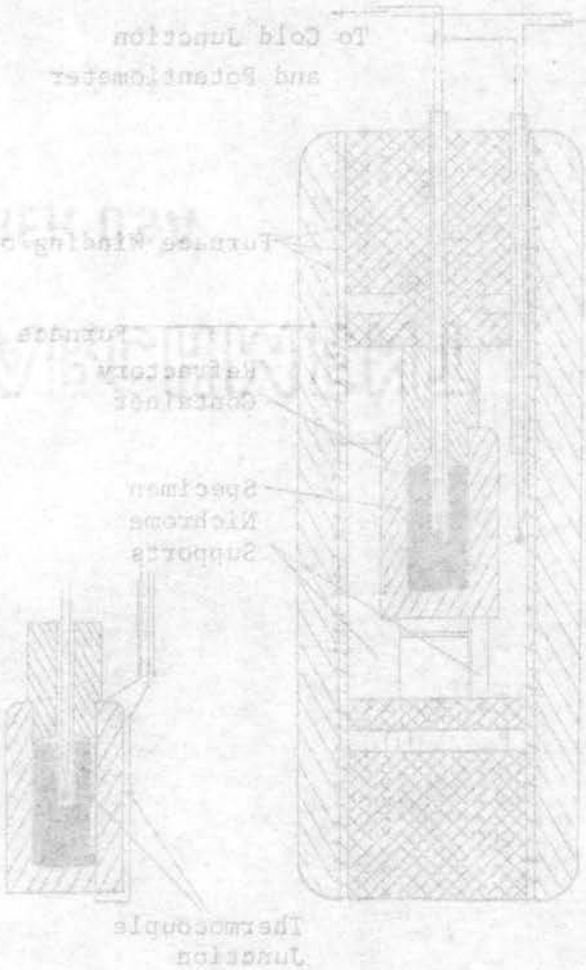


Figure 1. Smith's Furnace and Crucible

According to Smith, the constant temperature difference which was maintained across the crucible wall could be interpreted as indicating a constant energy flow into the crucible. This interpretation was based on the assumption that the constant temperature difference resulted in a constant temperature gradient on the entire outer surface of the crucible. With this assumption, analysis consisted of accounting for the energy flow into the exterior surface of the crucible. The energy would be absorbed in the crucible or the specimen contained. This is represented by the following equation:



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$$q = m_s c_s \frac{\Delta t}{\Delta \theta} + m_c c_c \frac{\Delta t}{\Delta \theta} \qquad \text{(II-1)}$$

where q = the energy flow rate through the outer surface in any convenient units

m_s = the mass of the sample

m_c = the effective mass of the crucible

c_c = the effective specific heat of the crucible

c_s = the specific heat of the sample

$\frac{\Delta t}{\Delta \theta}$ = the heating rate

It was then assumed that the unknown quantities in equation (II-1) could be determined by experimental heating runs in which the emf produced by the differentially connected thermocouples was maintained constant. In order to evaluate q and $m_c c_c$ the crucible was first operated as indicated with a specimen of well-known specific heat and then a second time with the crucible empty. From the measured heating rates obtained, q and $m_c c_c$ were evaluated over the temperature range of interest. Once these quantities were known, a specimen with unknown specific heat was placed in the crucible, and from the heating rate obtained, the specific heat was evaluated using equation (II-1). Smith applied this method to determine the specific heat of brass using copper as a standard material. This measurement was very successful in the temperature range of 100°F to 900°F.

The results of this work encouraged J. P. Rea (4) to do further work in this area. The results of Rea's work, while not conclusive, indicated that the method held promise as a rapid method of measuring

specific heat at higher temperatures. In his further evaluation of Smith's work, Rea used different materials but used the same general method of evaluation.

G. C. Beakley (5) attempted to use the method to determine the specific heat at higher temperatures. In his attempt to use the method of analysis indicated by Smith, Beakley encountered difficulty. It was evident from his work that use of the heating run with an empty crucible for evaluation of the constants in equation (II-1) was not correct at higher temperatures. This was attributed to the radiation effects which were more noticeable at higher temperature. His report indicated a method of avoiding the difficulty by using two materials with known properties. Basically, equation (II-1) was used twice with the value $m_s c_s$ being a known quantity. With the measured heating rates obtained using two standards, he evaluated the two unknown quantities $m_c c_c$ and q by simultaneous solution of the two equations resulting. By using this modification of the original theory, Beakley was able to measure the specific heat of several materials with fair accuracy up to a temperature of 1800°F. Any attempt to proceed beyond this temperature was precluded by the temperature limits of the materials in his apparatus and by the unexplained effect of the value $m_c c_c$ becoming negative at higher temperatures.

Recently, a comprehensive study of high temperature furnace calorimetry was initiated under the sponsorship of the United States Atomic Energy Commission. Initial work on the project was reported by M. E. Schlapbach. (6). His thesis reported the design of a vacuum

furnace system for use in comparative calorimetry. A vacuum system is well suited for high temperature measurements because (a) energy loss from a vacuum enclosure is small; (b) vacuum furnaces have a small heated mass which reduces the furnace control problem; and (c) the furnace atmosphere in a vacuum furnace is compatible to many materials at high temperatures. Schlapbach's work also included investigation of the effect of various heating rates on the accuracy of measurements. Results of this investigation were not conclusive, but the furnace system was found to be well suited for comparative calorimetry. Subsequently, R. A. Knezek (7) investigated the use of a suitable coating material for the samples. The original work by Smith indicated the desirability of having surfaces of nearly equal emissivity for the samples and standard materials. Because of the interest in using Smith's method in the higher temperature region a special coating material was required. This coating material was developed and tested in Knezek's experimental work. Knezek also reported a furnace design suitable for comparative calorimetry use at temperatures up to 3000°F.

CHAPTER III

THEORY OF COMPARATIVE CALORIMETRY

Since each of the previous investigators of this method of comparative calorimetry experienced difficulty, a different method was sought. A numerical solution using the IBM 650 computer was made in order to determine a mathematical model for the physical system. The computer study indicated that the following assumptions for the model were valid:

1. Infinite geometry applied would be valid if the control thermocouples were located on the vertical center line of the crucible
2. The physical properties were constant over a limited temperature range
3. A linear heating rate for the outer surface of the crucible

In the general case, an infinitely long hollow tube which is subjected to transient heating will have a temperature distribution which is described by the following expression when the physical properties are constant. (18).

$$\alpha \left(\frac{\partial^2 t}{\partial r^2} + \frac{1}{r} \frac{\partial t}{\partial r} \right) = \frac{\partial t}{\partial \theta} \qquad \text{(III-1)}$$

Williamson and Adams (8) report that a tube with a constant linear heating rate of the outer surface will have its temperature distribution described by the following equation after the initial transient effect has subsided.

$$\alpha\left(\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r}\right) = \frac{\partial t}{\partial \theta} = h = \text{a constant} \qquad \text{(III-2)}$$

The solution of equation (III-2) is given by Williamson and Adams as

$$t = h\theta + \frac{r^2 h}{4\alpha} + C_1 \ln r + C_2$$

The constants in this solution may be evaluated (see Appendix A) resulting in

$$t = h\theta + \frac{h}{4\alpha}(r^2 + r_o^2) + (r_i \phi - \frac{r_i^2 h}{2\alpha}) \ln \frac{r}{r_o} \qquad \text{(III-3)}$$

where t = temperature at any radial distance

r = radial distance

r_i = inner radius

r_o = outer radius

θ = time

α = thermal diffusivity

$\phi = \left(\frac{dt}{dr}\right)_{r = r_i}$

h = heating rate of the outer surface, a constant

In the crucible described, the thermal emf generated by the outer wall thermocouple is maintained a constant amount above the emf produced by the inner wall thermocouple. If the thermocouple material used has a constant thermoelectric power at all temperatures, the

differential emf will represent a constant temperature difference at all temperatures. Most thermocouple materials do not have this characteristic, but the variations from a constant value are continuous and of rather small magnitude. For this reason, the temperature difference between the two thermocouple locations can be assumed constant if a small temperature range is considered. If equation (III-3) is solved for the temperature at the two thermocouple locations r_a and r_b, the difference between the two quantities obtained will be a constant. Equation (9) of Appendix A results from this solution and may be transformed into the following simple equation if the energy flow from the inner wall into the sample is used to replace the quantity $\emptyset$.

$$C = MR - N \qquad \text{(III-4)}$$

where C = the heat capacity of the sample in energy per unit mass

R = the inverse of the heating rate h

M and N = constants dependent on the locations of the thermocouple elements, temperature difference, and the physical properties of the crucible

A simplified interpretation of the meaning of this solution is shown in Figure 2. The three samples shown in the figure would have continuously increasing heat capacity as the value of R increases. Actually, the plot of R versus t represents the heat capacity of any given sample multiplied by some constant at each temperature level. Thus, the determination of the heat capacity is reduced to the determination of a multiplier for the experimentally determined value of R at each temperature of interest.

Determination of this multiplier is easily accomplished as shown in Figure 3. In this figure, points 1, 2, and 3 are the values of R obtained from Figure 2 at any given temperature. Now, if the heat capacity of samples 1 and 3 are known at the temperature in question, the points 1 and 3 may be located. Examination of equation (III-4) indicates that the heat capacity C is a linear function of R; therefore, the determination of the heat capacity of sample 2 from the measured value of R is accomplished by linear interpolation of the measured values of R and the known heat capacity for the other two samples. It may be noted that the units for R and C are completely arbitrary in this procedure and only need to be consistent in any individual calculation of heat capacity.

The previous discussion assumes quasi-steady heating or cooling of the crucible and sample. In the physical arrangement which must be used, the crucible and sample cannot be in perfect thermal contact at the sample surface. For this reason, the temperature distribution at any given time will be similar to that shown in Figure 4. The temperature distribution necessarily has the discontinuity at the sample-crucible interface since the energy transfer at this location is accomplished by radiation. If the system is to operate with comparable results, the emissivity of the sample surface must be approximately constant from specimen to specimen. (7). This requires that each sample be coated with the same material.

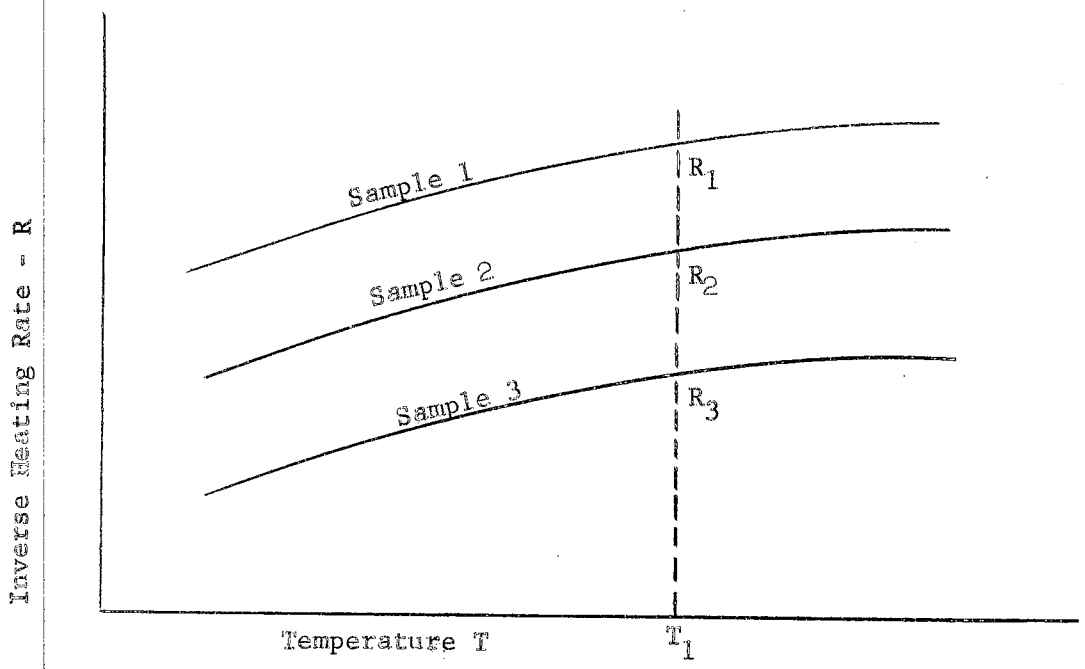


Figure 2. Inverse Heating Rate versus Temperature

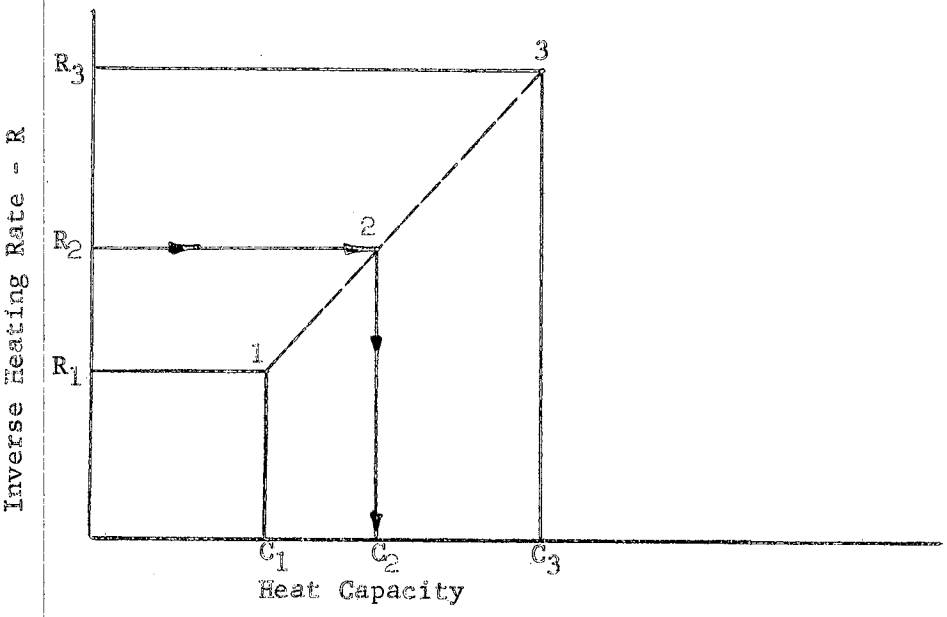


Figure 3. Inverse Heating Rate versus Heat Capacity

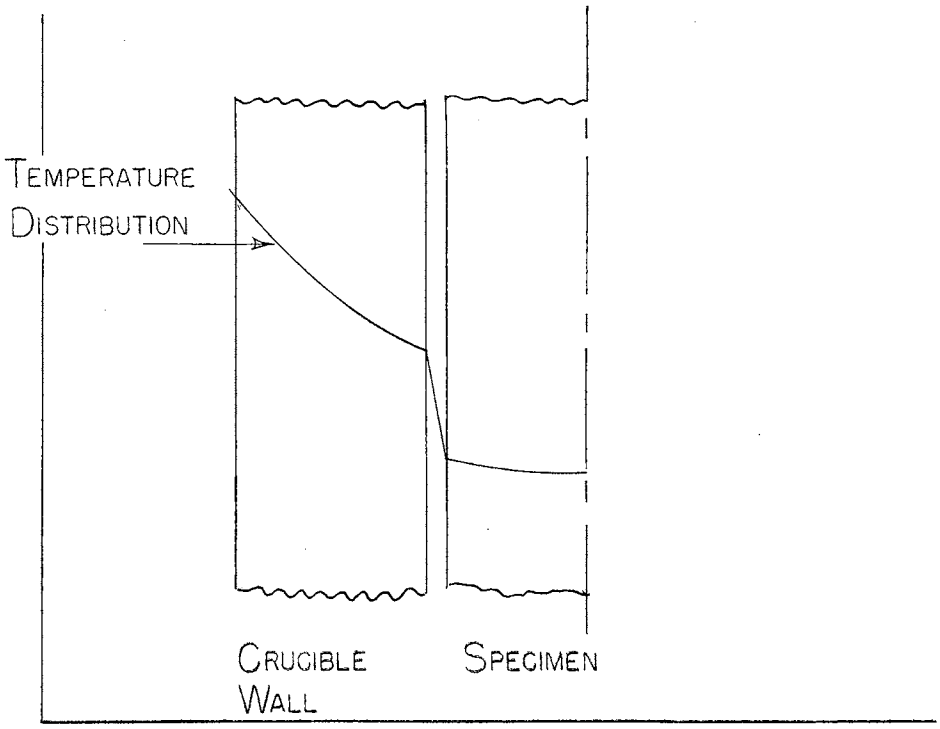


Figure 4. Temperature Distribution in the Crucible and Specimen

CHAPTER IV

EXPERIMENTAL APPARATUS

The experimental apparatus required for this investigation was made up of five separate items: (a) the crucible, (b) the samples and central sample thermocouple, (c) the vacuum furnace system, (d) the control system, and (e) the temperature measuring apparatus.

Each of these elements is briefly described in the following sections.

A. The Crucible

The crucible, according to the theory developed, should have been an infinitely long tube of low thermal conductivity material which contained an infinitely long cylinder of the specimen material. In order to approximate this with finite geometry, the crucible was given a length to diameter ratio of approximately four. With this relatively short crucible the only section which would act as though it had infinite geometry was the section at the exact center of the heated zone. For this reason, the differential thermocouples used for control purposes were located as nearly as possible in the center section.

Previous investigators had used lightweight insulating firebrick for the crucible material. In this investigation, several of the insulating firebrick available commercially were tried. These materials, although rated as being useful at high temperatures, were not satisfactory

for the crucible material. In every case the materials exhibited poor dimensional stability when subjected to temperatures above 2500°F. The material used in the final crucible was a commercial castable cement, Norton Company 33-I, which is primarily alumina bubblets. This material was passed through a wire screen of approximately 1/8-inch mesh in order to remove any large particles. Several test heating runs for this material indicated it was dimensionally stable up to temperatures of 3000°F.

The crucible was cast into the form shown in Figure 5 and Plate I. A supporting base for the crucible was machined out of Armstrong A-28 insulating firebrick. This supporting base served to center the crucible in the furnace as well as to support the crucible in an upright position.

Initial operation of the system with the crucible as shown in Plate I indicated the need for a shield between the crucible and the furnace element. This was predicated on the observation that the molybdenum heater operating in the high vacuum of the furnace was plating the outer surface of the crucible with molybdenum. The molybdenum evidently migrated into the crucible by molecular diffusion and subsequently contaminated the thermocouple wire cast into the crucible. In order to eliminate this difficulty, a non-porous ceramic tube was installed around the crucible as shown in Plate II. This ceramic tube was a 96% alumina protection tube 1 3/4-in. inside diameter, 2-in. outside diameter, supplied by the McDanel Refractory Porcelain Company.

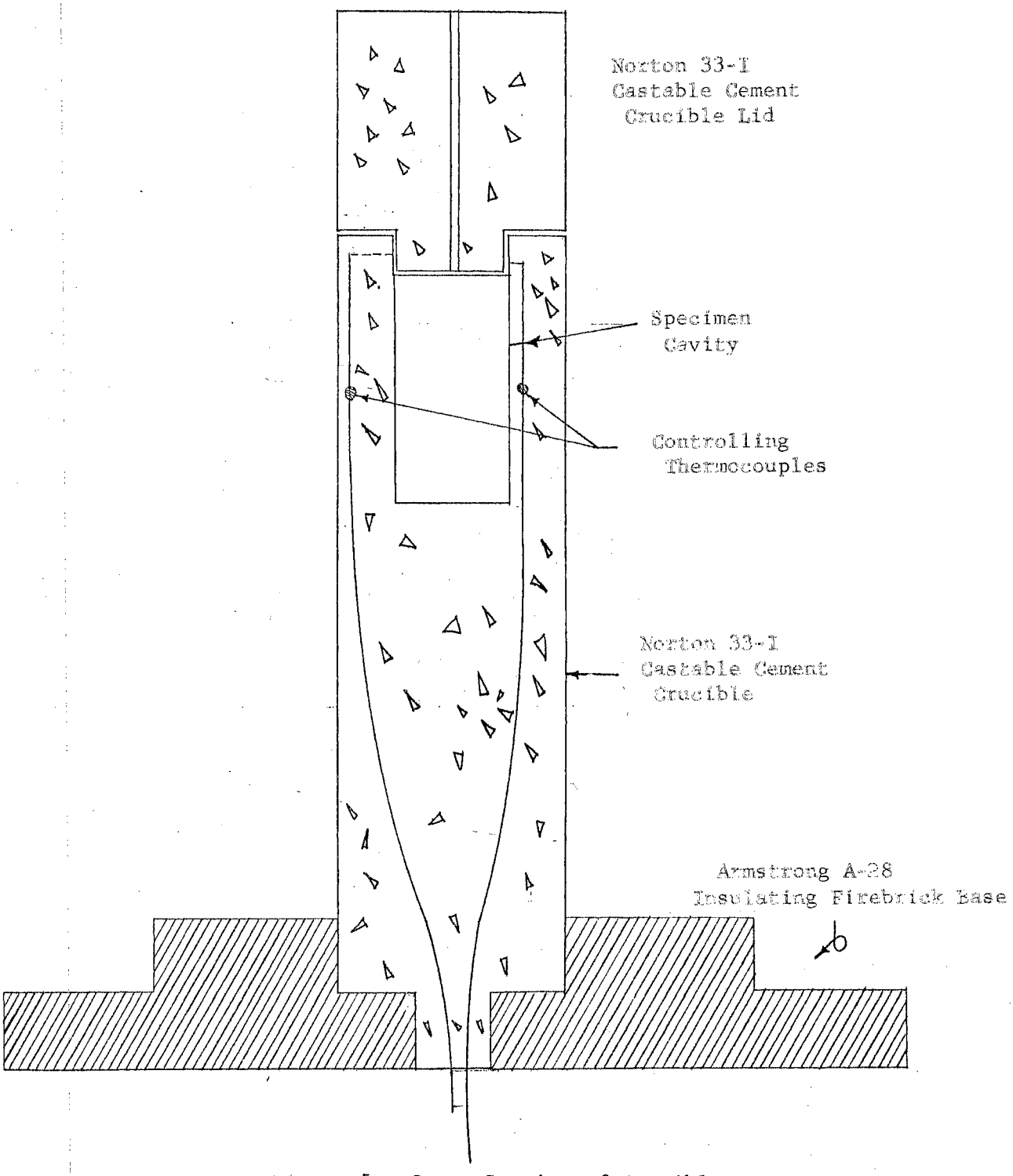


Figure 5. Cross Section of Crucible

PLATE I

CRUCIBLE WITHOUT CERAMIC SHIELD

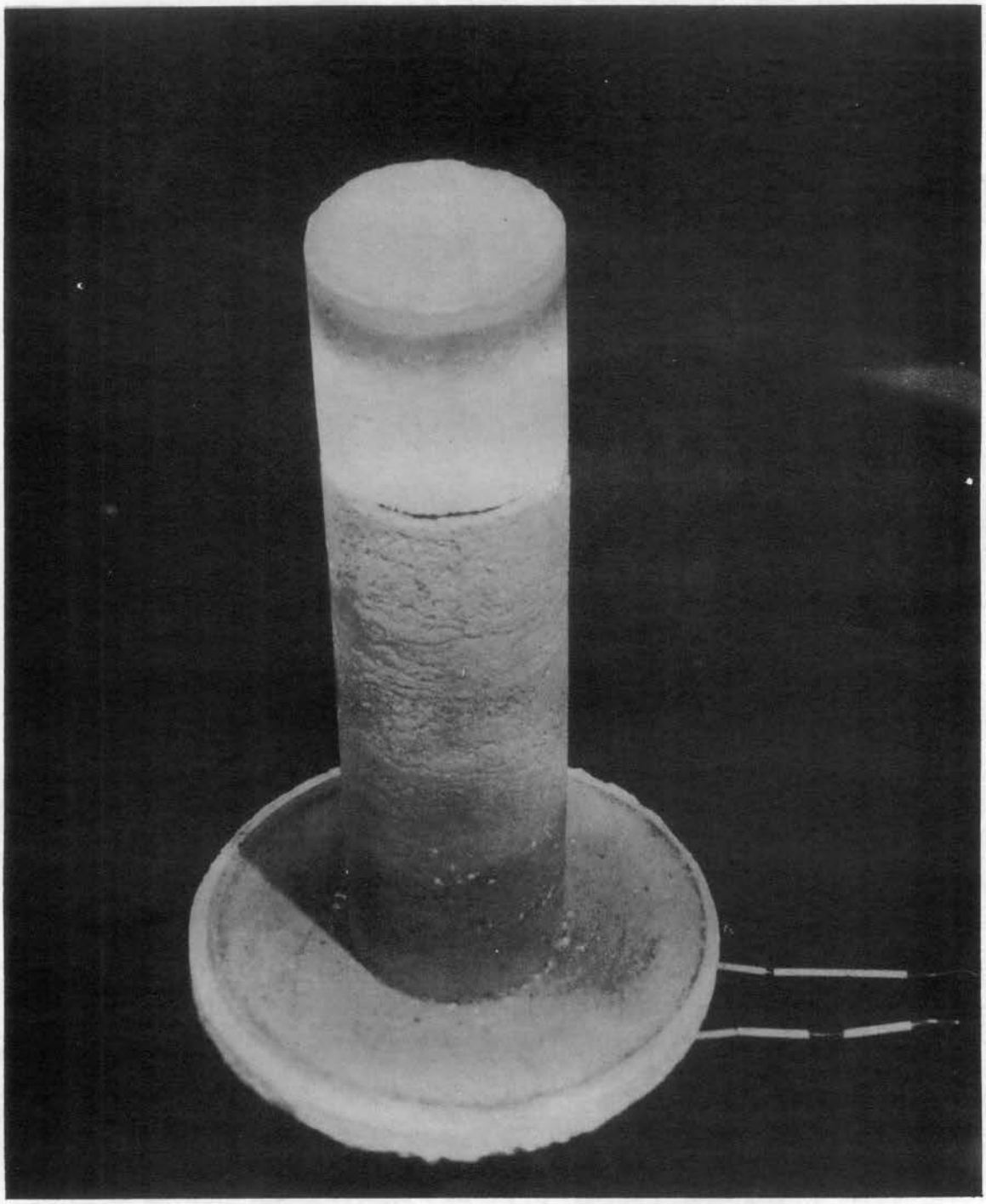
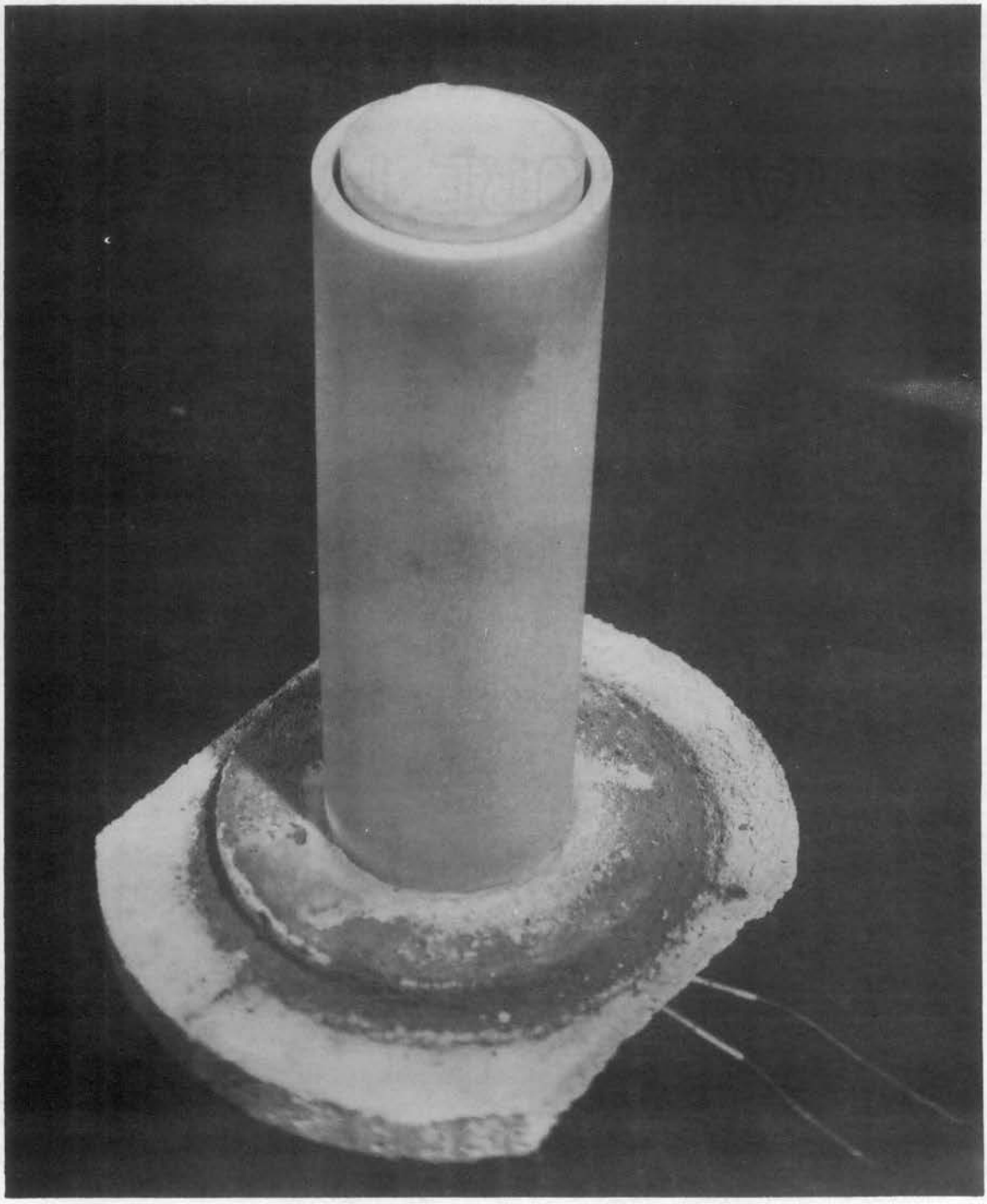


PLATE I

CHROMIUM WITHOUT CERAMIC SHIELD

PLATE II

CRUCIBLE WITH CERAMIC SHIELD



The control thermocouples were made of 24 gage platinum and platinum + 10% rhodium thermocouple wire supplied by the Leeds and Northrup Company. Eight individual thermocouples were made by butt welding. The thermocouples were connected differentially and placed in the crucible as shown in Figures 5 and 6. When casting these thermocouples in the crucible, care was taken to locate the junctions as close to the central plane as possible. It was not possible to install these thermocouples exactly in the central plane nor to have each of the thermocouples exactly spaced in the crucible. This should not have affected the operation of the thermocouples as control elements, since each of the thermocouple junctions reacted to its own surroundings and, therefore, reacted in a manner which maintained the constant temperature distribution required by the theory.

B. The Samples and Central Sample Thermocouple

The samples used in this investigation were cylinders 3/4-in. in diameter and 1 1/2-in. long. Each sample had a 1/16-in. hole drilled axially 3/4-in. deep to receive the central sample thermocouple. Two typical samples are shown in Plate III. These samples are tantalum and molybdenum. One of the samples is uncoated and the other is coated with the magnesium oxide coating developed by Knezek. (7).

A central temperature measuring thermocouple was required for use in the system. The thermocouple was constructed of 28 gage platinum and platinum + 10% rhodium thermocouple wire. This thermocouple wire was threaded through a 1/16-in. double bore insulating

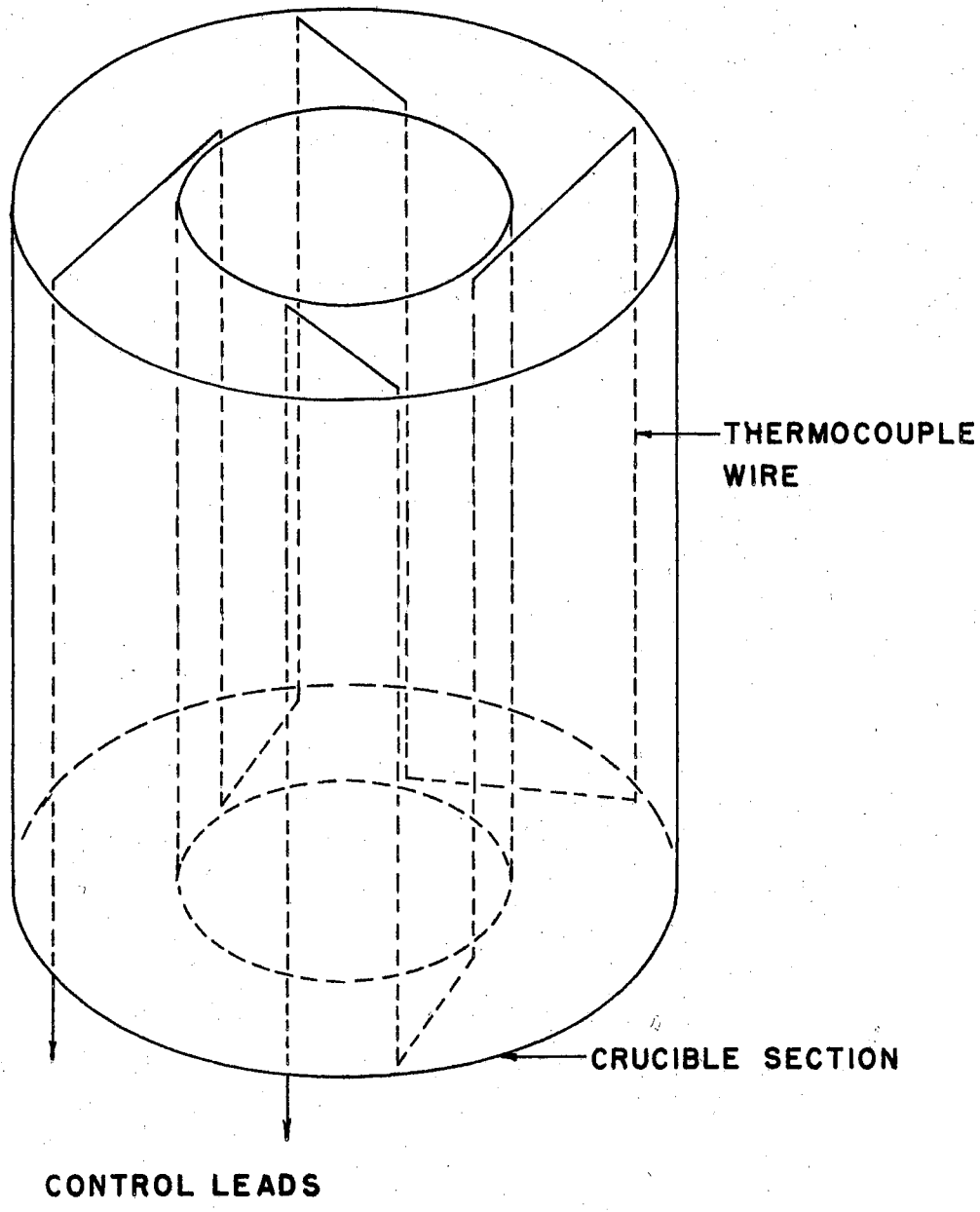
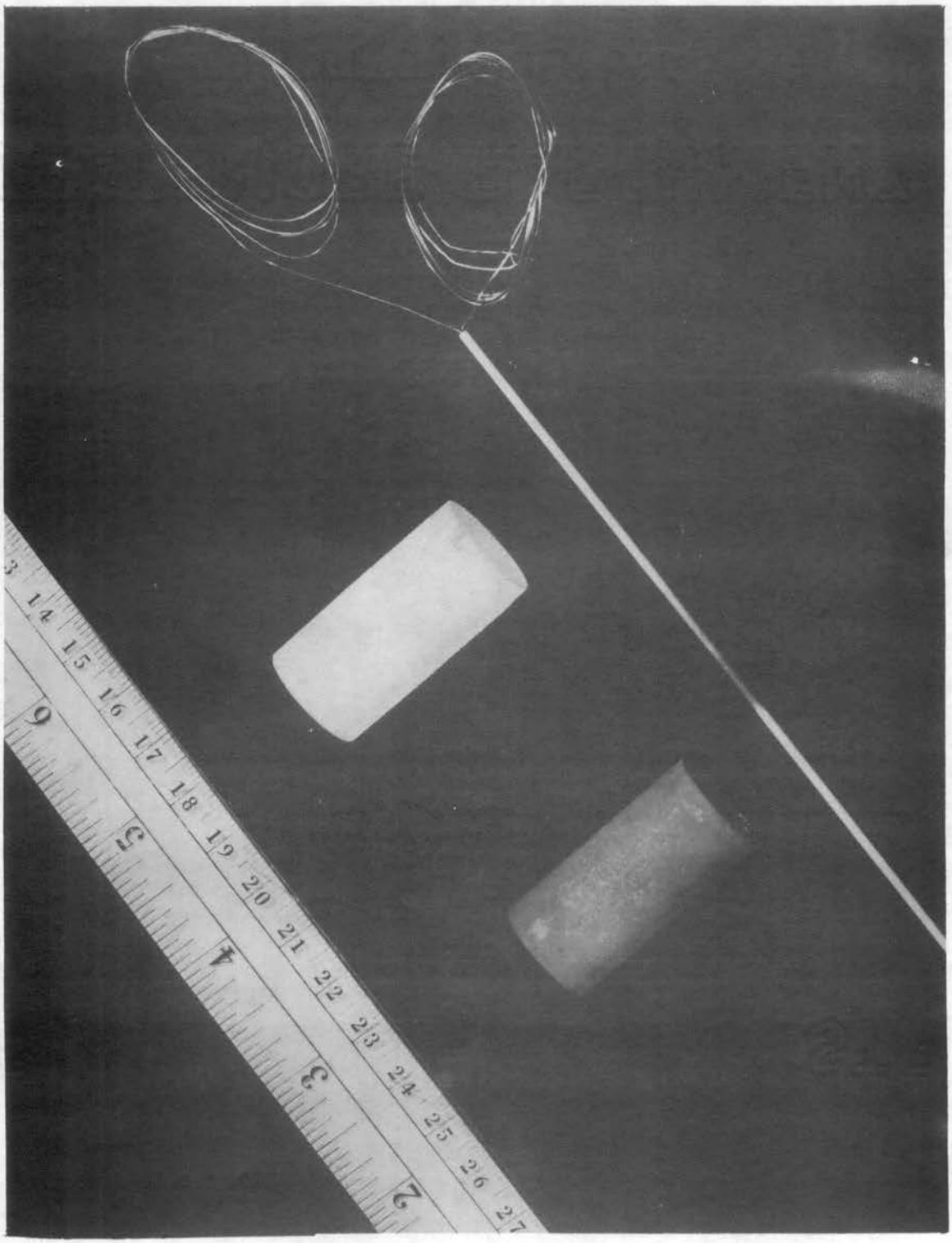


Figure 6. Thermocouple Arrangement in Crucible

PLATE III

COATED AND UNCOATED SAMPLES WITH CENTRAL SAMPLE THERMOCOUPLE




STRATHMORE PARCHMENT
100% COTTON FIBER USA

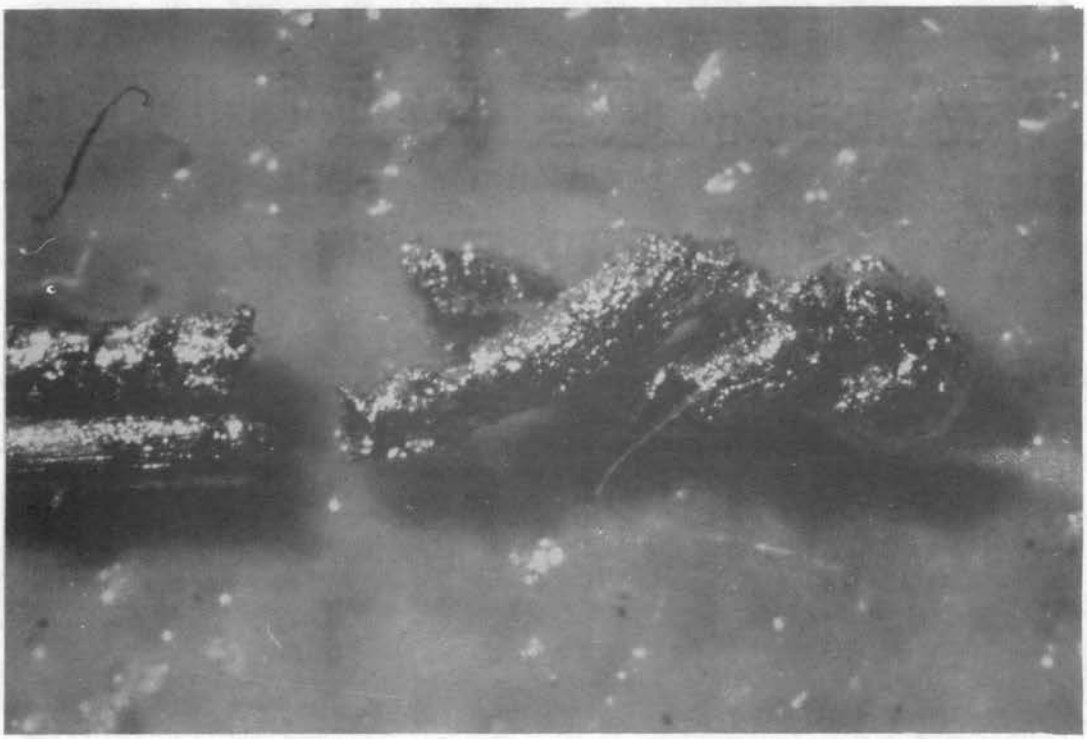
tube made of 96% alumina supplied by the McDanel Refractory Porcelain Company. These tubes were six inches long and were bored with two 0.015-in. holes. In using this arrangement for the central sample thermocouple it was impossible to shield the thermocouple junction from the surrounding atmosphere. The material used for thermocouple wire should not have been affected by the temperatures reached in this investigation but several failures were noted. Plate IV shows enlarged photographs of two such failures. It is believed that this failure was caused by diffusion of the sample material into the thermocouple material when the materials were in direct contact. This difficulty was partially eliminated by placing a small amount of crushed alumina in the hole which received the sample thermocouple. This alumina was in contact with the thermocouple junction rather than the sample material, and therefore, would eliminate the diffusion of the sample material into the thermocouple material. When a failure occurred it was normally noted in the cooling of the sample rather than during the heating run. The thermocouple wires were of a length which was sufficient to allow for pulling of the wire through the insulating tube to form a new junction. This precaution was necessary to avoid disturbance of the heating rate curves which might occur by use of thermocouple wire from a different melt.

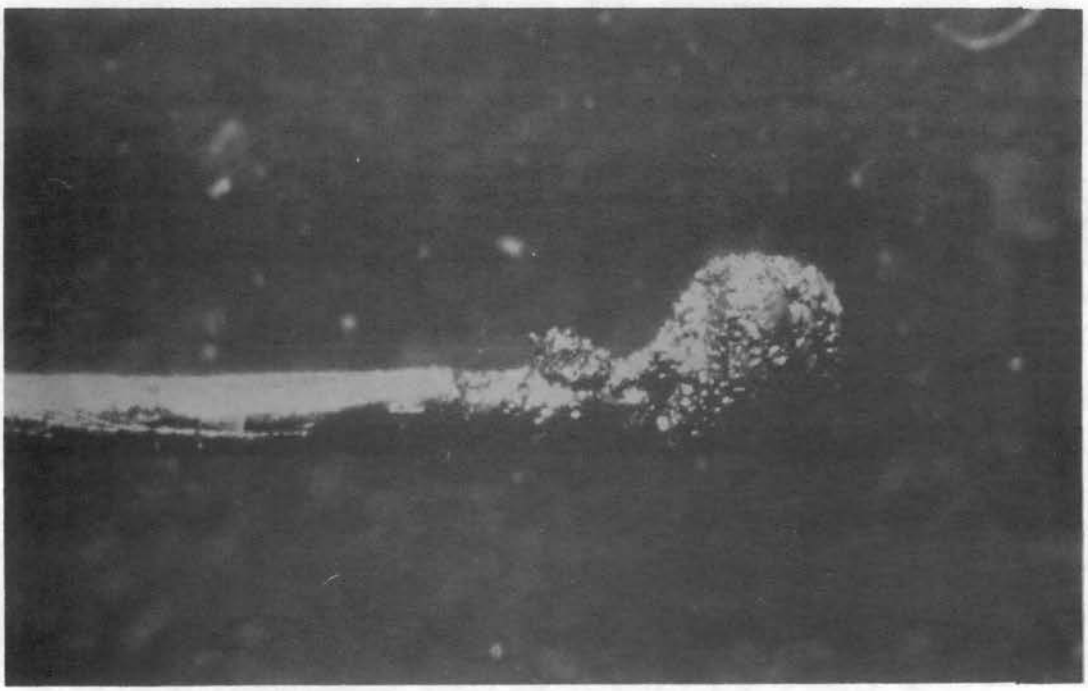
C. The Vacuum Furnace System

Since this investigation was originally planned to reach a temperature of 3000°F, the furnace system was designed for these temperatures. Success of measurements in this method was dependent on having an

PLATE IV

EXAMPLES OF THERMOCOUPLE JUNCTIONS WHICH FAILED



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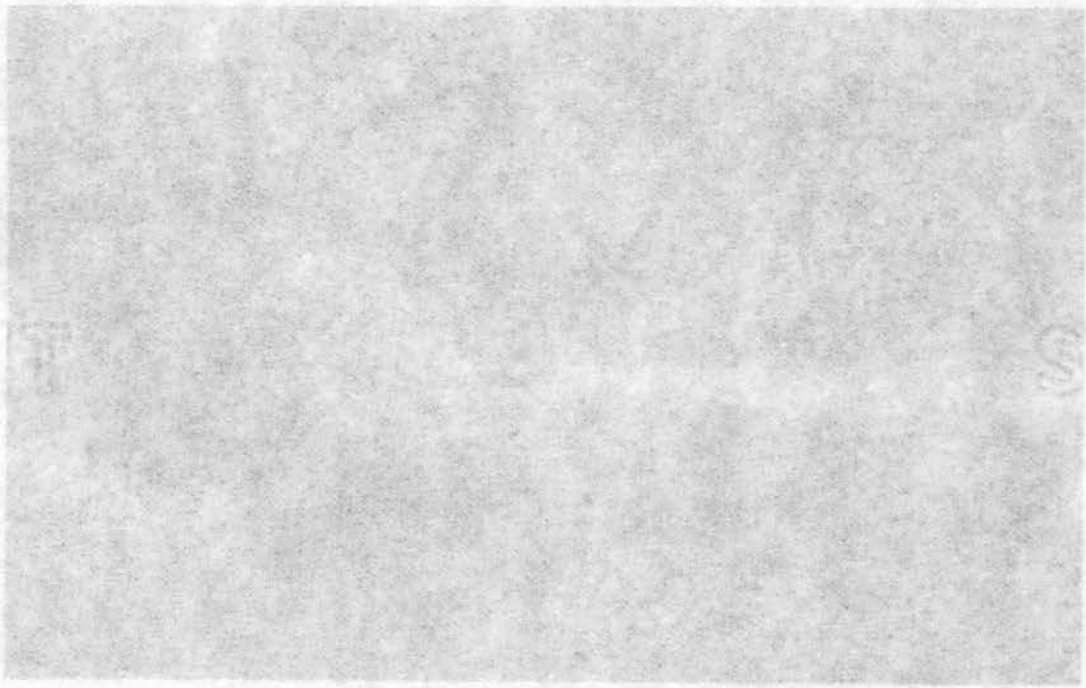


easily controlled furnace element. In order to obtain the most rapid response, the furnace system chosen was the vacuum system. Vacuum furnaces generally have low mass and are, therefore, easily controlled. Another item favoring the use of the vacuum furnace was the compatibility of the vacuum with many varied materials.

A general outline of the furnace is shown in Figure 7. The major parts of the furnace were the enclosure, ceramic insulating shell, molybdenum radiation shields, and the molybdenum heater element.

The furnace enclosure was constructed of a copper tube 6 1/8-in. outside diameter, 9-in. long with a 1/8-in. wall thickness. Copper tubing was soldered to the outside of the enclosure for cooling water. The bottom and top of the enclosure were made of three 1/8-in. thick stainless steel plates spaced approximately 1/4-in. apart.

A ceramic insulating shell 4-in. inside diameter, 5 1/2-in. outside diameter, and 7 1/2-in. long was machined from Armstrong A-28 firebrick. This ceramic insulation shell served to position the furnace element as well as to reduce the energy loss from the furnace volume.

Inside of the ceramic insulation shell a molybdenum radiation shield was installed. This shield was made of a single sheet of 0.010-in. molybdenum, 6-in. wide and 30-in. long. The sheet was coiled and installed inside the ceramic insulating tube.

The furnace heater element was an open filament design similar to that described in reference (6). It consisted of 18 coils of 0.037-in. molybdenum wire, wound 12 turns to the inch, 6-in. long. These coils

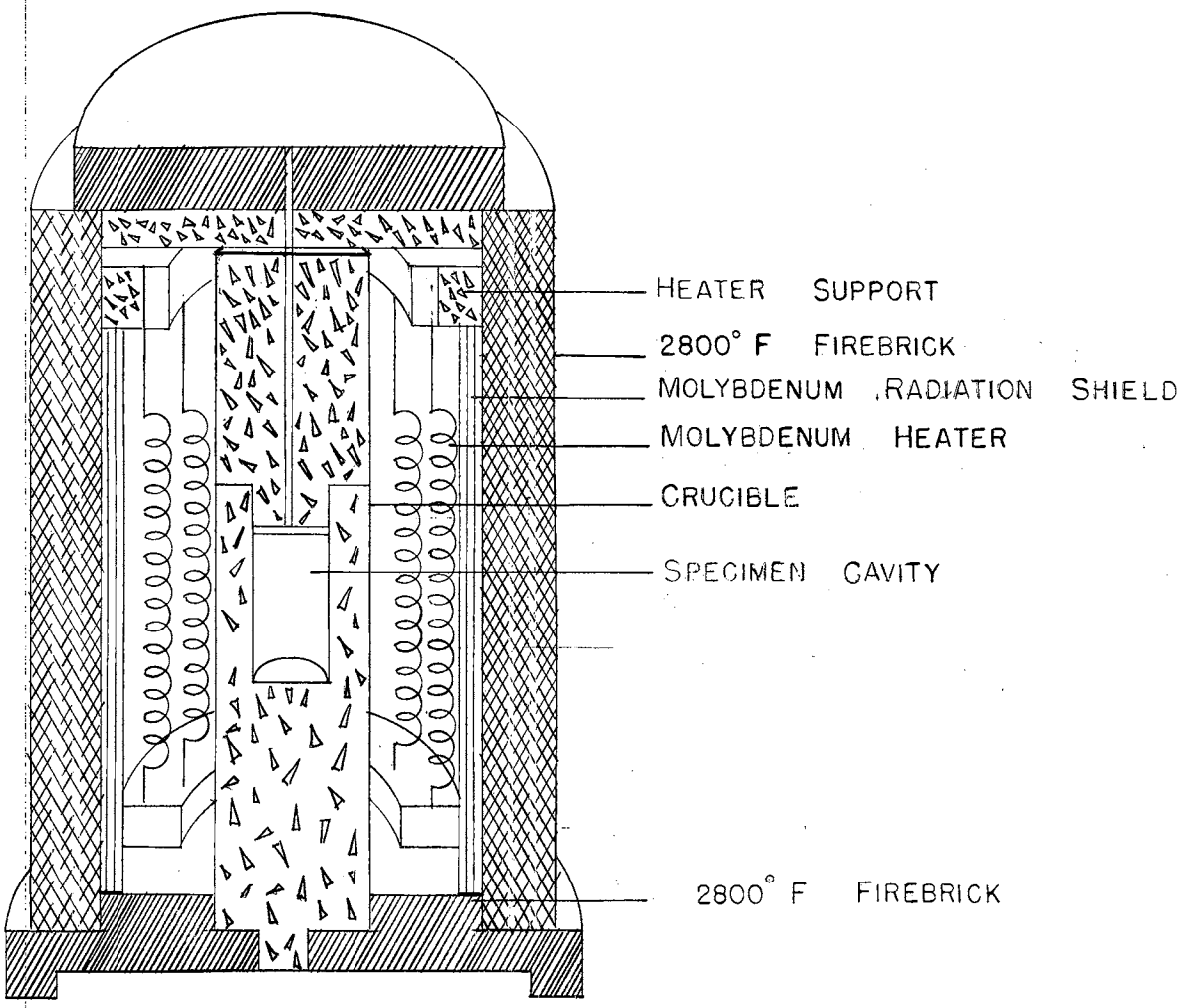


Figure 7. Schematic of High Temperature Furnace

were supported and held apart by two insulating rings of Johns-Manville JM-3000 insulating firebrick. The element was supported by resting on the molybdenum radiation shield inside the ceramic insulating shield. The heated zone was a cylinder approximately 3-in. in diameter and 5 1/4-in. long.

D. The Control System

In the operation of the system a thermal emf of approximately 0.35 millivolts was generated by the eight thermocouple junctions. This voltage represented the temperature difference between the inner wall thermocouple and the outer wall thermocouple junctions. A control system was necessary to maintain this value constant. This system had the requirement of slowly increasing the power input to the heater element to maintain the constant signal from the differential thermocouples. The arrangement of the control system is shown in Figure 8.

A Leeds and Northrup Speedomax Model H continuous balance recording potentiometer was used for sensing the control voltage. This indicator had a full scale range of 0-5 millivolts, a sensitivity of 0.01 millivolts, and indicated the input signal with an accuracy of 0.3% of the scale span.

The error signal output of this indicator was fed into a Leeds and Northrup Series 60 Controller. This unit is normally supplied by the Leeds and Northrup Company in conjunction with their Speedomax indicating instruments. The series 60 control unit had an output of 0-5 milliamperes which was amplified by a Fidelity Instrument Corporation magnetic amplifier. This amplifier had a D. C. output capacity of

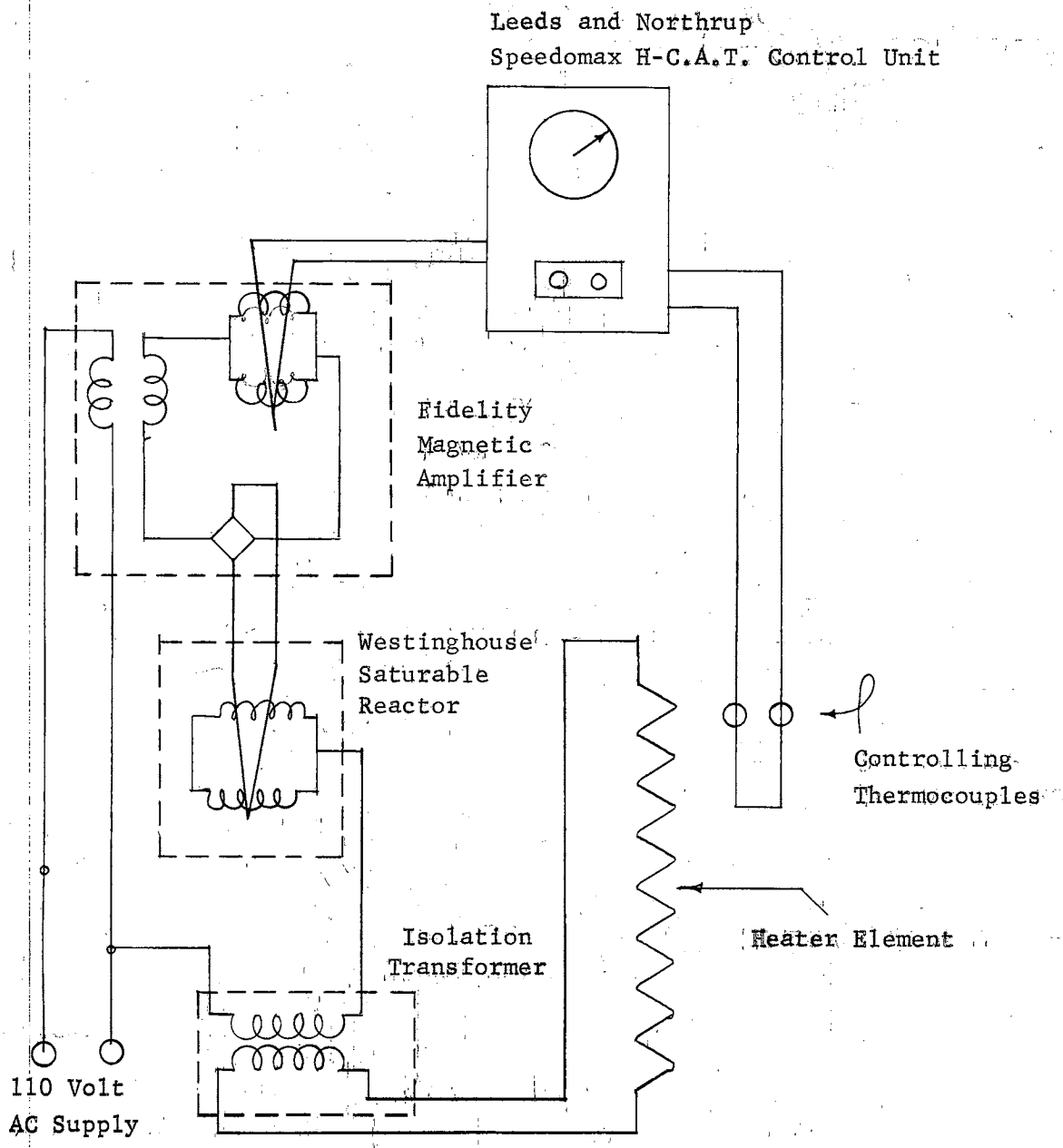


Figure 8. Power and Control Wiring Diagram

80 volts and 2.5 amperes. The output of the magnetic amplifier was used to control a Westinghouse saturable core reactor. This reactor regulated the voltage input of 110 volts A. C. to the heater element.

E. The Temperature Measuring Apparatus

In order to obtain the temperature-time relationships required for the analysis, the central temperature was measured at evenly spaced time periods. The temperature measurements were obtained using the platinum and platinum + 10% rhodium central sample thermocouple. The thermal emf generated by this thermocouple was referenced to the ice point and measured with a Leeds and Northrup Portable Precision Potentiometer, No. 8663, at even increments of time as indicated by a Standard Electric Company type SM 60 electric stopwatch. The values of the temperatures were obtained from the National Bureau of Standards Circular 561 (9), reference tables for thermocouples.

CHAPTER V

EXPERIMENTAL METHODS

Inasmuch as this system was entirely different from other systems used for comparative calorimetry, the entire apparatus had to be developed. The development of the vacuum furnace and the basic heater element design was reported in reference (6). After the basic system was designed, a system for use at high temperatures had to be developed and evaluated. At the time this system was being developed, it became evident that the sample coating would also have to be developed. The high temperature furnace and coating material development was reported by Knezek. (7).

After the development work by Knezek, the control system described previously was installed. With this installation, the completed system was used as follows: Each individual sample to be considered was prepared for the heating run by application of the coating. This coating was prepared in small quantities by mixing approximately 25 grams of magnesium oxide powder with 10 milliliters of methyl alcohol. After the coating material was well mixed, it was sprayed on the sample until a complete covering was obtained. The average mass increase of the sample from the coating material was 0.3 grams. When the sample coating had dried, the sample was installed in the calorimeter crucible and the entire system was

evacuated to an absolute pressure of approximately 0.2 microns. When the system pressure was sufficiently low, the cooling water flow to the furnace enclosure was started. This flow was adjusted to approximately 560 milliliters per minute. After the cooling water was flowing, the controller was turned on and the heating run begun.

Approximately 1 1/2 hours after the system was started, the temperature reached 1200°F. When this temperature was obtained, the central temperature was measured every two minutes. This measurement was obtained by carefully adjusting the potentiometer in a manner which caused the galvanometer indicator to be zero on the even minute increment. This procedure was followed until the central sample temperature reached the maximum temperature indicated for the particular run (usually 2600°F).

Upon completion of a run, the controller was used to cool the system slowly to room temperature. This was a necessary precaution to avoid thermal stress failures. Normally the heating and cooling process for a run required approximately 18 hours.

Data was taken for one of the standard materials and then the material considered the unknown specimen was run. After the specimen data was obtained, the other standard material was run. In this manner, the system required a maximum of two additional heating runs to obtain the data required to evaluate the specific heat of each unknown specimen.

The data for the high temperature runs is presented in the appendix. Other data was obtained for low temperature runs in

finalizing the system but these values are not considered to be valid for the final system; therefore, they are not included in this report.

CHAPTER VI

DISCUSSION OF THE EXPERIMENTAL TECHNIQUE

In the development of the apparatus for comparative calorimetry the choice of the vacuum furnace was made for the several reasons previously indicated; i. e., the requirement of low mass, low energy loss, and low contamination levels for the materials at high temperature. The main difficulty experienced in using the high vacuum furnace system was the evaporation of the sample materials. Each of the sample materials chosen for the investigation had a very low vapor pressure at the temperatures used in the test. (10). However, when the system is to be used for new materials, the vapor pressure is not likely to be as favorable. In using the system it would be necessary to estimate the maximum temperature for possible measurements by examining the vapor pressure characteristics of the constituents of the material under consideration.

The method used in obtaining data for maximum accuracy was to make a heating run for one of the standard materials, then one for the unknown specimen, and then to make the heating run for the other standard material. This procedure was used in accordance with a suggestion by W. P. White. (1). It was particularly necessary to use this method since the heating runs tended to vary slightly with time. The experimental procedures eliminated the effect of the

variation as much as was practicable.

In the reduction of the data obtained it was found necessary to follow a very definite procedure. The data obtained was a set of temperature values at even increments of time. These temperature values had a variation due to round-off in the temperature measurements. It was also evident that the values had other noise signals in them. The absolute values of the temperatures were not particularly important in comparison to the accuracy of the procedure, but the irregularities of the measurements had to be removed. For this reason, the thermocouples were not calibrated but the following procedure was used to obtain the inverse slopes.

First the temperature values were smoothed in accordance with a numerical procedure indicated by Hildebrand. (11).

$$t_{-1} = \frac{1}{6} (5t_{-1} + 2t_0 - t_1) \qquad \text{(VI-1)}$$

$$t_0 = \frac{1}{3} (t_{-1} + t_0 + t_1) \qquad \text{(VI-2)}$$

$$t_1 = \frac{1}{6} (-t_{-1} + 2_0 + 5t_1) \qquad \text{(VI-3)}$$

where t_0 = temperature value at the time of consideration

t_n = temperature value at a time before or after the time of consideration as indicated by the subscript n

After the data was reduced to the smooth values, the slope of the curve was obtained by numerical differentiation equations presented by Salvadori and Baron. (12).

$$12 \Delta\theta \frac{\Delta t}{\Delta\theta} = t_{-2} - 8t_{-1} + 8t_1 - t_2$$

$$2\,\Delta\theta\,\frac{\Delta t}{\Delta\theta} = -3t_0 + 4t_1 - t_2$$

$$2\,\Delta\theta\,\frac{\Delta t}{\Delta\theta} = t_{-2} - 4t_{-1} + 3t_0$$

where t_0 = temperature value at the time of consideration

t_n = temperature value at a time before or after the time of consideration

$\Delta\theta$ = time difference between the time at t_0 and at t_1

$\frac{\Delta t}{\Delta\theta}$ = slope at time when $t = t_0$

After the slopes of the temperature versus time curve at each time value and corresponding temperature were determined, the inverse values of these slopes were evaluated. In this manner the inverse slope at each smoothed value of the temperature was obtained. To further smooth and also to facilitate the use of the data, the inverse slope values were used to obtain an equation of the form $R = A + Bt + Ct^2$ using a least square deviation procedure. (11). Since the data reduction procedure was quite lengthy, it was programmed for the IBM 650 digital computer.

After the data was reduced to the equation form, the inverse heating rates for the two standard materials and the unknown specimen were calculated at each 100°F interval. Then from the known mass and specific heat for the standards and the known mass of the specimen, the specific heat of the unknown was calculated by linear interpolation or extrapolation as indicated in the theory. The values of the specific heat obtained in this manner were then reduced to the equation form $C_p = A + Bt$ using the least square deviation method.

CHAPTER VII

RESULTS

The results of the individual heating runs are presented in tabular form in Table I. In this table the inverse heating rate is represented by the equation $R = A + Bt + Ct^2$ as indicated previously.

TABLE I

INVERSE HEATING RATE EQUATIONS

$R = A + Bt + Ct^2$

where R is the inverse heating rate in minutes per degree Fahrenheit

t is the temperature in degrees Fahrenheit

Run Identification	A	B	C
TUN 9-3	0.5694×10^{1}	0.3621×10^{-4}	0.5590×10^{-8}
TAN 9-4	0.1924×10^{1}	-0.1152×10^{-3}	0.4673×10^{-7}
ALO 9-7	0.5880×10^{1}	-0.5085×10^{-3}	0.1521×10^{-6}
MOL 9-8	0.3126×10^{1}	-0.2569×10^{-3}	0.8565×10^{-7}
TUN 9-9	0.2553×10^{1}	-0.1964×10^{-3}	0.6812×10^{-7}
TUN 11-12	-0.6878×10^{-1}	0.1660×10^{-3}	-0.2840×10^{-7}
MOL 11-5	0.3009×10^{-2}	0.9134×10^{-4}	-0.9403×10^{-8}
ALO 11-7	-0.7652×10^{-1}	0.1943×10^{-3}	-0.3347×10^{-7}
TUN 10-20	0.9323×10^{-2}	0.7150×10^{-4}	-0.4128×10^{-8}
TAN 10-22	-0.5746×10^{-1}	0.1382×10^{-3}	-0.1961×10^{-7}
ALO 10-27	0.7908×10^{-2}	0.9946×10^{-4}	-0.9128×10^{-8}
TAN 10-29	-0.3106×10^{-1}	0.1252×10^{-3}	-0.1950×10^{-7}
TUN 10-31	-0.2975×10^{-1}	0.1327×10^{-3}	-0.2169×10^{-7}
TUN 11-3	0.3832×10^{-1}	0.5546×10^{-4}	-0.2354×10^{-8}

The samples molybdenum (MOL) and tantalum (TAN) were considered to be the unknown specimens. Specific heat values calculated at each 100°F and the equation obtained from them are tabulated in Table II.

TABLE II

SPECIFIC HEAT VALUES AND EQUATIONS

Run Identification--MOL 9-8		Run Identification--TAN 9-4	
t in °F	C_p in Btu/lb_m-°F	t in °F	C_p in Btu/lb_m- °F
1500	0.0728	1500	0.0418
1600	0.0732	1600	0.0402
1700	0.0738	1700	0.0387
1800	0.0746	1800	0.0376
1900	0.0756	1900	0.0379
2000	0.0766	2000	0.0395
2100	0.0757	2100	0.0419
2200	0.0788	2200	0.0441
2300	0.0798	2300	0.0460
2400	0.0807	2400	0.0475
2500	0.0814	2500	0.0487
2600	0.0821	2600	0.0493
Equation Representation		Equation Representation	
$C_p = 0.05906 + 8.793 \times 10^{-6}t$		$C_p = 0.02298 + 9.65 \times 10^{-6}t$	

TABLE II (Continued)

Run Identification--TAN 10-22	
t in °F	C_p in Btu/lb_m- °F
1500	0.0396
1600	0.0417
1700	0.0435
1800	0.0449
1900	0.0459
2000	0.0466
2100	0.0470
2200	0.0472
2300	0.0472
2400	0.0469
2500	0.0463
2600	0.0457
Equation Representation	
$C_p = 0.03425 + 5.345 \times 10^{-6}t$	

Run Identification--TAN 10-29	
t in °F	C_p in Btu/lb_m- °F
1500	0.0366
1600	0.0394
1700	0.0415
1800	0.0427
1900	0.0436
2000	0.0440
2100	0.0443
2200	0.0441
2300	0.0436
2400	0.0426
2500	0.0422
2600	0,0412
Equation Representation	
$C_p = 0.03579 + 3.103 \times 10^{-6}t$	

Run Identification--MOL 11-5	
t in °F	C_p in Btu/lb_m- °F
1500	0.0742
1600	0.0752
1700	0.0764
1800	0.0775
1900	0.0786
2000	0.0797
2100	0.0808
2200	0.0819
2300	0.0830
2400	0.0841
2500	0.0851
2600	0.0863
Equation Representation	
$C_p = 0.05762 + 11.03 \times 10^{-6}t$	

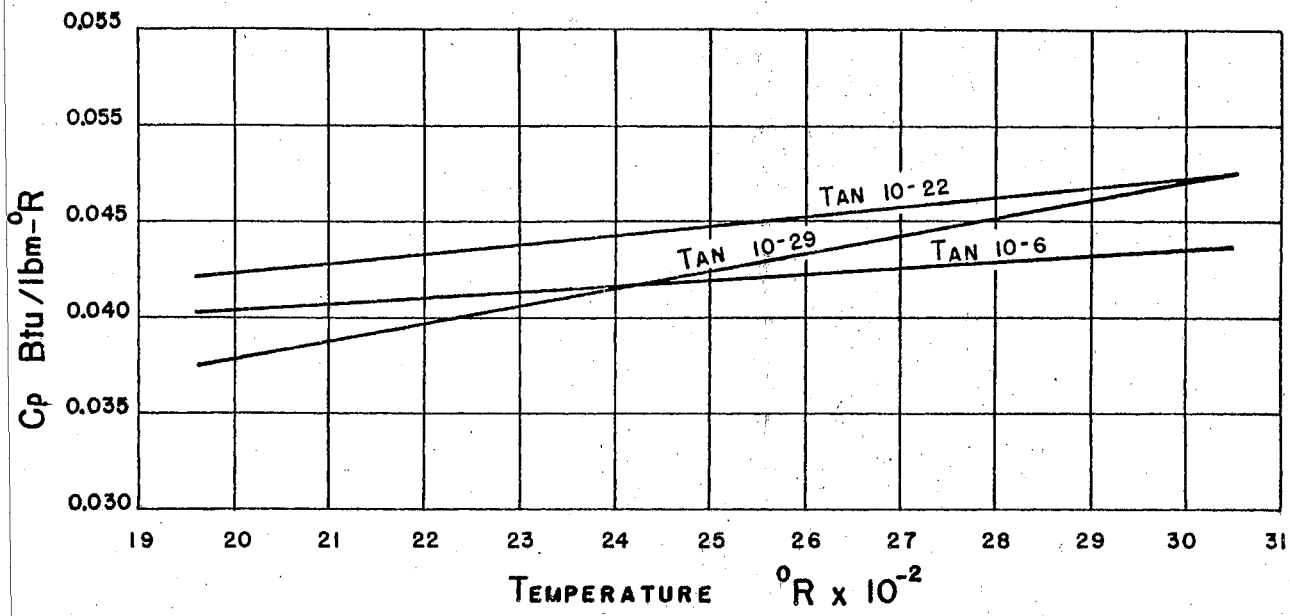
Run Identification--MOL 11-10	
t in °F	C_p in Btu/lb_m- °F
1500	0.0752
1600	0.0773
1700	0.0788
1800	0.0802
1900	0.0813
2000	0.0821
2100	0.0826
2200	0.0829
2300	0.0831
2400	0.0829
2500	0.0827
2600	0.0823
Equation Representation	
$C_p = 0.06858 + 6.034 \times 10^{-6}t$	

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

The data for the individual heating runs as shown in Tables III through XX indicate the change in total time required for a given material when the heating run was repeated. This change in the total heating time for some of the runs amounted to approximately $\pm$ 3%. It was noted that if a sample was run twice, one run after the other, the change in heating time was negligible. The change in heating time for a given sample invariably became larger when several other heating runs were made between the runs to be compared. It is believed that this slow change in the system was the result of contamination of the thermocouple wires in the crucible. As noted before, this effect was largely eliminated by running the standard materials and unknown specimens alternately.

In determining the reproducibility of the method, the several results are plotted in Figure 9. These were obtained for the two materials molybdenum and tantalum since these two materials have very low vapor pressure and would not tend to evaporate at high temperatures under the low pressure of the system. An examination of the curves indicates that the system reproduced the results within $\pm$ 6% when compared to the average value. The largest variation was indicated for the tantalum, which is a material of low specific heat. For a



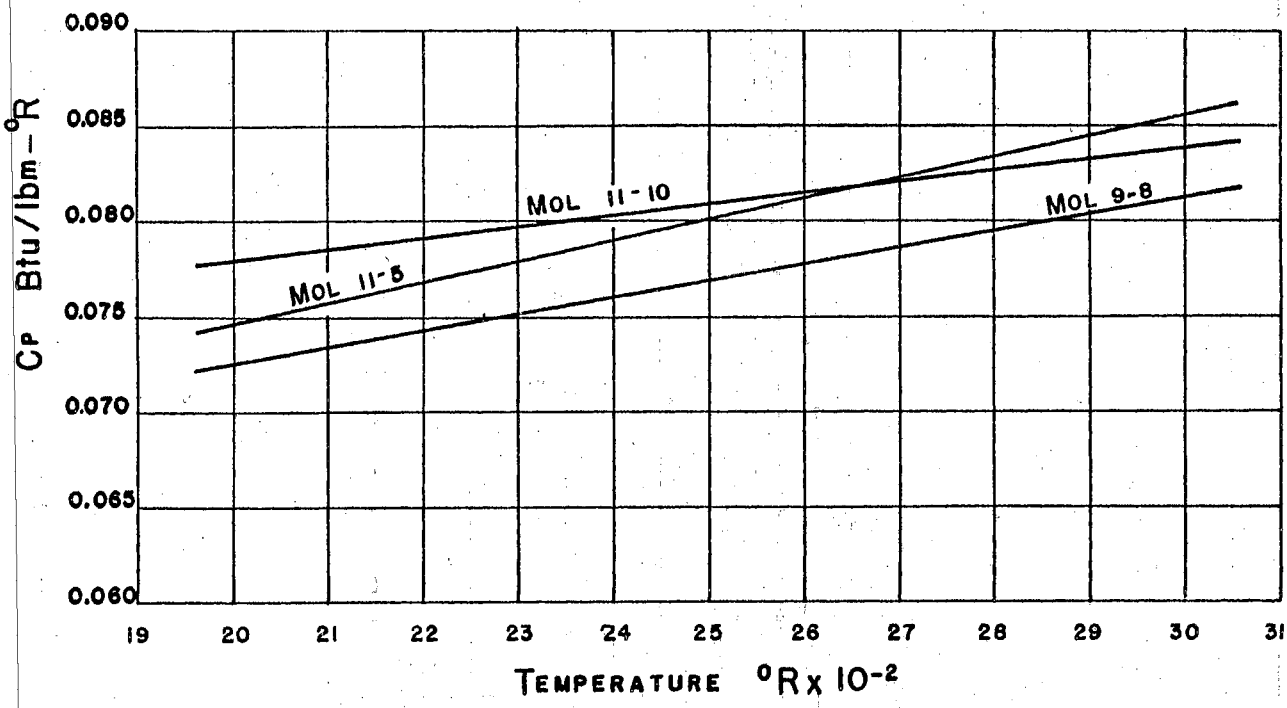


Figure 9. Specific Heat of Tantalum and Molybdenum Showing Reproducibility of the Method

material with higher specific heat, molybdenum, the reproducibility was $\pm$3%, again compared to the average.

Figure 10 indicates the value of the specific heat obtained for tantalum (this is the least square fit of the three aforementioned runs) compared with two values obtained from the literature. The curve above the values obtained in this investigation were reported by Goldsmith et al. (13) and the lower values were reported by K. K. Kelley. (14). Since each of the investigations was considered to be reliable, it was not possible to choose either set of values as being absolutely correct. For this reason, it was not possible to determine the absolute accuracy of the specific heat value obtained for tantalum in this investigation. Figure 10 also indicates the value of the specific heat of molybdenum obtained in this investigation (again this is the least square fit of all the data used for the three curves in determining the reproducibility) compared to the literature values reported by Goldsmith and Kelley. At lower temperatures, the values obtained in this investigation, when compared to the average of the two literature values, indicate a 5% variation. The variation at high temperatures is approximately 1.2%. It was believed that this variation may have resulted from a different composition in the sample used and the samples used in the investigations in the literature.

Any evaluation of the absolute value of the specific heat by this method depends to a very large degree on the use of good property information for the two standard materials. In order to eliminate this difficulty as much as possible the two standards used in this investigation were tungsten and Al_2O_3 (synthetic sapphire). The sample of

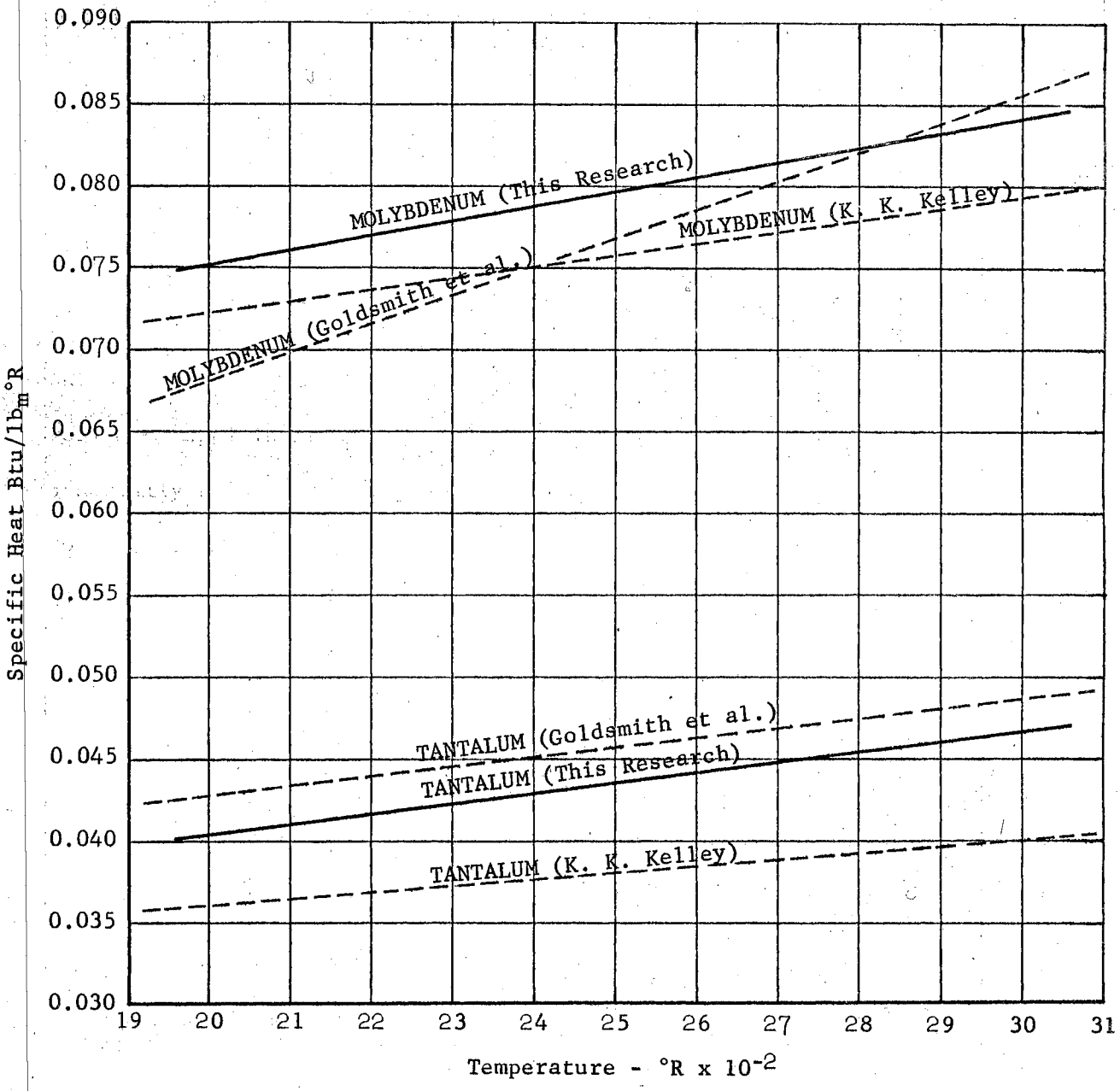


Figure 10. Specific Heat of Tantalum and Molybdenum

tungsten was obtained from the Fansteel Corporation. Its composition and the composition of the other specimens are presented in the appendix. Tungsten was chosen as one of the standard materials for two reasons: one, this material has very consistent specific heat values reported in the literature, and two, the material has a very low specific heat which eliminated excessive extrapolation in the evaluation procedure. The specific heat values used for the material in the evaluation of the specific heat were obtained from K. K. Kelley's work. (14). A comparison of these values with the values presented by Goldsmith et al. (13) showed very close agreement. The second standard material, Al_2O_3 or synthetic sapphire, was donated to the Oklahoma State University by the Linde Air Products Company for use in G. C. Beakley's investigation. This material was recommended by the Calorimetry Conference (U. S.) as a standard for intercomparison of calorimeters at high temperatures. (15). The values of the heat capacity of this material were obtained from the equation presented by Furukawa et al. (15). This equation was indicated by reference (15) to be valid up to 1200°K, which is somewhat less than the temperatures which this investigation covered. The extrapolation of the Furukawa equation up to 1500°C was indicated by Dr. T. B. Douglas (16) of the National Bureau of Standards as probably the most reliable information available at the time of the investigation. It should be noted that Dr. Douglas and his co-workers are presently engaged in measuring the heat capacity of Al_2O_3 up to 1500°C and these values should be available for any future investigation.

In the reduction of the experimental data obtained in this investigation, it was necessary to use the smoothing and least square deviation fitting techniques described previously. Such an analysis was necessary due to the difficulty of obtaining the inverse slope of the temperature-time data. The raw data had such large noise signals (when compared to the changes in temperature from data point to data point) that coherent slope evaluation at each data point was impossible. Since the values of the inverse slope were obtained from the least square deviation fit, it was felt that specific heat values should be treated similarly. Figure 11 shows the individual calculated specific heat values plotted for one molybdenum run and also the least square fit straight line representation. The gently curving trend of the data point plot is typical of the results obtained. It is believed that these values should not be used in this form since any extrapolation would result in specific heat values which are not reasonable.

If a material which undergoes a change of phase is evaluated by this method, the reduction of the data cannot be accomplished as herein indicated. Originally, this method was not designed to be used in the case where a change of phase occurs, but other investigations indicated the possibility of using the method under these conditions. (3) (5). Since the smoothing procedure indicated would mask the phase change, it would be necessary to change the method of analysis radically. It is recommended that materials with phase changes be avoided if possible, but if they are unavoidably involved, the slope evaluation would normally be most tractable by numerical

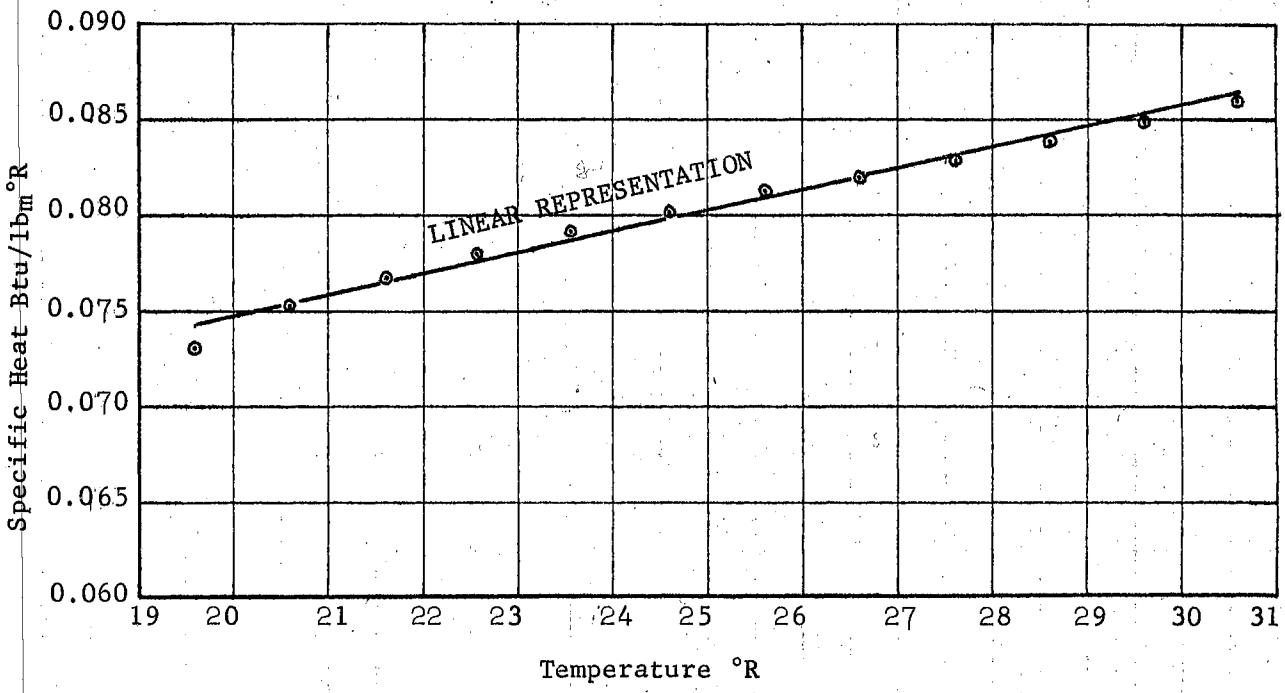


Figure 11. Specific Heat for Molybdenum

differentiation of the raw data and smoothing graphically. This procedure was used by Beakley (5) in order to evaluate the results of his investigation.

When this method is applied by other investigators, it is believed that several things can be done to improve the accuracy and upper temperature limit. These items are (a) use of better materials and (b) modification of the size. At the time this work was done the best materials available were used, but new materials are always being developed. The crucible material used in the future could be improved if a material which has the required dimensional stability and also has a lower heat capacity per unit volume can be obtained. The comparative method depends on the change in the heat capacity for that volume occupied by the sample and the crucible. If the crucible contributes a small amount of the total, the inverse heating rate curves for samples of differing heat capacity will be further displaced from each other. This will improve the accuracy of the method. Another material used in this investigation which will be improved in the future is the thermocouple material. The platinum and platinum + 10% rhodium thermocouples used were susceptible to contamination. At present, there is considerable effort being made to obtain a material which will be superior to these materials for high temperature measurements. Of the materials under investigation, the platinum-rhenium system appears to offer the most promise. (17). Any improvement in the thermocouple material used in the controlling thermocouples will improve the accuracy of the method and perhaps

allow the extension of the upper temperature limit.

The second item which might be changed to improve the accuracy of the method is the size of the heated zone in the furnace. In the theory developed the crucible tube was assumed to be infinitely long, but the system developed had a crucible with a 1/d ratio of 4. It is believed that the system accuracy would be improved by increasing the 1/d ratio. Since the external diameter of the crucible cannot be decreased very much without losing the control signal, the length should be increased.

As a final analysis of the method, it can be said that the method as developed was accurate enough for most engineering calculations of the present. The time involved in obtaining the specific heat of any given material was a maximum of 48 hours or a minimum of 36 hours. This compares with several weeks required by most other methods; however, the other methods will be more accurate.

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APPENDIX A

A PARTICULAR SOLUTION OF EQUATION (III-2)

Williamson and Adams (8) indicate the solution of equation (III-2) for the quasi-steady condition of linear heating or cooling of an infinitely long hollow tube to be

$$t = h\theta + \frac{r^2 h}{4\alpha} + C_1 \ln r + C_2$$

Introducing the boundary conditions

$$t = h\theta \quad \text{at } r = r_o \tag{1}$$

and

$$\frac{\partial t}{\partial r} = \emptyset \quad \text{at } r = r_i \tag{2}$$

gives

$$h\theta = h\theta + \frac{r_o^2 h}{4\alpha} + C_1 \ln r_o + C_2 \tag{3}$$

$$\emptyset = \frac{2 r_i h}{4\alpha} + \frac{C_1}{r_i} \tag{4}$$

Solution of (1) and (4) for C_1 and C_2 gives

$$C_1 = r_i \emptyset - \frac{r_i^2 h}{2\alpha} \tag{5}$$

$$C_2 = -\frac{r_o^2 h}{4\alpha} - \left(r_i \emptyset - \frac{r_i^2 h}{2\alpha}\right) \ln r_o \tag{6}$$

Introducing C_1 and C_2 into (1)

$$t = h\theta + \frac{r^2 h}{4\alpha} + \left(r_i \phi - \frac{r_i^2 h}{2\alpha}\right) \ln r - \frac{r_o^2 h}{4\alpha} - \left(r_i \phi - \frac{r_i^2 h}{2\alpha}\right) \ln r_o \qquad (7)$$

Simplifying equation (7)

$$t = h\theta + \frac{h}{4\alpha} (r^2 - r_o^2) + \left(r_i \phi - \frac{r_i^2 h}{2\alpha}\right) \ln \frac{r}{r_o} \qquad (8)$$

Now consider the temperatures t_a and t_b in the crucible wall at radii r_a and r_b, where $r_a > r_b$:

$$\Delta t = t_a - t_b = \frac{h}{4\alpha} (r_a^2 - r_b^2) + \left(r_i \phi - \frac{r_i^2 h}{2\alpha}\right) \ln \frac{r_a}{r_b} \qquad (9)$$

From Fourier's equation for heat flow:

$$q = -kA \frac{\partial t}{\partial r} \qquad (10)$$

at the inner wall

$$q_{r=r_i} = -kA \left.\frac{\partial t}{\partial r}\right)_{r=r_i} = -kA\, \phi \qquad (11)$$

Substitution ϕ from (11) into (9),

$$\Delta t = \frac{h}{4\alpha} (r_a^2 - r_b^2) - \frac{r_i q}{kA} \ln \frac{r_a}{r_b} - \frac{r_i^2 h}{2\alpha} \ln \frac{r_a}{r_b} \qquad (12)$$

For the enclosed sample which absorbs the energy transferred through the inner wall

$$-q = Wc \frac{dt}{d\theta} = Wch \qquad (13)$$

Introducing this into equation (12) for q,

$$\Delta t = h\left(\frac{r_a^2 - r_b^2}{4\alpha}\right) - \frac{r_i^2}{2\alpha} \ln\frac{r_a}{r_b} + hWc\left(\frac{r_i}{Ak}\ln\frac{r_a}{r_b}\right) \tag{14}$$

Now, since Δt is maintained constant experimentally, the heat capacity of the sample may be evaluated as

$$Wc = \frac{\Delta t}{h\left(\frac{r_i}{Ak}\ln\frac{r_a}{r_b}\right)} - \frac{\left(\frac{r_a^2 - r_b^2}{4\alpha}\right) - \frac{r_i^2}{2\alpha}\ln\frac{r_a}{r_b}}{\left(\frac{r_i}{Ak}\ln\frac{r_a}{r_b}\right)} \tag{15}$$

Or:

$$C = \frac{1}{h}M - N = MR - N \tag{16}$$

Where

$$M = \frac{\Delta t}{\left(\frac{r_i}{Ak}\ln\frac{r_a}{r_b}\right)}$$

$$N = \frac{\left(\frac{r_a^2 - r_b^2}{4\alpha}\right) - \frac{r_i^2}{2\alpha}\quad\frac{r_a}{r_b}}{\left(\frac{r_i^2}{Ak}\ln\frac{r_a}{r_b}\right)}$$

$$R = \frac{1}{h}$$

APPENDIX B

TEST DATA

TABLE III

TEST DATA FOR TUNGSTEN RUN TUN 9-3 WITH A CONTROL EMF OF 0.25 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.11	1266.3	2	10.87	2031.5	102
6.22	1285.2	4	10.95	2043.7	104
6.33	1304.0	6	11.04	2057.3	106
6.43	1321.0	8	11.12	2069.4	108
6.54	1339.7	10	11.20	2081.4	110
6.64	1356.7	12	11.29	2095.0	112
6.75	1375.3	14	11.37	2107.1	114
6.85	1392.1	16	11.46	2120.6	116
6.96	1410.5	18	11.54	2132.7	118
7.07	1428.9	20	11.63	2146.2	120
7.17	1445.6	22	11.71	2158.2	122
7.27	1462.2	24	11.79	2170.2	124
7.38	1480.5	26	11.87	2182.2	126
7.48	1497.0	28	11.95	2194.2	128
7.58	1513.5	30	12.03	2206.2	130
7.67	1528.2	32	12.11	2218.2	132
7.78	1546.3	34	12.19	2230.2	134
7.88	1562.6	36	12.28	2243.6	136
7.97	1577.3	38	12.36	2255.6	138
8.07	1593.5	40	12.44	2267.6	140
8.17	1609.7	42	12.52	2279.5	142
8.26	1624.2	44	12.60	2291.5	144
8.36	1640.4	46	12.68	2303.5	146
8.45	1654.8	48	12.76	2315.4	148
8.55	1670.9	50	12.84	2327.4	150
8.64	1685.3	52	12.93	2340.9	152
8.73	1699.6	54	13.00	2351.4	154
8.82	1713.9	56	13.08	2363.4	156
8.91	1728.2	58	13.16	2375.3	158
9.01	1744.1	60	13.24	2387.3	160
9.10	1758.3	62	13.32	2399.3	162
9.19	1772.5	64	13.39	2409.8	164
9.28	1786.6	66	13.47	2421.8	166
9.37	1800.7	68	13.54	2432.3	168
9.46	1814.8	70	13.61	2442.8	170
9.55	1828.9	72	13.68	2453.3	172
9.64	1842.9	74	13.76	2465.3	174
9.73	1856.9	76	13.83	2475.8	176
9.82	1870.8	78	13.90	2486.3	178
9.92	1886.3	80	13.98	2498.3	180
10.00	1898.7	82	14.05	2508.9	182
10.09	1912.5	84	14.12	2519.4	184
10.18	1926.4	86	14.19	2529.9	186
10.27	1940.1	88	14.27	2541.9	188
10.35	1952.4	90	14.34	2552.4	190
10.44	1966.1	92	14.41	2563.0	192
10.53	1979.9	94	14.48	2573.5	194
10.61	1992.0	96	14.55	2584.1	196
10.70	2005.7	98	14.62	2594.6	198
10.78	2017.9	100	14.69	2605.1	200

TABLE IV

TEST DATA FOR TANTALUM RUN TAN 9-4 WITH A CONTROL EMF OF 0.25 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.11	1266.3	2	10.94	2042.1	102
6.22	1285.2	4	11.03	2055.8	104
6.34	1305.7	6	11.11	2067.9	106
6.45	1324.4	8	11.20	2081.4	108
6.56	1343.1	10	11.28	2093.5	110
6.67	1361.8	12	11.37	2107.1	112
6.78	1380.3	14	11.46	2120.6	114
6.89	1398.8	16	11.54	2132.7	116
7.00	1417.2	18	11.62	2144.7	118
7.10	1433.9	20	11.70	2156.7	120
7.20	1450.6	22	11.79	2170.2	122
7.31	1468.9	24	11.87	2182.2	124
7.41	1485.4	26	11.96	2195.7	126
7.52	1503.6	28	12.04	2207.7	128
7.62	1520.0	30	12.12	2219.7	130
7.72	1536.4	32	12.20	2231.7	132
7.82	1552.8	34	12.28	2243.6	134
7.92	1569.1	36	12.37	2257.1	136
8.02	1585.4	38	12.45	2269.1	138
8.11	1600.0	40	12.53	2281.0	140
8.22	1617.8	42	12.61	2293.0	142
8.31	1632.3	44	12.69	2305.0	144
8.41	1648.4	46	12.77	2316.9	146
8.51	1664.5	48	12.85	2328.9	148
8.60	1678.9	50	12.92	2339.4	150
8.70	1694.8	52	13.00	2351.4	152
8.79	1709.2	54	13.07	2361.9	154
8.89	1725.1	56	13.15	2373.8	156
8.98	1739.3	58	13.22	2384.3	158
9.07	1753.5	60	13.29	2394.8	160
9.17	1769.3	62	13.37	2406.8	162
9.26	1783.5	64	13.44	2417.3	164
9.35	1797.6	66	13.52	2429.3	166
9.45	1813.3	68	13.59	2439.8	168
9.54	1827.2	70	13.65	2448.8	170
9.63	1841.3	72	13.72	2459.3	172
9.72	1855.3	74	13.78	2468.3	174
9.81	1869.3	76	13.85	2478.8	176
9.90	1883.2	78	13.92	2489.3	178
9.99	1897.1	80	13.98	2498.3	180
10.07	1909.4	82	14.05	2508.9	182
10.16	1923.3	84	14.12	2519.4	184
10.25	1937.1	86	14.19	2529.9	186
10.34	1950.9	88	14.25	2538.9	188
10.42	1963.1	90	14.32	2549.4	190
10.51	1976.8	92	14.39	2560.0	192
10.60	1990.5	94	14.45	2569.0	194
10.68	2002.7	96	14.52	2579.5	196
10.77	2016.4	98	14.58	2588.6	198
10.86	2030.0	100	14.64	2597.6	200

TABLE V

TEST DATA FOR SYNTHETIC SAPPHIRE RUN ALO 9-7 WITH A CONTROL EMF OF 0.25 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.14	1271.5	2	11.07	2061.8	130
6.23	1286.9	4	11.14	2072.4	132
6.32	1302.3	6	11.21	2083.0	134
6.41	1317.6	8	11.27	2092.0	136
6.50	1333.0	10	11.34	2102.6	138
6.59	1348.2	12	11.41	2113.1	140
6.68	1363.4	14	11.48	2123.6	142
6.77	1378.5	16	11.54	2132.7	144
6.85	1392.1	18	11.61	2143.2	146
6.94	1407.2	20	11.68	2153.7	148
7.02	1420.6	22	11.75	2164.2	150
7.10	1433.9	24	11.82	2174.7	152
7.18	1447.3	26	11.88	2183.7	154
7.27	1462.2	28	11.95	2194.2	156
7.35	1475.5	30	12.02	2204.7	158
7.44	1490.4	32	12.09	2215.2	160
7.52	1503.6	34	12.16	2225.7	162
7.60	1516.7	36	12.22	2234.7	164
7.68	1529.9	38	12.28	2243.6	166
7.76	1543.0	40	12.35	2254.1	168
7.84	1556.1	42	12.41	2263.1	170
7.92	1569.1	44	12.48	2273.6	172
8.00	1582.1	46	12.54	2282.5	174
8.08	1595.1	48	12.60	2291.5	176
8.15	1606.5	50	12.66	2300.5	178
8.23	1619.4	52	12.73	2311.0	180
8.31	1632.3	54	12.79	2319.9	182
8.39	1645.2	56	12.86	2330.4	184
8.47	1658.0	58	12.92	2339.4	186
8.54	1669.3	60	12.98	2348.4	188
8.61	1680.5	62	13.03	2355.9	190
8.69	1693.2	64	13.09	2364.9	192
8.77	1706.0	66	13.15	2373.8	194
8.84	1717.1	68	13.22	2384.3	196
8.92	1729.8	70	13.28	2393.3	198
8.99	1740.9	72	13.34	2402.3	200
9.07	1753.5	74	13.40	2411.3	202
9.14	1764.6	76	13.46	2420.3	204
9.21	1775.6	78	13.51	2427.8	206
9.29	1788.2	80	13.57	2436.8	208
9.37	1800.7	82	13.63	2445.8	210
9.44	1811.7	84	13.68	2453.3	212
9.51	1822.6	86	13.74	2462.3	214
9.58	1833.5	88	13.79	2469.8	216
9.66	1846.0	90	13.84	2477.3	218
9.72	1855.3	92	13.90	2486.3	220
9.80	1867.7	94	13.95	2493.8	222
9.87	1878.6	96	14.00	2501.3	224
9.94	1889.4	98	14.04	2507.4	226
10.02	1901.8	100	14.09	2514.9	228
10.09	1912.5	102	14.14	2522.4	230
10.16	1923.3	104	14.18	2528.4	232
10.23	1934.0	106	14.23	2535.9	234
10.30	1944.8	108	14.27	2541.9	236
10.37	1955.4	110	14.32	2549.4	238
10.44	1966.1	112	14.36	2555.5	240
10.51	1976.8	114	14.41	2563.0	242
10.58	1987.5	116	14.45	2569.0	244
10.65	1998.1	118	14.50	2576.5	246
10.73	2010.3	120	14.54	2582.5	248
10.80	2020.9	122	14.59	2590.1	250
10.87	2031.5	124	14.63	2596.1	252
10.94	2042.1	126	14.67	2602.1	254
11.00	2051.2	128			

TABLE VI

TEST DATA FOR MOLYBDENUM RUN MOL 9-8 WITH A CONTROL EMF OF 0.25 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.12	1268.0	2	11.10	2066.3	100
6.25	1290.3	4	11.18	2078.4	102
6.37	1310.8	6	11.27	2092.0	104
6.49	1331.3	8	11.36	2105.6	106
6.61	1351.6	10	11.44	2117.6	108
6.72	1370.2	12	11.53	2131.2	110
6.84	1390.4	14	11.61	2143.2	112
6.95	1408.9	16	11.70	2156.7	114
7.06	1427.3	18	11.79	2170.2	116
7.17	1445.6	20	11.87	2182.2	118
7.28	1463.9	22	11.95	2194.2	120
7.39	1482.1	24	12.04	2207.7	122
7.50	1500.3	26	12.13	2221.2	124
7.61	1518.4	28	12.21	2233.2	126
7.72	1536.4	30	12.30	2246.6	128
7.83	1554.4	32	12.38	2258.6	130
7.93	1570.7	34	12.46	2270.6	132
8.04	1588.6	36	12.54	2282.5	134
8.14	1604.8	38	12.62	2294.5	136
8.25	1622.6	40	12.70	2306.5	138
8.35	1638.8	42	12.78	2318.4	140
8.45	1654.8	44	12.86	2330.4	142
8.55	1670.9	46	12.94	2342.4	144
8.65	1686.9	48	13.02	2354.4	146
8.75	1702.8	50	13.09	2364.9	148
8.85	1718.7	52	13.17	2376.8	150
8.95	1734.6	54	13.24	2387.3	152
9.05	1750.4	56	13.31	2397.8	154
9.15	1766.2	58	13.39	2409.8	156
9.25	1781.9	60	13.46	2420.3	158
9.34	1796.0	62	13.53	2430.8	160
9.44	1811.7	64	13.60	2441.3	162
9.59	1827.2	66	13.67	2451.8	164
9.63	1841.3	68	13.74	2462.3	166
9.73	1856.9	70	13.81	2472.8	168
9.83	1872.4	72	13.87	2481.8	170
9.92	1886.3	74	13.94	2492.3	172
10.02	1901.8	76	14.01	2502.8	174
10.11	1915.6	78	14.07	2511.9	176
10.20	1929.4	80	14.12	2519.4	178
10.29	1943.2	82	14.18	2528.4	180
10.38	1957.0	84	14.25	2538.9	182
10.47	1970.7	86	14.31	2547.9	184
10.56	1984.4	88	14.37	2557.0	186
10.65	1998.1	90	14.42	2564.5	188
10.74	2011.8	92	14.48	2573.5	190
10.84	2027.0	94	14.54	2582.5	192
10.93	2040.6	96	14.60	2591.6	194
11.01	2052.7	98	14.66	2600.6	196

TABLE VII

TEST DATA FOR TUNGSTEN RUN TUN 9-9 WITH A CONTROL EMF OF 0.25 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.09	1262.9	2	11.08	2063.3	96
6.21	1283.5	4	11.17	2076.9	98
6.34	1304.0	6	11.27	2092.0	100
6.46	1326.2	8	11.36	2105.6	102
6.58	1346.5	10	11.45	2119.1	104
6.70	1366.8	12	11.55	2134.2	106
6.82	1387.0	14	11.64	2147.7	108
6.93	1405.5	16	11.72	2159.7	110
7.05	1425.6	18	11.82	2174.7	112
7.17	1445.6	20	11.91	2188.2	114
7.28	1463.9	22	11.99	2200.2	116
7.40	1483.8	24	12.08	2213.7	118
7.51	1501.9	26	12.16	2225.7	120
7.63	1521.7	28	12.25	2239.2	122
7.74	1539.7	30	12.34	2252.6	124
7.85	1557.7	32	12.43	2266.1	126
7.95	1574.0	34	12.51	2278.1	128
8.06	1591.9	36	12.60	2291.5	130
8.17	1609.7	38	12.68	2203.5	132
8.28	1627.5	40	12.77	2316.9	134
8.39	1645.2	42	12.85	2328.9	136
8.50	1662.9	44	12.93	2340.9	138
8.61	1680.5	46	13.01	2352.9	140
8.71	1696.4	48	13.09	2364.9	142
8.81	1712.3	50	13.17	2376.8	144
8.92	1729.8	52	13.25	2388.8	146
9.02	1745.6	54	13.32	2399.3	148
9.12	1761.4	56	13.40	2411.3	150
9.22	1777.2	58	13.48	2423.3	152
9.32	1792.9	60	13.56	2435.3	154
9.43	1810.1	62	13.64	2447.3	156
9.53	1825.8	64	13.71	2457.8	158
9.63	1841.3	66	13.78	2468.3	160
9.73	1856.9	68	13.85	2478.8	162
9.83	1872.4	70	13.92	2489.3	164
9.93	1887.8	72	13.99	2499.8	166
10.02	1901.8	74	14.06	2510.4	168
10.12	1917.2	76	14.12	2519.4	170
10.22	1932.5	78	14.19	2529.9	172
10.32	1947.8	80	14.26	2540.4	174
10.42	1963.1	82	14.33	2550.9	176
10.51	1976.8	84	14.39	2560.0	178
10.61	1992.0	86	14.46	2570.5	180
10.70	2005.7	88	14.53	2581.0	182
10.80	2020.9	90	14.59	2590.1	184
10.90	2036.1	92	14.65	2599.1	186
10.99	2049.7	94			

TABLE VIII

TEST DATA FOR SYNTHETIC SAPPHIRE RUN ALO 9-17 WITH A CONTROL EMF OF 0.25 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.09	1262.9	2	10.88	2033.0	106
6.19	1280.1	4	10.96	2045.2	108
6.30	1298.9	6	11.05	2058.8	110
6.40	1315.9	8	11.13	2070.9	112
6.51	1334.7	10	11.21	2083.0	114
6.62	1353.3	12	11.29	2095.0	116
6.72	1370.2	14	11.37	2107.1	118
6.83	1388.7	16	11.45	2119.1	120
6.93	1405.5	18	11.53	2131.2	122
7.02	1420.6	20	11.61	2143.2	124
7.13	1438.9	22	11.70	2156.7	126
7.23	1455.6	24	11.78	2168.7	128
7.32	1470.5	26	11.86	2180.7	130
7.42	1487.1	28	11.94	2192.7	132
7.52	1503.6	30	12.02	2204.7	134
7.62	1520.0	32	12.09	2215.2	136
7.71	1534.8	34	12.17	2227.2	138
7.81	1551.2	36	12.25	2239.2	140
7.90	1565.9	38	12.33	2251.1	142
7.99	1580.5	40	12.41	2263.1	144
8.09	1596.7	42	12.48	2273.6	146
8.18	1611.3	44	12.56	2285.5	148
8.27	1625.9	48	12.63	2296.0	150
8.37	1642.0	48	12.70	2306.5	152
8.46	1656.4	50	12.78	2318.4	154
8.55	1670.9	52	12.86	2330.4	156
8.64	1685.3	54	12.94	2342.4	158
8.73	1699.6	56	13.02	2354.4	160
8.82	1713.9	58	13.10	2366.4	162
8.91	1728.2	60	13.17	2376.8	164
9.00	1742.5	62	13.24	2387.3	166
9.09	1756.7	64	13.31	2397.8	168
9.18	1770.9	66	13.38	2408.3	170
9.27	1785.0	68	13.46	2420.3	172
9.36	1799.2	70	13.53	2430.8	174
9.44	1811.7	72	13.61	2442.8	176
9.53	1825.8	74	13.68	2453.3	178
9.62	1839.8	76	13.75	2463.8	180
9.70	1852.2	78	13.83	2475.8	182
9.78	1864.6	80	13.90	2486.3	184
9.87	1878.6	82	13.97	2496.8	186
9.96	1892.5	84	14.04	2507.4	188
10.04	1904.9	86	14.11	2517.9	190
10.13	1918.7	88	14.18	2528.4	192
10.21	1930.9	90	14.25	2538.9	194
10.29	1943.2	92	14.32	2549.4	196
10.37	1955.4	94	14.39	2560.0	198
10.46	1969.2	96	14.46	2570.5	200
10.54	1981.4	98	14.52	2579.5	202
10.63	1995.1	100	14.58	2588.6	204
10.71	2007.2	102	14.65	2599.1	206
10.80	2020.9	104			

TABLE IX

TEST DATA FOR SYNTHETIC SAPPHIRE RUN ALO 9-22 WITH A CONTROL EMF OF 0.25 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.03	1252.6	2	10.95	2043.7	108
6.14	1271.5	4	11.03	2055.8	110
6.25	1290.3	6	11.11	2066.3	112
6.36	1309.1	8	11.19	2079.9	114
6.46	1326.2	10	11.27	2092.0	116
6.57	1344.8	12	11.35	2104.1	118
6.68	1363.4	14	11.43	2116.1	120
6.78	1380.3	16	11.51	2128.2	122
6.88	1397.1	18	11.59	2140.2	124
6.98	1413.9	20	11.66	2150.7	126
7.09	1432.3	22	11.74	2162.7	128
7.19	1448.9	24	11.82	2174.7	130
7.29	1465.6	26	11.89	2185.2	132
7.39	1482.1	28	11.97	2197.2	134
7.49	1493.6	30	12.04	2207.7	136
7.59	1515.1	32	12.12	2219.7	138
7.68	1529.9	34	12.20	2231.7	140
7.78	1546.3	36	12.27	2242.2	142
7.88	1562.6	38	12.35	2254.1	144
7.97	1577.3	40	12.42	2264.6	146
8.07	1593.5	42	12.50	2276.6	148
8.16	1608.1	44	12.58	2288.5	150
8.26	1624.2	46	12.65	2299.0	152
8.36	1640.4	48	12.73	2311.0	154
8.45	1654.8	50	12.81	2322.9	156
8.54	1669.3	52	12.88	2333.4	158
8.62	1682.1	54	12.95	2343.9	160
8.71	1696.4	56	13.02	2354.4	162
8.80	1710.8	58	13.09	2364.9	164
8.89	1725.1	60	13.17	2376.8	166
8.98	1739.3	62	13.24	2387.3	168
9.07	1753.5	64	13.31	2397.8	170
9.16	1767.7	66	13.38	2408.3	172
9.25	1781.9	68	13.45	2418.8	174
9.34	1796.0	70	13.52	2429.3	176
9.43	1810.1	72	13.59	2439.8	178
9.52	1824.2	74	13.65	2448.8	180
9.61	1838.2	76	13.72	2459.3	182
9.69	1850.7	78	13.79	2469.8	184
9.78	1864.6	80	13.86	2480.3	186
9.87	1878.6	82	13.93	2490.8	188
9.96	1892.5	84	13.99	2499.8	190
10.05	1906.4	86	14.05	2508.9	192
10.13	1918.7	88	14.11	2517.9	194
10.22	1932.5	90	14.18	2528.4	196
10.30	1944.8	92	14.24	2537.4	198
10.38	1957.0	94	14.30	2546.4	200
10.47	1970.7	96	14.37	2557.0	202
10.55	1982.9	98	14.42	2564.5	204
10.64	1996.6	100	14.48	2573.5	206
10.72	2008.8	102	14.54	2582.5	208
10.80	2020.9	104	14.60	2591.6	210
10.88	2033.0	106	14.65	2599.1	212

TABLE X

TEST DATA FOR SYNTHETIC SAPPHIRE RUN ALO 10-15 WITH A CONTROL EMF OF 0.35 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.02	1250.8	2	10.14	1920.2	146
6.08	1261.2	4	10.19	1927.9	148
6.15	1273.2	6	10.25	1937.1	150
6.22	1285.2	8	10.31	1946.3	152
6.28	1295.5	10	10.37	1955.4	154
6.35	1307.4	12	10.43	1964.6	156
6.42	1319.3	14	10.49	1973.8	158
6.48	1329.6	16	10.56	1984.4	160
6.54	1339.7	18	10.62	1993.6	162
6.61	1351.6	20	10.69	2004.2	164
6.67	1361.8	22	10.76	2014.8	166
6.73	1371.9	24	10.82	2023.9	168
6.80	1383.7	26	10.88	2033.0	170
6.86	1393.8	28	10.95	2043.7	172
6.92	1403.8	30	11.01	2052.7	174
6.99	1415.6	32	11.08	2063.3	176
7.04	1423.9	34	11.14	2072.4	178
7.11	1435.6	36	11.20	2081.4	180
7.17	1445.6	38	11.26	2090.5	186
7.23	1455.6	40	11.33	2101.1	184
7.29	1465.6	42	11.39	2110.1	186
7.35	1475.5	44	11.45	2119.1	188
7.41	1485.4	46	11.51	2128.2	190
7.48	1497.0	48	11.58	2138.7	192
7.54	1506.9	50	11.64	2147.7	194
7.59	1515.1	52	11.70	2156.7	196
7.65	1525.0	54	11.76	2165.7	198
7.71	1534.8	56	11.82	2174.7	200
7.78	1546.3	58	11.88	2183.7	202
7.83	1554.4	60	11.94	2192.7	204
7.90	1565.9	62	12.00	2201.7	206
7.95	1574.0	64	12.06	2210.7	208
8.01	1583.8	66	12.12	2219.7	210
8.07	1593.5	68	12.18	2228.7	212
8.12	1601.6	70	12.24	2237.7	214
8.18	1611.3	72	12.30	2246.6	216
8.24	1621.0	74	12.36	2255.6	218
8.29	1629.1	76	12.42	2264.6	220
8.35	1638.8	78	12.47	2272.1	222
8.40	1646.8	80	12.53	2281.0	224
8.46	1656.4	82	12.59	2290.0	226
8.51	1664.5	84	12.64	2297.5	228
8.57	1674.1	86	12.70	2306.5	230
8.62	1307.4	88	12.76	2315.4	232
8.67	1690.0	90	12.82	2324.4	234
8.73	1699.6	92	12.87	2331.9	236
8.78	1707.6	94	12.93	2340.9	238
8.83	1715.5	96	12.98	2348.4	240
8.89	1725.1	98	13.04	2357.4	242
8.94	1733.0	100	13.10	2366.4	244
8.99	1740.9	102	13.16	2375.3	246
9.04	1748.8	104	13.22	2384.3	248
9.10	1758.3	106	13.28	2393.3	250
9.15	1766.2	108	13.33	2400.8	252
9.20	1774.0	110	13.40	2411.3	254
9.25	1781.9	112	13.46	2420.3	256
9.31	1791.3	114	13.52	2429.3	258
9.36	1799.2	116	13.58	2438.3	260
9.42	1808.6	118	13.64	2447.3	262
9.47	1816.4	120	13.70	2456.3	264
9.52	1824.2	122	13.76	2465.3	266
9.57	1832.0	124	13.82	2474.3	268
9.62	1839.8	126	13.89	2484.8	270
9.67	1847.6	128	13.95	2493.8	272
9.72	1855.3	130	14.01	2502.8	274
9.77	1863.1	132	14.07	2511.9	276
9.83	1872.4	134	14.14	2522.4	278
9.88	1880.1	136	14.20	2531.4	280
9.93	1887.8	138	14.27	2541.9	282
9.99	1897.1	140	14.33	2550.9	284
10.04	1904.9	142	14.40	2561.5	286
10.09	1912.5	144	14.47	2572.0	288
			14.53	2581.0	290

TABLE XI

TEST DATA FOR TUNGSTEN RUN TUN 10-20 WITH A CONTROL EMF OF 0.35 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.04	1254.3	2	10.72	2008.8	88
6.16	1274.9	4	10.81	2022.4	90
6.28	1295.5	6	10.90	2036.1	92
6.40	1315.9	8	10.99	2049.7	94
6.52	1336.4	10	11.08	2063.3	96
6.64	1356.7	12	11.17	2076.9	98
6.76	1376.9	14	11.26	2090.5	100
6.88	1397.1	16	11.35	2104.1	102
6.99	1415.6	18	11.43	2116.1	104
7.10	1433.9	20	11.52	2129.7	106
8.21	1452.3	22	11.61	2143.2	108
7.33	1472.3	24	11.70	2156.7	110
7.44	1490.1	26	11.79	2170.2	112
7.55	1508.5	28	11.89	2185.2	114
7.66	1526.6	30	11.98	2198.7	116
7.77	1544.6	32	12.07	2212.2	118
7.88	1562.6	34	12.16	2225.7	120
7.98	1578.9	36	12.25	2239.2	122
8.09	1596.7	38	12.34	2252.6	124
8.20	1614.6	40	12.43	2266.1	126
8.31	1632.3	42	12.52	2279.5	128
8.41	1648.4	44	12.61	2293.0	130
8.52	1666.1	46	12.70	2306.5	132
8.62	1682.1	48	12.79	2319.9	134
8.72	1698.0	50	12.88	2333.4	136
8.82	1713.9	52	12.96	2345.4	138
8.93	1731.4	54	13.05	2358.9	140
9.03	1747.2	56	13.14	2372.3	142
9.14	1764.6	58	13.23	2385.8	144
9.25	1781.9	60	13.31	2397.8	146
9.36	1799.2	62	13.40	2411.3	148
9.48	1817.9	64	13.48	2423.3	150
9.59	1835.1	66	13.57	2436.8	152
9.70	1852.2	68	13.65	2448.8	154
9.82	1870.8	70	13.74	2462.3	156
8.93	1887.8	72	13.82	2474.3	158
10.04	1904.9	74	13.90	2486.3	160
10.14	1920.2	76	13.99	2499.8	162
10.25	1937.1	78	14.07	2511.9	164
10.35	1952.4	80	14.15	2523.9	166
10.45	1967.7	82	14.23	2535.9	168
10.54	1981.4	84	14.31	2547.9	170
10.63	1995.1	86	14.39	2560.0	172

TABLE XII

TEST DATA FOR TANTALUM RUN TAN 10-22 WITH A CONTROL EMF OF 0.35 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.03	1252.6	2	10.93	2040.6	94
6.15	1273.2	4	11.03	2055.8	96
6.28	1295.5	6	11.11	2067.9	98
6.41	1317.6	8	11.20	2081.4	100
6.59	1339.7	10	11.29	2095.0	102
6.66	1360.1	12	11.39	2110.1	104
6.78	1380.3	14	11.48	2123.6	106
6.90	1400.5	16	11.57	2137.2	108
7.02	1420.6	18	11.66	2150.7	110
7.14	1440.6	20	11.75	2164.2	112
7.25	1458.9	22	11.84	2177.7	114
7.37	1478.8	24	11.92	2189.7	116
7.48	1497.0	26	12.01	2203.2	118
7.60	1516.7	28	12.10	2216.7	120
7.71	1534.8	30	12.18	2228.7	122
7.82	1552.8	32	12.27	2242.2	124
7.93	1570.7	34	12.36	2255.6	126
8.04	1588.6	36	12.45	2269.1	128
8.15	1606.5	38	12.53	2281.0	130
8.26	1624.2	40	12.62	2294.5	132
8.37	1642.0	42	12.70	2306.5	134
8.48	1659.7	44	12.79	2319.9	136
8.58	1675.7	46	12.88	2333.4	138
8.68	1691.6	48	12.96	2345.4	140
8.79	1709.2	50	13.04	2357.4	142
8.89	1725.1	52	13.13	2370.8	144
8.99	1740.9	54	13.21	2382.8	146
9.09	1756.7	56	13.29	2394.8	148
9.19	1772.5	58	13.38	2408.3	150
9.30	1789.8	60	13.46	2420.3	152
9.40	1805.4	62	13.54	2432.3	154
9.50	1821.1	64	13.62	2444.3	156
9.60	1836.7	66	13.70	2456.3	158
9.69	1850.7	68	13.78	2468.3	160
9.79	1866.2	70	13.86	2480.3	162
9.89	1881.7	72	13.94	2492.3	164
9.99	1897.1	74	14.02	2504.3	166
10.08	1911.0	76	14.10	2516.4	168
10.18	1926.4	78	14.18	2528.4	170
10.27	1940.1	80	14.26	2540.4	172
10.36	1953.9	82	14.35	2554.0	174
10.46	1969.2	84	14.43	2566.0	176
10.56	1984.4	86	14.50	2576.5	178
10.65	1998.1	88	14.58	2588.6	180
10.74	2011.8	90	14.66	2600.6	182
10.83	2025.5	92			

TABLE XIII

TEST DATA FOR SYNTHETIC SAPPHIRE RUN ALO 10-27 WITH A CONTROL EMF OF 0.35 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.00	1247.4	2	10.71	2007.2	112
6.10	1264.6	4	10.79	2019.4	114
6.19	1280.1	6	10.86	2030.0	116
6.29	1297.2	8	10.94	2042.1	118
6.39	1314.2	10	11.02	2054.2	120
6.49	1331.3	12	11.09	2064.8	122
6.59	1348.2	14	11.16	2075.4	124
6.69	1365.1	16	11.24	2087.5	126
6.78	1380.3	18	11.32	2099.5	128
6.87	1395.4	20	11.39	2110.1	130
6.96	1410.5	22	11.47	2122.1	132
7.06	1427.3	24	11.54	2132.7	134
7.15	1442.3	26	11.62	2144.7	136
7.24	1457.3	28	11.69	2155.2	138
7.33	1472.2	30	11.76	2165.7	140
7.42	1487.1	32	11.84	2177.7	142
7.51	1501.9	34	11.91	2188.2	144
7.60	1516.7	36	11.98	2198.7	146
7.69	1531.5	38	12.06	2210.7	148
7.78	1546.3	40	12.13	2221.2	150
7.87	1561.0	42	12.20	2231.7	152
7.95	1574.0	44	12.28	2243.6	154
8.04	1588.6	46	12.35	2254.1	156
8.13	1603.2	48	12.42	2264.6	158
8.21	1616.2	50	12.50	2276.6	160
8.30	1630.7	52	12.57	2287.0	162
8.39	1645.2	54	12.64	2297.5	164
8.47	1658.0	56	12.71	2308.0	166
8.55	1670.9	58	12.78	2318.4	168
8.63	1683.7	60	12.85	2328.9	170
8.72	1698.0	62	12.92	2339.4	172
8.80	1710.8	64	12.99	2349.9	174
8.88	1723.5	66	13.07	2361.9	176
8.97	1737.7	68	13.13	2370.8	178
9.04	1748.8	70	13.20	2381.3	180
9.13	1763.0	72	13.27	2391.8	182
9.21	1775.6	74	13.34	2402.3	184
9.29	1788.2	76	13.41	2412.8	186
9.37	1800.7	78	13.48	2423.3	188
9.45	1813.3	80	13.55	2433.8	190
9.54	1827.2	82	13.62	2444.3	192
9.62	1839.8	84	13.68	2453.3	194
9.70	1852.2	86	13.75	2463.8	196
9.78	1864.6	88	13.82	2474.3	198
9.86	1877.0	90	13.88	2483.3	200
9.93	1887.8	92	13.95	2493.8	202
10.01	1900.2	94	14.02	2504.3	204
10.09	1912.5	96	14.09	2514.9	206
10.17	1924.8	98	14.16	2525.4	208
10.24	1935.6	100	14.22	2534.4	210
10.32	1947.8	102	14.29	2544.9	212
10.40	1960.0	104	14.36	2555.5	214
10.48	1972.2	106	14.42	2564.5	216
10.55	1982.9	108	14.48	2573.5	218
10.63	1995.1	110			

TABLE XIV

TEST DATA FOR TANTALUM RUN TAN 10-29 WITH A CONTROL EMF OF 0.35 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.09	1262.9	2	10.82	2023.9	94
6.20	1281.8	4	10.90	2036.1	96
6.32	1302.3	6	11.00	2051.2	98
6.44	1322.7	8	11.09	2064.8	100
6.56	1343.1	10	11.18	2078.4	102
6.67	1361.8	12	11.27	2092.0	104
6.79	1382.0	14	11.36	2105.6	106
6.90	1400.5	16	11.45	2119.1	108
7.01	1418.9	18	11.54	2132.7	110
7.12	1437.3	20	11.63	2146.2	112
7.23	1455.6	22	11.72	2159.7	114
7.34	1473.8	24	11.81	2173.2	116
7.45	1492.0	26	11.90	2186.7	118
7.56	1510.2	28	11.98	2198.7	120
7.66	1526.6	30	12.07	2212.2	122
7.77	1544.6	32	12.16	2225.7	124
7.87	1561.0	34	12.25	2239.2	126
7.97	1577.3	36	12.34	2252.6	128
8.07	1593.5	38	12.43	2266.1	130
8.18	1611.3	40	12.52	2279.5	132
8.29	1629.1	42	12.60	2291.5	134
8.39	1645.2	44	12.68	2303.5	136
8.50	1662.9	46	12.77	2316.9	138
8.60	1678.9	48	12.86	2330.4	140
8.70	1694.8	50	12.95	2343.9	142
8.80	1710.8	52	13.03	2355.9	144
8.90	1726.6	54	13.12	2369.3	146
9.00	1742.5	56	13.21	2382.8	148
9.10	1758.3	58	13.29	2394.8	150
9.20	1774.0	60	13.38	2408.3	152
9.29	1788.2	62	13.47	2421.8	154
9.39	1803.9	64	13.55	2433.8	156
9.49	1819.5	66	13.64	2447.3	158
9.59	1835.1	68	13.72	2459.3	160
9.69	1850.7	70	13.80	2471.3	162
9.78	1864.6	72	13.89	2484.8	164
9.87	1878.6	74	13.98	2498.3	166
9.97	1894.0	76	14.06	2510.4	168
10.07	1909.4	78	14.14	2522.4	170
10.16	1923.3	80	14.22	2534.4	172
10.26	1938.6	82	14.30	2546.4	174
10.36	1953.9	84	14.39	2560.0	176
10.45	1967.7	86	14.47	2572.0	178
10.54	1981.4	88	14.55	2584.1	180
10.64	1996.6	90	14.63	2596.1	182
10.72	2008.8	92			

TABLE XV

TEST DATA FOR TUNGSTEN RUN TUN 10-31 WITH A CONTROL EMF OF 0.35 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.07	1259.4	2	10.20	1929.4	86
6.19	1280.1	4	10.29	1943.2	88
6.30	1298.9	6	10.38	1957.0	90
6.41	1317.6	8	10.47	1970.7	92
6.52	1336.4	10	10.56	1984.8	94
6.63	1355.0	12	10.64	1996.6	96
6.73	1371.9	14	10.72	2008.8	98
6.84	1390.4	16	10.81	2022.4	100
6.95	1408.9	18	10.90	2036.1	102
7.05	1425.6	20	10.98	2048.2	104
7.15	1442.3	22	11.06	2070.3	106
7.26	1460.6	24	11.15	2073.9	108
7.37	1478.8	26	11.24	2087.4	110
7.47	1495.3	28	11.33	2101.1	112
7.58	1513.5	30	11.41	2113.1	114
7.68	1529.9	32	11.50	2126.6	116
7.77	1544.6	34	11.57	2137.2	118
7.87	1561.0	36	11.65	2149.2	120
7.97	1577.3	38	11.74	2162.7	122
8.07	1593.5	40	11.83	2176.2	124
8.17	1609.7	42	11.95	2194.2	126
8.27	1625.9	44	12.03	2206.2	128
8.36	1640.4	46	12.11	2218.2	130
8.46	1656.4	48	12.23	2236.2	132
8.56	1672.5	50	12.32	2249.6	134
8.65	1686.9	52	12.41	2263.1	136
8.75	1702.8	54	12.49	2275.1	138
8.84	1717.1	56	12.57	2287.0	140
8.94	1733.0	58	12.65	2299.0	142
9.03	1747.2	60	12.73	2311.0	144
9.12	1761.4	62	12.82	2324.4	146
9.22	1777.2	64	12.90	2336.8	148
9.31	1796.3	66	12.99	2349.9	150
9.40	1805.4	68	13.06	2360.4	152
9.49	1819.5	70	13.14	2372.3	154
9.58	1833.5	72	13.23	2385.8	156
9.67	1847.6	74	13.30	2396.3	158
9.76	1861.5	76	13.39	2409.8	160
9.85	1875.5	78	13.46	2420.3	162
9.94	1889.4	80	13.54	2432.3	164
10.02	1901.8	82	13.62	2444.3	166
10.11	1915.6	84			

TABLE XVI

TEST DATA FOR TUNGSTEN RUN TUN 11-3 WITH A CONTROL EMF OF 0.35 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.21	1283.5	2	10.75	2013.3	90
6.35	1307.4	4	10.84	2027.0	92
6.49	1331.3	6	10.94	2042.1	94
6.60	1349.9	8	11.03	2055.8	96
6.72	1370.2	10	11.13	2070.9	98
6.83	1388.7	12	11.22	2084.5	100
6.95	1408.9	14	11.31	2098.0	102
7.05	1425.6	16	11.39	2110.1	104
7.17	1445.6	18	11.48	2123.6	106
7.28	1463.9	20	11.58	2138.7	108
7.40	1483.8	22	11.66	2150.7	110
7.51	1501.9	24	11.77	2167.2	112
7.62	1520.0	26	11.86	2180.7	114
7.73	1538.1	28	11.94	2192.7	116
7.84	1556.1	30	12.03	2206.2	118
7.95	1574.0	32	12.12	2219.7	120
8.04	1588.6	34	12.21	2233.2	122
8.16	1608.1	36	12.30	2246.6	124
8.25	1622.6	38	12.40	2261.6	126
8.34	1637.1	40	12.49	2275.1	128
8.45	1654.8	42	12.58	2288.5	130
8.54	1669.3	44	12.66	2300.5	132
8.65	1686.9	46	12.76	2315.4	134
8.73	1699.6	48	12.84	2327.4	136
8.85	1718.7	50	12.94	2342.4	138
8.94	1733.0	52	13.02	2354.4	140
9.05	1750.4	54	13.12	2369.3	142
9.14	1764.6	56	13.21	2382.8	144
9.23	1778.8	58	13.29	2394.8	146
9.32	1792.9	60	13.38	2408.3	148
9.42	1808.6	62	13.46	2420.3	150
9.51	1822.6	64	13.54	2432.3	152
9.61	1838.2	66	13.62	2444.3	154
9.71	1853.8	68	13.72	2459.3	156
9.80	1867.7	70	13.79	2469.8	158
9.90	1883.2	72	13.88	2483.0	160
9.99	1897.1	74	13.95	2493.8	162
10.09	1912.5	76	14.02	2504.3	164
10.19	1927.9	78	14.10	2516.4	166
10.29	1943.2	80	14.18	2528.4	168
10.38	1957.0	82	14.27	2541.9	170
10.48	1972.2	84	14.34	2552.4	172
10.57	1985.9	86	14.43	2566.0	174
10.66	1999.6	88			

TABLE XVII

TEST DATA FOR MOLYBDENUM RUN MOL 11-5 WITH A CONTROL EMF OF 0.35 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.02	1250.8	2	10.83	2025.5	100
6.13	1269.8	4	10.91	2037.6	102
6.25	1290.3	6	11.00	2051.2	104
6.36	1309.1	8	11.09	2064.8	106
6.48	1329.6	10	11.18	2078.4	108
6.59	1348.2	12	11.27	2092.0	110
6.70	1366.8	14	11.35	2104.1	112
6.80	1383.7	16	11.44	2117.6	114
6.90	1400.5	18	11.53	2131.2	116
7.01	1418.9	20	11.61	2143.2	118
7.12	1437.3	22	11.69	2155.2	120
7.22	1453.9	24	11.78	2168.7	122
7.33	1472.1	26	11.86	2182.2	124
7.44	1490.4	28	11.95	2194.2	126
7.54	1506.9	30	12.03	2206.2	128
7.64	1523.3	32	12.11	2218.2	130
7.74	1539.7	34	12.20	2231.7	132
7.84	1556.1	36	12.28	2243.6	134
7.95	1574.0	38	12.37	2257.1	136
8.05	1590.3	40	12.45	2269.1	138
8.14	1604.8	42	12.54	2282.5	140
8.24	1621.0	44	12.62	2294.5	142
8.34	1637.1	46	12.70	2306.5	144
8.44	1653.2	48	12.79	2319.9	146
8.54	1669.3	50	12.87	2331.9	148
8.64	1685.3	52	12.95	2343.9	150
8.73	1699.6	54	13.03	2355.9	152
8.83	1715.5	56	13.11	2367.8	154
8.92	1729.8	58	13.19	2379.8	156
9.01	1744.1	60	13.27	2391.8	158
9.11	1759.9	62	13.35	2403.8	160
9.21	1775.6	64	13.43	2415.8	162
9.30	1789.8	66	13.51	2427.8	164
9.40	1805.4	68	13.59	2439.8	166
9.49	1819.5	70	13.67	2457.8	168
9.58	1833.5	72	13.75	2463.8	170
9.68	1849.1	74	13.83	2475.8	172
9.77	1863.1	76	13.91	2487.8	174
9.86	1877.0	78	13.98	2498.3	176
9.94	1889.4	80	14.06	2510.4	178
10.04	1904.9	82	14.14	2522.4	180
10.12	1917.2	84	14.22	2534.4	182
10.21	1930.9	86	14.29	2544.9	184
10.30	1944.8	88	14.36	2555.5	186
10.39	1958.5	90	14.44	2567.5	188
10.48	1972.2	92	14.51	2578.0	190
10.57	1985.9	94	14.59	2590.1	192
10.66	1999.6	96	14.96	2600.6	194
10.74	2011.8	98			

TABLE XVIII

TEST DATA FOR SYNTHETIC SAPPHIRE RUN ALO 11-7 WITH A CONTROL EMF OF 0.35 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.01	1249.1	2	10.75	2013.3	116
6.12	1266.3	4	10.82	2023.9	118
6.23	1286.9	6	10.89	2034.6	120
6.33	1304.0	8	10.97	2046.7	122
6.42	1319.3	10	11.03	2055.8	124
6.52	1336.4	12	11.10	2066.3	126
6.62	1353.3	14	11.19	2079.9	128
6.71	1368.5	16	11.27	2092.0	130
6.80	1383.7	18	11.34	2102.6	132
6.90	1400.5	20	11.42	2114.6	134
6.99	1415.6	22	11.49	2125.1	136
7.08	1430.6	24	11.55	2134.2	138
7.17	1445.6	26	11.62	2144.7	140
7.26	1460.6	28	11.69	2155.2	142
7.35	1475.5	30	11.76	2165.7	144
7.45	1492.0	32	11.82	2174.7	146
7.53	1505.2	34	11.90	2186.7	148
7.62	1520.0	36	11.97	2197.2	150
7.70	1533.2	38	12.05	2209.2	152
7.78	1562.6	40	12.12	2219.7	154
7.87	1561.0	42	12.19	2230.2	156
7.96	1575.6	44	12.25	2239.2	158
8.04	1588.6	47	12.33	2251.1	160
8.12	1601.6	48	12.40	2261.6	162
8.20	1614.6	50	12.47	2272.1	164
8.29	1629.1	52	12.54	2282.5	166
8.37	1642.0	54	12.61	2293.0	168
8.45	1654.8	56	12.68	2303.5	170
8.53	1667.7	58	12.75	2314.0	172
8.61	1680.5	60	12.82	2324.4	174
8.70	1694.8	62	12.89	2334.9	176
8.77	1706.0	64	12.96	2345.4	178
8.85	1718.7	66	13.03	2355.9	180
8.93	1731.4	68	13.10	2366.4	182
9.01	1744.1	70	13.16	2375.3	184
9.09	1756.7	72	13.23	2385.8	186
9.17	1769.3	74	13.30	2396.3	188
9.24	1780.3	76	13.37	2406.8	190
9.33	1794.5	78	13.44	2417.3	192
9.40	1805.4	80	13.51	2427.8	194
9.48	1817.9	82	13.57	2436.8	196
9.55	1828.9	84	13.64	2447.3	198
9.63	1841.3	86	13.71	2457.8	200
9.70	1852.2	88	13.78	2468.3	202
9.78	1864.6	90	13.84	2477.3	204
9.85	1875.5	92	13.91	2487.8	206
9.93	1887.8	94	13.98	2498.3	208
10.00	1898.7	96	14.04	2507.4	210
10.08	1911.0	98	14.11	2517.9	212
10.15	1921.7	100	14.18	2528.4	214
10.23	1934.0	102	14.24	2537.4	216
10.30	1944.8	104	14.31	2547.9	218
10.38	1957.0	106	14.37	2557.0	220
10.45	1967.7	108	14.44	2567.5	222
10.53	1979.9	110	14.50	2576.5	224
10.60	1990.5	112	14.57	2587.1	226
10.67	2001.2	114	14.63	2596.1	228

TABLE XIX

TEST DATA FOR MOLYBDENUM RUN MOL 11-10 WITH A CONTROL EMF OF 0.35 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
5.96	1240.5	2	10.81	2022.4	104
6.08	1261.2	4	10.89	2034.6	106
6.19	1280.1	6	10.98	2048.2	108
6.30	1298.9	8	11.06	2060.3	110
6.42	1319.3	10	11.14	2072.4	112
6.52	1336.4	12	11.22	2084.5	114
6.63	1355.0	14	11.30	2096.5	116
6.74	1373.6	16	11.38	2108.6	118
6.85	1392.1	18	11.47	2122.1	120
6.95	1408.9	20.	11.55	2134.2	122
7.06	1427.3	22	11.63	2146.2	124
7.16	1443.9	24	11.71	2158.2	126
7.26	1460.6	26	11.79	2170.2	128
7.36	1477.1	28	11.87	2182.2	130
8.46	1493.7	30	11.95	2194.2	132
7.57	1511.8	32	12.04	2207.7	134
7.66	1526.6	34	12.11	2218.2	136
7.76	1543.0	36	12.19	2230.2	138
7.86	1559.3	38	12.27	2242.2	140
7.95	1574.0	40	12.35	2254.1	142
8.05	1590.3	42	12.43	2266.1	144
8.14	1604.8	44	12.51	2278.1	146
8.24	1621.0	46	12.59	2290.0	148
8.34	1637.1	48	12.67	2302.0	150
8.44	1653.2	50	12.75	2314.0	152
8.53	1667.7	52	12.83	2325.9	154
8.62	1682.1	54	12.91	2337.9	156
8.71	1696.4	56	12.99	2349.9	158
8.81	1712.3	58	13.07	2361.9	160
8.90	1726.6	60	13.15	2373.8	162
8.99	1740.9	62	13.22	2384.3	164
9.08	1755.1	64	13.30	2396.3	166
9.18	1770.9	66	13.38	2408.3	168
9.26	1783.5	68	13.45	2418.8	170
9.35	1797.6	70	13.53	2430.8	172
9.44	1811.7	72	13.60	2441.3	174
9.54	1827.2	74	13.68	2453.3	176
9.62	1839.8	76	13.76	2465.3	178
9.71	1853.8	78	13.83	2475.8	180
9.80	1867.7	80	13.91	2487.8	182
9.88	1880.1	82	13.98	2498.3	184
9.97	1894.0	84	14.06	2510.4	186
10.06	1907.9	86	14.13	2520.9	188
10.14	1920.2	88	14.21	2532.9	190
10.23	1934.0	90	14.28	2543.4	192
10.31	1946.3	92	14.36	2555.5	194
10.40	1960.0	94	14.43	2566.0	196
10.48	1972.2	96	14.51	2578.0	198
10.56	1984.4	98	14.59	2590.1	200
10.65	1998.1	100	14.66	2600.6	202
10.73	2010.3	102			

TABLE XX

TEST DATA FOR TUNGSTEN RUN TUN 11-12 WITH A CONTROL EMF OF 0.35 MILLIVOLTS

Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)	Potentiometer Reading (millivolts)	Temperature (°F)	Time (minutes)
6.03	1252.6	2	10.78	2017.9	98
6.15	1273.2	4	10.87	2031.5	100
6.27	1293.8	6	10.96	2045.2	102
6.39	1314.2	8	11.04	2057.3	104
6.50	1333.0	10	11.13	2070.9	106
6.62	1353.3	12	11.21	2083.0	108
6.73	1371.9	14	11.30	2096.5	110
6.85	1392.1	16	11.38	2108.6	112
6.96	1410.5	18	11.47	2122.1	114
7.07	1428.9	20	11.56	2135.7	116
7.18	1447.3	22	11.64	2147.7	118
7.28	1463.9	24	11.72	2159.7	120
7.38	1480.9	26	11.81	2173.2	122
7.49	1498.6	28	11.90	2186.7	124
7.60	1516.7	30	11.98	2198.7	126
7.70	1533.2	32	12.06	2210.7	128
7.80	1549.5	34	12.14	2222.7	130
7.90	1565.9	36	12.23	2236.2	132
8.00	1582.1	38	12.32	2249.6	134
8.10	1598.4	40	12.40	2261.6	136
8.20	1614.6	42	12.48	2273.6	138
8.30	1630.7	44	12.56	2285.5	140
8.40	1646.8	46	12.64	2297.5	142
8.50	1662.9	48	12.73	2311.0	144
8.59	1677.3	50	12.81	2322.8	146
8.69	1693.2	52	12.89	2334.9	148
8.78	1707.6	54	12.97	2346.9	150
8.88	1723.5	56	13.05	2358.9	152
8.97	1737.7	58	13.14	2372.3	154
9.07	1753.5	60	13.22	2384.3	156
9.16	1767.7	62	13.30	2396.3	158
9.26	1783.5	64	13.38	2408.3	160
9.35	1797.6	66	13.46	2420.3	162
9.45	1813.3	68	13.54	2432.3	164
9.54	1827.2	70	13.62	2444.3	166
9.63	1841.3	72	13.70	2456.3	168
9.71	1853.8	74	13.78	2468.3	170
9.81	1869.3	76	13.86	2480.3	172
9.90	1883.2	78	13.94	2492.3	174
9.99	1897.1	80	14.02	2504.3	176
10.08	1911.0	82	14.10	2516.4	178
10.16	1923.3	84	14.18	2528.4	180
10.26	1938.6	86	14.25	2538.9	182
10.35	1952.4	88	14.33	2550.9	184
10.43	1964.6	90	14.41	2563.0	186
10.52	1978.3	92	14.48	2573.5	188
10.61	1992.0	94	14.56	2585.6	190
10.70	2005.7	96	14.64	2597.6	192

APPENDIX C

CALCULATION OF SPECIFIC HEATS

TABLE XXI

EVALUATION OF THE INVERSE SLOPES

T (°F)	$T^2 \times 10^{-6}$ ($°F^2$)	R $\frac{\text{minutes}}{°F}$	T (°F)	$T^2 \times 10^{-6}$ ($°F^2$)	R $\frac{\text{minutes}}{°F}$
	RUN TUN 9-3			RUN TUN 9-3	
1500	2.25	0.1675	1500	2.25	0.1238
1600	2.56	0.1638	1600	2.56	0.1292
1700	2.89	0.1631	1700	2.89	0.1346
1800	3.24	0.1655	1800	3.24	0.1402
1900	3.61	0.1709	1900	3.61	0.1459
2000	4.00	0.1794	2000	4.00	0.1517
2100	4.41	0.1909	2100	4.41	0.1576
2200	4.84	0.2054	2200	4.84	0.1636
2300	5.29	0.2230	2300	5.29	0.1698
2400	5.76	0.2437	2400	5.76	0.1760
2500	6.25	0.2673	2500	6.25	0.1824
2600	6.76	0.2940	2600	6.76	0.1889
	RUN MOL 9-8			RUN TAN 9-4	
1500	2.25	0.1200	1500	2.25	0.1247
1600	2.56	0.1208	1600	2.56	0.1277
1700	2.89	0.1234	1700	2.89	0.1317
1800	3.24	0.1277	1800	3.24	0.1364
1900	3.61	0.1397	1900	3.61	0.1422
2000	4.00	0.1414	2000	4.00	0.1489
2100	4.41	0.1509	2100	4.41	0.1566
2200	4.84	0.1620	2200	4.84	0.1651
2300	5.29	0.1749	2300	5.29	0.1746
2400	5.76	0.1894	2400	5.76	0.1851
2500	6.25	0.2057	2500	6.25	0.1965
2600	6.76	0.2237	2600	6.76	0.2087

TABLE XXI (Cont'd)

EVALUATION OF THE INVERSE SLOPES

T (^oF)	$T^2 \times 10^{-6}$ ($^oF^2$)	R $\frac{\text{minutes}}{^oF}$	T (^oF)	$T^2 \times 10^{-6}$ ($^oF^2$)	R $\frac{\text{minutes}}{^oF}$
	RUN TUN 9-9			RUN MOL 11-5	
1500	2.25	0.1140	1500	2.25	.1189
1600	2.56	0.1154	1600	2.56	.1251
1700	2.89	0.1183	1700	2.89	.1311
1800	3.24	0.1225	1800	3.24	.1370
1900	3.61	0.1280	1900	3.61	.1426
2000	4.00	0.1350	2000	4.00	.1481
2100	4.41	0.1433	2100	4.41	.1534
2200	4.84	0.1529	2200	4.84	.1584
2300	5.29	0.1639	2300	5.29	.1633
2400	5.76	0.1763	2400	5.76	.1681
2500	6.25	0.1900	2500	6.25	.1726
2600	6.76	0.2052	2600	6.76	.1769
	RUN TUN 11-12			RUN ALO 11-7	
1500	2.25	.1163	1500	2.25	.1396
1600	2.56	.1241	1600	2.56	.1486
1700	2.89	.1313	1700	2.89	.1571
1800	3.24	.1380	1800	3.24	.1648
1900	3.61	.1441	1900	3.61	.1718
2000	4.00	.1496	2000	4.00	.1782
2100	4.41	.1546	2100	4.41	.1839
2200	4.84	.1590	2200	4.84	.1889
2300	5.29	.1628	2300	5.24	.1933
2400	5.76	.1660	2400	5.76	.1970
2500	6.25	.1687	2500	6.25	.2000
2600	6.76	.1708	2600	6.76	.2024

TABLE XXI (Cont'd)

EVALUATION OF THE INVERSE SLOPES

T (°F)	$T^2 \times 10^{-6}$ ($°F^2$)	R minutes/°F	T (°F)	$T^2 \times 10^{-6}$ ($°F^2$)	R minutes/°F
	RUN TUN 10-20			RUN ALO 10-27	
1500	2.25	.1073	1500	2.25	.1366
1600	2.56	.1132	1600	2.56	.1437
1700	2.89	.1189	1700	2.89	.1506
1800	3.24	.1246	1800	3.24	.1574
1900	3.61	.1302	1900	3.61	.1639
2000	4.00	.1358	2000	4.00	.1703
2100	4.41	.1413	2100	4.41	.1765
2200	4.84	.1466	2200	4.84	.1825
2300	5.29	.1519	2300	5.29	.1884
2400	5.76	.1571	2400	5.76	.1940
2500	6.25	.1623	2500	6.25	.1995
2600	6.76	.1673	2600	6.76	.2048
	RUN TAN 10-22			RUN TAN 10-29	
1500	2.25	.1057	1500	2.25	.1129
1600	2.56	.1134	1600	2.56	.1193
1700	2.89	.1208	1700	2.89	.1254
1800	3.24	.1278	1800	3.24	.1311
1900	3.61	.1343	1900	3.61	.1364
2000	4.00	.1405	2000	4.00	.1413
2100	4.41	.1463	2100	4.41	.1459
2200	4.84	.1517	2200	4.84	.1500
2300	5.29	.1567	2300	5.29	.1537
2400	5.76	.1613	2400	5.76	.1566
2500	6.25	.1655	2500	6.25	.1601
2600	6.76	.1693	2600	6.76	.1626

TABLE XXI (Cont'd)

EVALUATION OF THE INVERSE SLOPES

T (^{o}F)	$T^2 \times 10^{-6}$ ($^{o}F^2$)	R $\frac{\text{minutes}}{^{o}F}$	T (^{o}F)	$T^2 \times 10^{-6}$ ($^{o}F^2$)	R $\frac{\text{minutes}}{^{o}F}$
RUN TUN 10-31			RUN MOL 11-10		
1500	2.25	.1205	1500	2.25	.1197
1600	2.56	.1270	1600	2.56	.1285
1700	2.89	.1332	1700	2.89	.1365
1800	3.24	.1388	1800	3.24	.1439
1900	3.61	.1441	1900	3.61	.1506
2000	4.00	.1489	2000	4.00	.1565
2100	4.41	.1533	2100	4.41	.1617
2200	4.84	.1572	2200	4.84	.1662
2300	5.29	.1607	2300	5.29	.1700
2400	5.76	.1638	2400	3.76	.1730
2500	6.25	.1664	2500	6.25	.1754
2600	6.76	.1686	2600	6.76	.1770
RUN TUN 11-3					
1500	2.25	.1161			
1600	2.56	.1209			
1700	2.89	.1256			
1800	3.24	.1305			
1900	3.61	.1351			
2000	4.00	.1398			
2100	4.41	.1443			
2200	4.84	.1488			
2300	5.29	.1534			
2400	5.76	.1578			
2500	6.25	.1622			
2600	6.76	.1665			

TABLE XXII

DETERMINATION OF THE SPECIFIC HEAT OF TANTALUM

A Temperature ^{o}F	B $R_{TAN} - R_{TUN}$ $\frac{minutes}{^{o}F}$	C $R_{ALO} - R_{TUN}$ $\frac{minutes}{^{o}F}$	D B/C	E $C_{ALO} - C_{TUN}$ $\frac{Btu-gm}{lb_m-^{o}F}$	F D x E	G C_{TUN} $\frac{Btu-gm}{lb_m-^{o}F}$	H C_{TAN} $\frac{Btu-gm}{lb_m-^{o}F}$	I Weight (gm)	J $c_p = \frac{H}{I}$ $\frac{Btu}{lb_m-^{o}F}$
FROM RUN TAN 9-4 USING STANDARD RUNS TUN 9-3 AND ALO 9-7									
1500	+.0009	.0437	+.0206	5.323	+.110	7.479	7.589	181.5	.0418
1600	-.0015	.0346	-.0434	5.349	-.232	7.527	7.295	181.5	.0402
1700	-.0029	.0285	-.1018	5.362	-.546	7.575	7.029	181.5	.0387
1800	-.0038	.0253	-.1502	5.369	-.806	7.624	6.818	181.5	.0376
1900	-.0037	.0250	-.1480	5.375	-.796	7.670	6.874	181.5	.0379
2000	-.0028	.0277	-.1011	5.373	-.543	7.720	7.177	181.5	.0395
2100	-.0010	.0333	-.0300	5.364	-.161	7.768	7.607	181.5	.0419
2200	+.0015	.0418	+.0359	5.352	+.192	7.814	8.006	181.5	.0441
2300	+.0048	.0532	+.0902	5.335	+.481	7.862	8.343	181.5	.0460
2400	+.0091	.0677	+.1344	5.314	+.714	7.913	8.627	181.5	.0475
2500	+.0141	.0849	+.1663	5.294	+.880	7.959	8.839	181.5	.0487
2600	+.0189	.1051	+.1798	5.267	+.947	8.007	8.954	181.5	.0493
FROM RUN TAN 10-22 USING STANDARD RUNS TUN 10-20 AND ALO 10-27									
1500	-.0016	.0293	-.0546	5.323	-.291	7.479	7.188	181.5	.0396
1600	+.0002	.0305	+.0066	5.349	+.035	7.527	7.562	181.5	.0417
1700	+.0019	.0317	+.0599	5.362	+.321	7.575	7.896	181.5	.0435
1800	+.0032	.0328	+.0976	5.369	+.524	7.624	8.148	181.5	.0449
1900	+.0041	.0337	+.1217	5.375	+.654	7.670	8.324	181.5	.0459
2000	+.0047	.0345	+.1362	5.373.	+.732	7.720	8.452	181.5	.0466
2100	+.0050	.0352	+.1420	5.364	+.762	7.768	8.530	181.5	.0470
2200	+.0051	.0359	+.1421	5.352	+.761	7.814	8.575	181.5	.0472
2300	+.0048	.0365	+.1315	5.335	+.702	7.862	8.564	181.5	.0472
2400	+.0042	.0369	+.1138	5.314	+.605	7.913	8.518	181.5	.0469
2500	+.0032	.0372	+.0860	5.294	+.455	7.959	8.414	181.5	.0463
2600	+.0020	.0375	+.0533	5.267	+.281	8.007	8.288	181.5	.0457

TABLE XXII (Continued)

DETERMINATION OF THE SPECIFIC HEAT OF TANTALUM

A Temperature ^{o}F	B $R_{TAN} - R_{TUN}$ $\frac{minutes}{^{o}F}$	C $R_{ALO} - R_{TUN}$ $\frac{minutes}{^{o}F}$	D B/C	E $C_{ALO} - C_{TUN}$ $\frac{Btu\text{-}gm}{lb_m\text{-}^{o}F}$	F D x E	G C_{TUN} $\frac{Btu\text{-}gm}{lb_m\text{-}^{o}F}$	H C_{TAN} $\frac{Btu\text{-}gm}{lb_m\text{-}^{o}F}$	I Weight (gm)	J $c_p = \frac{H}{I}$ $\frac{Btu}{lb_m\text{-}^{o}F}$
FROM RUN TAN 10-29 USING STANDARD RUNS TUN 11-3 AND ALO 10-27									
1500	-.0032	.0205	-.1561	5.323	-.831	7.479	6.648	181.5	.0366
1600	-.0016	.0228	-.0702	5.349	-.375	7.527	7.152	181.5	.0394
1700	-.0002	.0250	-.0080	5.362	-.043	7.575	7.532	181.5	.0415
1800	+.0006	.0269	+.0223	5.369	+.120	7.624	7.744	181.5	.0427
1900	+.0013	.0288	+.0451	5.375	+.242	7.670	7.912	181.5	.0436
2000	+.0015	.0305	+.0492	5.373	+.264	7.720	7.984	181.5	.0440
2100	+.0016	.0322	+.0497	5.364	+.267	7.768	8.035	181.5	.0443
2200	+.0012	.0337	+.0356	5.352	+.190	7.814	8.004	181.5	.0441
2300	+.0003	.0350	+.0086	5.335	+.046	7.862	7.908	181.5	.0436
2400	-.0012	.0362	-.0331	5.314	-.176	7.913	7.737	181.5	.0426
2500	-.0021	.0373	-.0563	5.294	-.298	7.959	7.661	181.5	.0422
2600	-.0039	.0383	-.1018	5.267	-.536	8.007	7.471	181.5	.0412

TABLE XXIII

DETERMINATION OF THE SPECIFIC HEAT OF MOLYBDENUM

A Temperature ^{o}F	B $R_{MOL} - R_{TUN}$ $\frac{minutes}{^{o}F}$	C $R_{ALO} - R_{TUN}$ $\frac{minutes}{^{o}F}$	D B/C	E $C_{ALO} - C_{TUN}$ $\frac{Btu-gm}{lb_m-^{o}F}$	F D x E	G C_{TUN} $\frac{Btu-gm}{lb_m-^{o}F}$	H C_{MOL} $\frac{Btu-gm}{lb_m-^{o}F}$	I Weight (gm)	J $c_p = \frac{H}{I}$ $\frac{Btu}{lb_m-^{o}F}$
FROM RUN MOL 9-8 USING STANDARD RUNS ALO 9-7 AND TUN 9-9									
1500	+.0060	.0535	+.1121	5.323	+.597	7.479	8.076	110.9	.0728
1600	+.0054	.0484	+.1116	5.349	+.597	7.527	8.124	110.9	.0732
1700	+.0051	.0448	+.1138	5.362	+.610	7.575	8.185	110.9	.0738
1800	+.0052	.0430	+.1209	5.369	+.649	7.624	8.273	110.9	.0746
1900	+.0057	.0429	+.1329	5.375	+.714	7.670	8.384	110.9	.0756
2000	+.0064	.0444	+.1441	5.373	+.774	7.720	8.494	110.9	.0766
2100	+.0056	.0476	+.1176	5.364	+.774	7.720	8.494	110.9	.0757
2200	+.0091	.0525	+.1733	5.352	+.928	7.814	8.742	110.9	.0788
2300	+.0110	.0591	+.1861	5.335	+.993	7.862	8.855	110.9	.0798
2400	+.0131	.0674	+.1944	5.314	+1.033	7.913	8.946	110.9	.0807
2500	+.0157	.0773	+.2031	5.294	+1.075	7.959	9.034	110.9	.0814
2600	+.0185	.0888	+.2083	5.267	+1.097	8.007	9.104	110.9	.0821
FROM RUN MOL 11-5 USING STANDARD RUNS TUN 11-3 AND ALO 11-7									
1500	+.0027	.0235	+.1149	5.323	+.612	8.091	7.479	110.9	.0730
1600	+.0042	.0278	+.1511	5.349	+.808	8.335	7.527	110.9	.0752
1700	+.0055	.0315	+.1746	5.362	+.936	8.511	7.575	110.9	.0767
1800	+.0065	.0343	+.1895	5.369	+1.017	8.641	7.624	110.9	.0779
1900	+.0075	.0367	+.2044	5.375	+1.099	8.769	7.670	110.9	.0791
2000	+.0083	.0384	+.2161	5.373	+1.161	8.881	7.720	110.9	.0801
2100	+.0091	.0396	+.2298	5.364	+1.233	9.001	7.768	110.9	.0812
2200	+.0096	.0401	+.2394	5.352	+1.281	9.095	7.814	110.9	.0820
2300	+.0099	.0399	+.2481	5.335	+1.324	9.186	7.862	110.9	.0828
2400	+.0103	.0392	+.2628	5.314	+1.397	9.310	7.913	110.9	.0839
2500	+.0104	.0378	+.2751	5.294	+1.456	9.415	7.959	110.9	.0849
2600	+.0104	.0359	+.2897	5.267	+1.526	9.533	8.007	110.9	.0860

TABLE XXIII (Continued)

DETERMINATION OF THE SPECIFIC HEAT OF MOLYBDENUM

A Temperature ^{o}F	B $R_{MOL} - R_{TUN}$ $\frac{\text{minutes}}{^{o}F}$	C $R_{ALO} - R_{TUN}$ $\frac{\text{minutes}}{^{o}F}$	D B/C	E $C_{ALO} - C_{TUN}$ $\frac{\text{Btu-gm}}{lb_m\text{-}^{o}F}$	F D x E	G C_{TUN} $\frac{\text{Btu-gm}}{lb_m\text{-}^{o}F}$	H C_{MOL} $\frac{\text{Btu-gm}}{lb_m\text{-}^{o}F}$	I Weight (gm)	J $c_p = \frac{H}{I}$ $\frac{\text{Btu}}{lb_m\text{-}^{o}F}$
FROM RUN MOL 11-10 USING STANDARD RUNS TUN 11-12 AND ALO 11-7									
1500	+.0034	.0233	+.1459	5.323	+0.777	7.479	8.256	110.9	.0752
1600	+.0044	.0246	+.1789	5.349	+0.957	7.527	8.484	110.9	.0773
1700	+.0052	.0258	+.2016	5.362	+1.081	71575	8.656	110.9	.0788
1800	+.0059	.0268	+.2201	5.369	+1.182	7.624	8.806	110.9	.0802
1900	+.0065	.0277	+.2346	5.375	+1.261	7.670	8.931	110.9	.0813
2000	+.0069	.0286	+.2412	5.373	+1.296	7.720	9.016	110.9	.0821
2100	+.0071	.0293	+.2423	5.364	+1.300	7.768	9.068	110.9	.0826
2200	+.0072	.0299	+.2408	5.352	+1.289	7.814	9.103	110.9	.0829
2300	+.0072	.0305	+.2361	5.335	+1.260	7.862	9.122	110.9	.0831
2400	+.0070	.0310	+.2258	5.314	+1.200	7.913	9.113	110.9	.0829
2500	+.0067	.0313	+.2140	5.294	+1.122	7.959	9.081	110.9	.0827
2600	+.0062	.0316	+.1962	5.267	+1.033	8.007	9.040	110.9	.0823

APPENDIX D

SPECIFIC HEAT DATA FOR THE STANDARD MATERIALS

TABLE XXIV

SPECIFIC HEAT OF SYNTHETIC SAPPHIRE (AL_2O_3) FROM THE EQUATION PRESENTED IN REFERENCE 15

A T (°F)	B T (°K)	C $148.57 - 3.421 \times 10^{-3} \times B$	D $\frac{20,409.6}{B}$	E $C_p = C - D$ $\frac{\text{Abs. J.}}{^\circ K\text{-mole}}$	F $C_p = \frac{0.239 \times E}{101.94}$ $\frac{\text{Btu}}{lb_m\text{-}^\circ R}$	G Weight (gm)	H $C_{ALO} = F \times G$ $\frac{\text{Btu-gm}}{lb_m\text{-}^\circ R}$
1500	1088.9	144.84	18.74	126.10	.2956	43.26	12.802
1600	1144.4	144.66	17.83	126.83	.2973	43.26	12.876
1700	1200.0	144.46	17.01	127.45	.2987	43.26	12.937
1800	1255.5	144.27	16.26	128.01	.3000	43.26	12.993
1900	1311.1	144.08	15.57	128.51	.3012	43.26	13.045
2000	1366.6	143.89	14.93	128.96	.3023	43.26	13.093
2100	1422.2	143.70	14.35	129.35	.3032	43.26	13.132
2200	1477.8	143.51	13.81	129.70	.3040	43.26	13.166
2300	1533.3	143.32	13.31	130.01	.3047	43.26	13.197
2400	1588.9	143.13	12.84	130.29	.3054	43.26	13.227
2500	1644.4	142.94	12.41	130.53	.3060	43.26	13.253
2600	1700.0	142.75	12.00	130.75	.3065	43.26	13.274

TABLE XXV

SPECIFIC HEAT OF TUNGSTEN FROM THE EQUATION PRESENTED IN REFERENCE 14

T (^{o}F)	T (^{o}K)	$C_p = 5.74 + 0.76 \times 10^{-3} \times B$ $\frac{CAL}{^{o}K\text{-mole}}$	$C_p = \frac{C}{183.92}$ $\frac{Btu}{lb_m\text{-}^{o}R}$	Weight (gm)	$C_{TUN} = D \times E$ $\frac{Btu\text{-}gm}{lb_m\text{-}^{o}R}$
1500	1088.9	6.568	.03571	209.4	7.479
1600	1144.4	6.610	.03594	209.4	7.527
1700	12.00.0	6.652	.03617	209.4	7.575
1800	1255.5	6.694	.03640	209.4	7.624
1900	1311.1	6.736	.03662	209.4	7.670
2000	1366.6	6.779	.03686	209.4	7.720
2100	1422.2	6.821	.03709	209.4	7.768
2200	1477.8	6.863	.03731	209.4	7.814
2300	1533.3	6.905	.03754	209.4	7.862
2400	1588.9	6.948	.03778	209.4	7.913
2500	1644.4	6.990	.03800	209.4	7.959
2600	1700.0	7.032	.03823	209.4	8.007

APPENDIX E

COMPOSITION OF SAMPLES

Molybdenum

Mo----------99.9%

Fe----------0.005% maximum

C----------0.003% maximum

Tungsten

W----------99.9+%

R_2O_3----------0.02% maximum

Tantalum

Contaminates

C----------0.005%

O_2----------0.014%

Fe----------0.004%

Cb----------0.050%

W----------less than 0.02%

Mo----------less than 0.003%

Si----------less than 0.02%

Ti----------less than 0.02%

Synthetic Sapphire

This sample was supplied by Linde Air Products Company and was essentially pure Al_2O_3.

APPENDIX F

SYMBOLS

q	Energy flow rate
m	Mass of the sample
c	Specific heat
t	Temperature
θ	Time
α	Thermal diffusivity
r	Radial distance
h	Heating rate $\frac{\partial t}{\partial \theta}$
$\emptyset$	Temperature gradient $\frac{dT}{dr}$ evaluated at the inner wall of the crucible
C	Heat capacity
M	Constant dependent on crucible properties
N	Constant dependent on crucible properties
R	Inverse heating rate, $\frac{1}{h}$
W	Weight per unit length

SUBSCRIPTS

s	Sample
c	Crucible
o	Outer radius
i	Inner radius

APPENDIX G

SYSTEM DETAILS

A. The Crucible

The crucible required for the investigation was cast from Norton 33-I castable cement. It was necessary to prepare this crucible without any taper to the sides so a mold made with no draw was necessary. This mold was prepared by making a paraffin pattern as shown in Figure 12. The mold itself was made out of plaster of Paris and the paraffin pattern was removed by immersing the mold and pattern in hot water. After the pattern was melted out the mold appeared as shown in Figure 13. A wax core was prepared in the shape shown in Figure 14. This core was inserted in the hole at the bottom of the mold with the core extending 1 3/4-inches up into the mold. This formed the sample cavity in the final crucible.

After the mold was prepared the thermocouple control elements, formed into the basket-like configuration shown in Figure 6, were inserted into the mold and positioned using a two ring positioner as shown in Figure 15. The purpose of this device was to maintain the thermocouple wires entirely inside of the completed crucible.

The Norton 33-I cement was prepared for use by passing the cement as received through a wire screen of approximately 1/8-inch mesh. This removed any large particles. Mixtures of this material

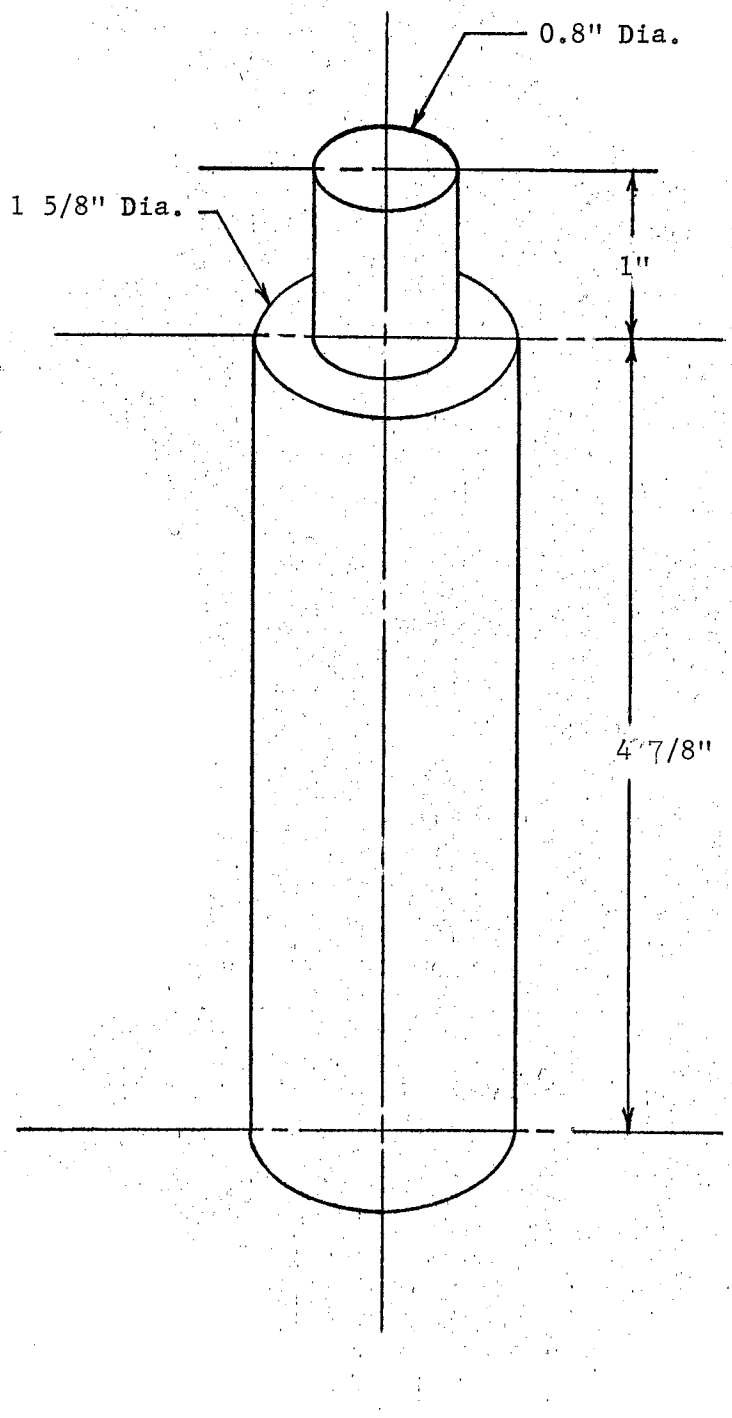
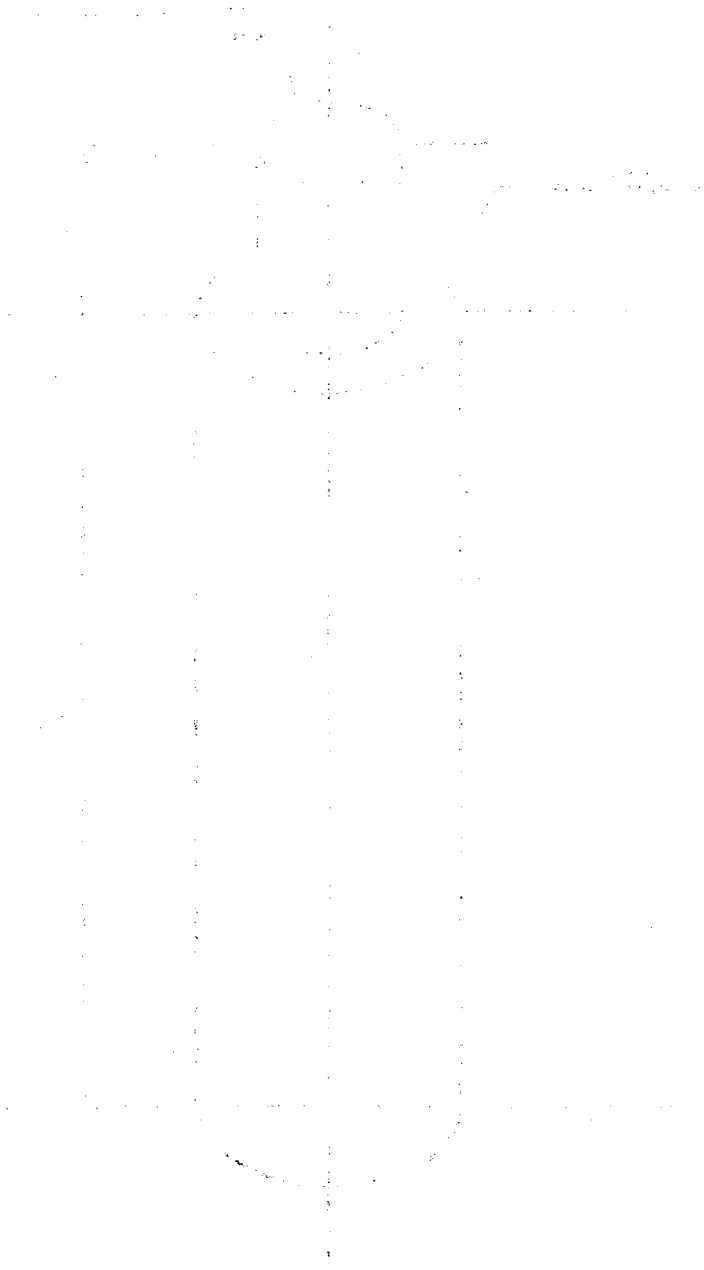


Figure 12. Paraffin Pattern



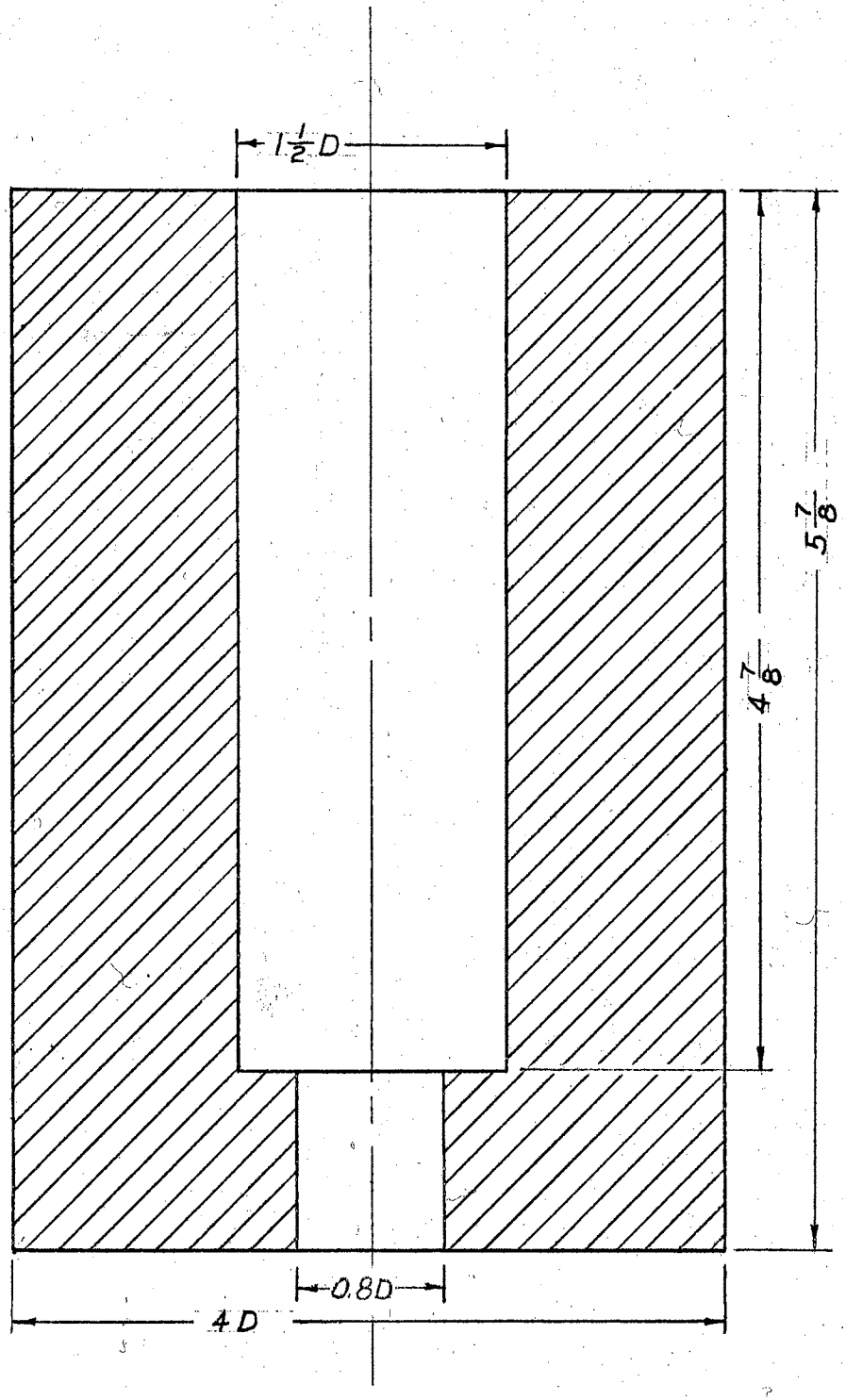


Figure 13. Plaster of Paris Mold

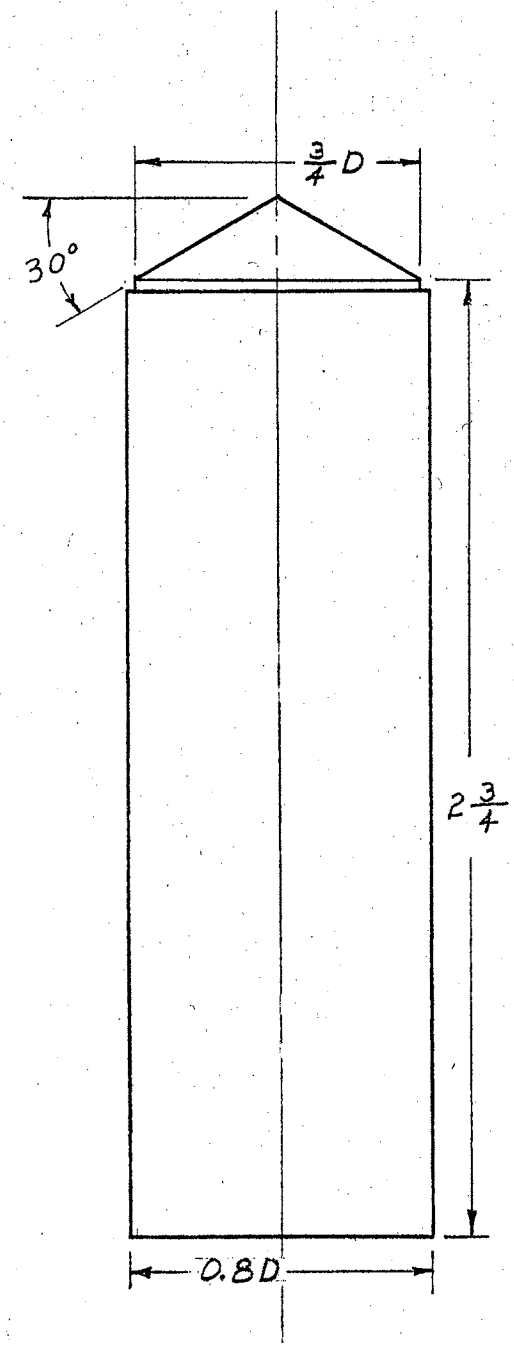


Figure 14. Paraffin Core

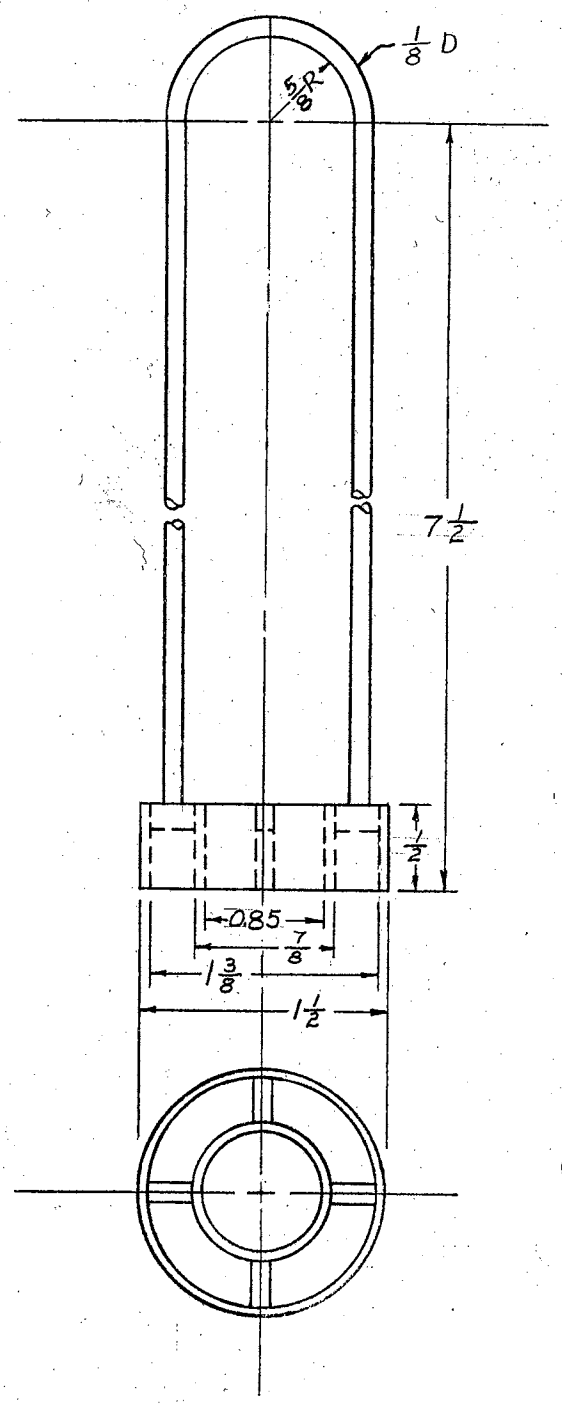


Figure 15. Two Ring Thermocouple Positioner

with water were poured into the mold slowly and the positioner was withdrawn as the mold was filled. Before the mold was filled completely, the firebrick base was fitted in place and then the casting was completed.

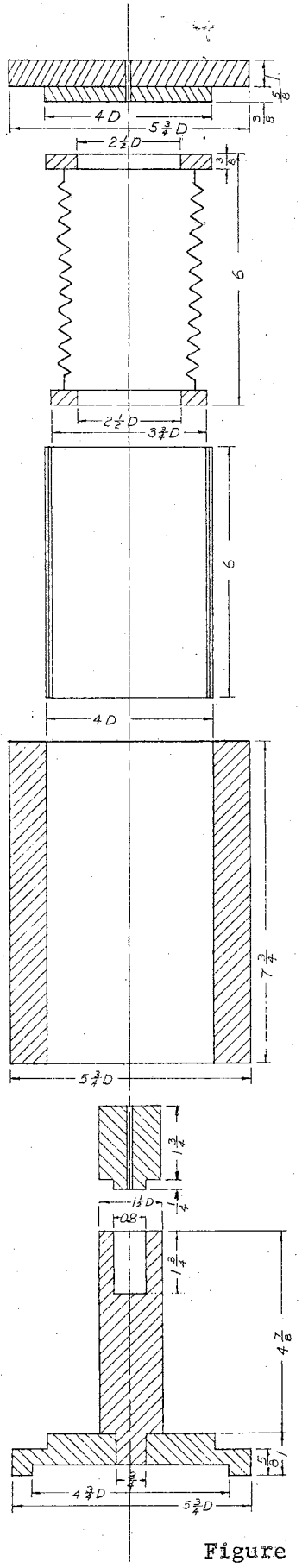
The crucible was removed from the mold by placing the entire mold in a furnace and raising the temperature to approximately 1200°F. This caused the plaster of Paris mold to fracture and it was easily removed.

B. The Central Sample Thermocouple

A thermocouple to measure the central temperature of the sample was not available commercially. This small diameter thermocouple element was constructed by threading 28 gauge thermocouple wires approximately 20 inches long through a six inch ceramic double bore insulating tube. These tubes were obtained from the McDanel Refractory Porcelain Company. Preparation of the thermocouple junction was accomplished by welding the two leads together and pulling the junction snug against the bottom of the protection tube. This tube was of sufficient length to extend into the sample from the outside of the furnace enclosure.

C. The Vacuum Furnace System

The vacuum system and the original furnace enclosure were described in reference (6) but the internal portion of the furnace was modified as shown in Figure 16. The main modifications consisted of the furnace portion and the manner of leading the power and control thermocouple



Babcock and Wilcox K-30 Furnace Lid

Babcock and Wilcox K-30
Heater Support Ring

Molybdenum Heater Element

Babcock and Wilcox K-30
Heater Support Ring

0.010" x 40" Molybdenum Sheet
Coiled - Radiation Shield

Armstrong A-28 Ceramic Shield

Norton 33-I Crucible Top

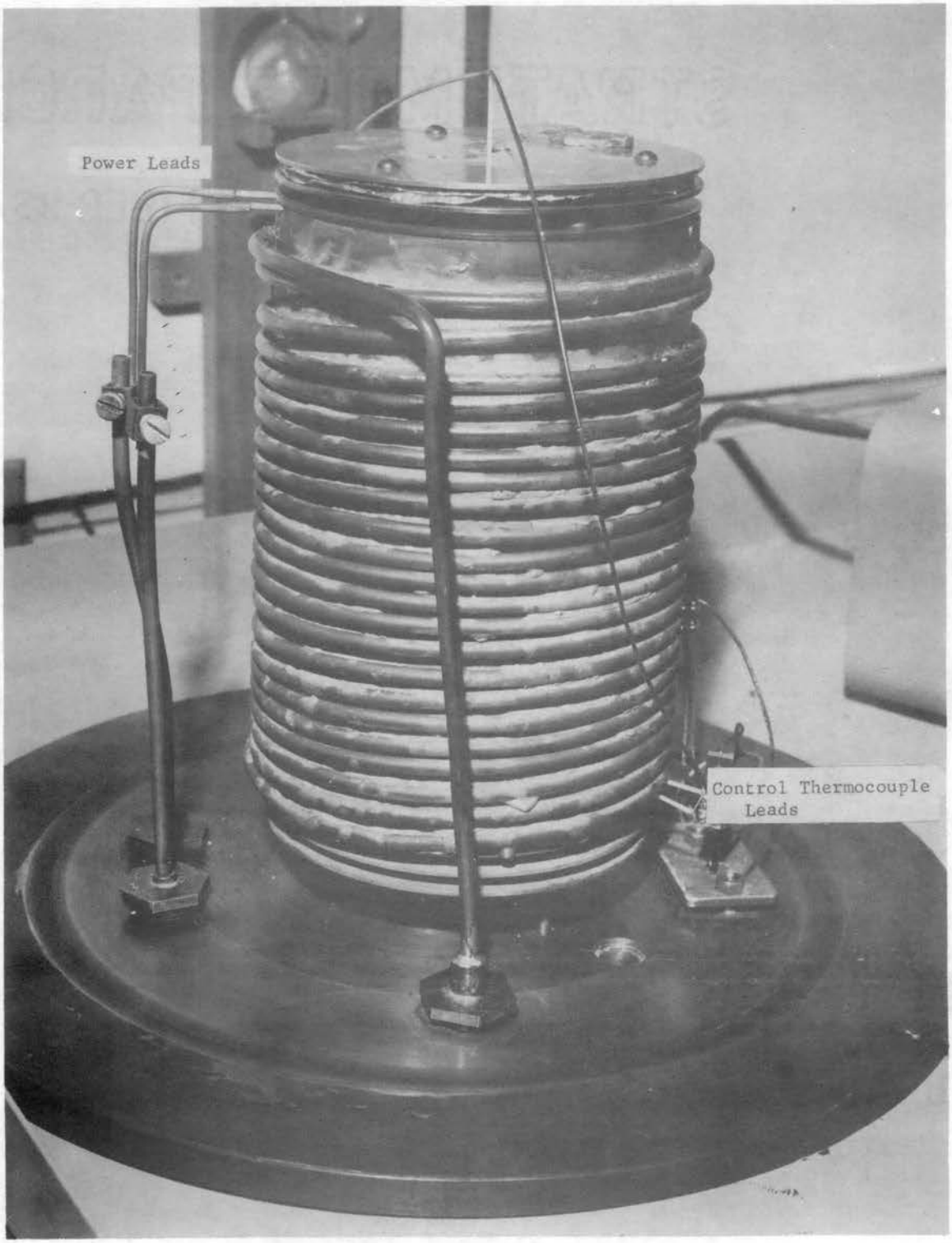
Norton 33-I Crucible

Armstrong A-28 Crucible Base

Figure 16. Furnace Details

PLATE V

INNER ENCLOSURE



leads out of the furnace enclosures. In the original design the power leads came out through the removable top of the furnace enclosure. In the final system, the power leads were carried out through the side of the enclosure near the top as shown in Plate V. Also the thermocouple control leads were carried out through the enclosure near the bottom of the container.

VITA

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