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NBS Line-Heat-Source Guarded Hot-Plate for Thick Materials

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ABSTRACT

The use of thicker thermal insulation material with greater thermal resistance resulted in a need for the National Bureau of Standards to produce a new apparatus for absolute measurement of the thermal resistance of thick insulation samples to be used as transfer standards. These standards are used to calibrate or verify heat-flowmeter (ASTM C-518) or guarded-hot-plate (ASTM C-177) equipment.

This paper gives the background and description of the line-source heater in the hot plate and discusses the need to measure thick samples. The actually constructed apparatus is described, with emphasis given to innovative features. The data-acquisition system is discussed and data are presented. Finally, a summary of the error analysis is presented, indicating an overall absolute uncertainty of less than ± 1% in the measured thermal conductivity.

The hot plate is made of aluminum and has a 40-in. (1-m) diameter and a 16-in. (406 mm) measuring diameter, and contains circular line-source electric resistance heaters. The plates are housed in an environmental chamber that can be rotated for vertical or horizontal measurements on a pair of specimens up to 15-in. (380-mm) thick. The range of material thermal conductivity that can be measured is 0.14 to 2.1 Btu·in/hr·ft^2·°F (0.02 to 0.30 W/m·K). The hot plate can be controlled over the temperature range of -4 to 302°F (-20 to 150°C) and the cold plates cover a range from -40 to 212°F (-40 to 100°C).

INTRODUCTION

The purpose of this paper is to briefly describe the 40-in. (1016-mm) National Bureau of Standards (NBS) guarded-hot-plate (GHP) apparatus in terms of its actual construction, its data acquisition capability, and its absolute accuracy. Earlier papers have presented a detailed analysis of the temperature distribution expected with the line-source heater[1] and a detailed error analysis.[2]

The guarded-hot-plate apparatus is used worldwide to determine thermal conductivity and thermal resistance of thermal insulation and building materials. The first apparatus at NBS was designed in 1909 and construction was completed in 1912.[3] The test method has been standardized in several countries[4,5,6] and the International Standards Organization (ISO), technical committee 163, thermal insulation, is in the process of producing an international standard method of test.

Many guarded-hot-plate apparatuses are made by uniformly distributing an electric resistance heater winding over a square or rectangular laminated metal hot plate. This construction has several disadvantages: (1) construction and repair are complicated and difficult, (2) differential thermal expansion can cause warpage of the plate, resulting in inaccurate measurement of specimen thickness and nonuniform thermal contact between the specimen and the plate, (3) repeated thermal cycling can lead to permanent plate deformation,

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(4) the location of the gap thermopile for one-sided tests is problematical, and (5) square corners make mathematical analysis difficult.

Ideas to overcome these difficulties were presented by Robinson in 1964.[7] These ideas involved the use of a circular metal hot plate containing a line-source electric resistance heater. Analysis was given to show that the circular line-source heater could be located at such a radius that the temperature at the outside edge of the meter area (on the meter side of the gap) would be equal to the average temperature of the entire meter areas. Thus, plate surface temperature measurements would not be necessary.

In 1971, under the sponsorship of NBS, Hahn completed an in-depth analysis of these ideas and examined several design options.[8] The concept, mathematical analysis, and proposed design features were published in Ref. 2. The development of a prototype line-source apparatus[9] and its description and results of measurements were reported[10] before undertaking the design and construction of the 40-in. (1016 mm) apparatus under discussion here.

Many guarded-hot-plate apparatuses were designed to accommodate test samples of 1 or 2-in. (25 or 50-mm) thicknesses. Such equipment was satisfactory, provided the value of thermal resistance obtained for a 1-in. (25-mm) thick sample could be used to calculate the value of thermal resistance for thicker materials by linear extrapolation. With the use of greater thicknesses of insulation to reduce building heating and cooling energy consumption, it became necessary to know more precisely the thermal resistance of thick insulations (up to 12-in. [300 mm] thick products are available). In the case of low-density fiberglass insulation, there were indications that linear extrapolation from a 1-in. (25-mm) thick sample could be in error. The thermal testing community and manufacturing industry required thick specimens to calibrate their guarded-hot-plate and heat flowmeter apparatuses. Furthermore, the test methods of the American Society for Testing and Materials (ASTM) required calibration with transfer standards traceable to a national standards laboratory, and the Federal Trade Commission promulgated a rule requiring that advertised thermal resistance values be derived from a "representative thickness" of the material. Representative thickness was defined as the thickness of material whose measured thermal resistance can be extrapolated linearly to obtain a thermal resistance at a greater thickness that is within ±2% of the measured value of the thick material.

This paper presents a technical description of the as-built NBS line-source, 40-in. (1016-mm) diameter guarded-hot-plate apparatus, with emphasis given to innovative features. Sample results and data that indicate that the absolute uncertainty of measured thermal resistance values is ±1% are given. The development of the equipment was jointly sponsored by the National Bureau of Standards and the Department of Energy and was supported by a research associate from the Mineral Insulation Manufacturers Association.

PRINCIPLE OF MEASUREMENT

The principle of measurement of a guarded-hot-plate is illustrated in Fig. 1. Electric power is supplied to the meter heater and guard heaters to maintain constant and equal temperatures of each of these plates. The guard and meter sections of the hot plate are separated by an air gap. Differential thermocouples are connected across the air gap to indicate whether heat is flowing radially across the gap. The electric power to the guard heaters is controlled to maintain net gap heat flow as nearly as possible to zero. The cold plates are controlled to produce a constant, uniform surface temperature. Under these steady conditions heat flows unidirectionally from the meter plate to the cold plates. A layer of thermal insulation surrounds the peripheral edges of the specimens. If none of the heat produced by the meter plate is lost to the guard heater (or gained from the guard plate) or transferred from or to the environment surrounding the plates, the following steady-state relationship can be used to determine the total thermal resistance of both specimens (assuming the heater power, Q, is split evenly between the two sides):

$$R = \frac{A(T_h - T_c)}{(Q/2)} \tag{1}$$

where

R = total sample thermal resistance of thickness L in. (m), $ft^2 \cdot hr \cdot °F/Btu$ ($m^2/K \cdot W$)
A = metered area, in.^{2} (m^2)
T_h = average temperature over the meter section of the hot plate, °F (K)

T_C = average cold plate temperature, °F (K)
Q = electrical energy consumed by the meter plate to maintain its temperature, W

By definition, the apparent thermal conductivity, λ, is

$$\lambda = L/R \qquad (2)$$

It is possible to operate the hot-plate apparatus with one of the cooled plates maintained at the same temperature as the hot plate. In this case, a single specimen is measured instead of a pair of specimens. This brief explanation of the principle of measurement was given to enable to reader to see the various sources of measurement uncertainty summarized later.

DESCRIPTION OF APPARATUS

Hot Plate

The hot plate is circular and has a uniform thickness of 0.635 in. (16.13 mm). It is made of type 6061-T6 aluminum, Fig. 2. The center part is a solid diameter 11.299 in. (287.0 mm). A commercially available nichrome ribbon heater (~ 4 mil [0.1 mm] thick and 160 mil [4 mm wide]) encased in plastic surrounds the edge of the center. The circular ribbon heater is referred to as a line-heat-source hot-plate design. The section surrounding the center part has an inside diameter of 11.299 in. (287.0 mm) and an outside diameter of 15.970 in. (405.6 mm). These two inner sections comprise the heated, metered area of the hot plate. When fabricated, the center part was cooled to liquid nitrogen temperature and placed inside the outer section (held at room temperature), with the nichrome heater between, forming a shrink-fit assembly. Three equally spaced pins (120 mil [3 mm] diameter stainless-steel) are used to support the meter-area part within the guard ring as shown in Fig. 2. The guard ring has an inner diameter of 16.040 in. (407.4 mm) and an outer diameter of 40.000 in. (1016 mm). The gap between the guard and meter-area parts is 35 mil (0.9 mm) wide. There are two circular heaters on each side of the guard surface at diameters of 20.658 in. (524.7 mm) and 31.584 in. (802.2 mm). These are located in circular grooves, cut into the guard surface, and are embedded in epoxy. Several holes (160 mil [4 mm] in diameter) penetrate the guard ring from its outer edge to the gap to permit access for thermistor, heater leads, platinum resistance thermometer, and thermocouple wires. The plate thickness of 0.635 in. (16.13 mm) was selected as a balance between a desired large thickness with great structural rigidity and a small thickness with less heat capacity. The plate surfaces are black anodized to achieve a normal, visible emittance value of 0.89 ± 0.01.

The gap shape was chosen to allow maximum gap volume and a greater thermal resistance across the gap, without having too large a plate-surface gap separation with its accompanying potential for a larger uncertainty in meter-area value. The measured flatness of the meter-area is ±1 mil (25 μm) across its diameter.

The design mathematical analysis, and experimental results related to the line heat source are discussed in Refs 1 and 2. For a 1-in. (25-mm) thick sample with a heat flowrate per unit area of ~ 28 Btu/hr·ft^2 (90 W/m^2) and a hot-to-cold-plate temperature difference of 50°F (28 K), the measured temperature difference between that of the hot plate surface at the line-source-heater location and that of the plate center was 180 mF (60 mK). Thus, the results given in Ref 1 indicate the plate temperature is quite uniform. In addition, the temperature at the outside edge of the meter section (at a radius of 7.985 in. [202.8 mm]) was equal to the average temperature over the entire meter area, within the limits of the measurement accuracy (~ 27 mF or 15 mK). This result justifies the use of a platinum resistance thermometer at the edge of the meter section (inside the gap on the meter side) to determine the average absolute temperature of the meter area.

Cold Plates

The construction of the liquid (ethylene glycol) cooled cold plates is shown in Fig. 3. Each aluminum plate is 1 in. (25.4 mm) thick and consists of a 0.25 in. (6.4 mm) thick cover plate bonded with epoxy to a 0.75 in. (19.0 mm) thick base plate. The base plate contains milled grooves 0.375 in. (9.5 mm) deep and 0.375 in. (9.5 mm) wide arranged in a double-spiral configuration. This arrangement allows leak-tight counterflow channels in which the incoming coolant passes next to outgoing coolant for a more uniform temperature distribution over the cold-plate surface. A 0.125-in. (3.2-mm) diameter hole was bored from the side to within 2.5 in. (63 mm) of the plate center to provide access for a platinum resistance thermometer, which is used to measure the absolute temperature of the cold plates. The backs and edges of the cold plates are insulated with 4 in. (102 mm) thick expanded polystyrene.

Supporting Structure

Figures 4 and 5 show how the three plates are supported by four stainless-steel rods of 2-in. (51-mm) diameter. The rods are mounted in an airtight insulated chamber for environmental control.

The hot plate is rigidly and permanently mounted on the four support rods. Each cold plate is supported at its center, and, at the point of support, has a load cell to measure the force that the sample exerts on the plate. This support has a ball joint so that the plate can tilt to conform to a nonparallel rigid sample. The cold plates are constrained in the radial direction by steel cables attached to four spring loaded bearings mounted on the hotplate support rods. This construction ensures that the plates remain aligned when the whole of the apparatus is rotated 180° in either direction.

Environmental Chamber

The environmental chamber is cube-shaped and 5.2 ft (1.6 m) on an inner side (see Fig. 4). The inside and outside surfaces are of sheet aluminum, and the core consists of 3 in. (75 mm) thick expanded polystyrene insulation. Rigidity is provided by 2-in. (50-mm) square box-beam members. The plate-support rods are secured at the top only, to hang within the chamber. Axles extending from the center of two opposite sides are mounted on gimbals, allowing 180° rotation of the entire apparatus. Full access to the plates is allowed by doors on both the front and back of the chamber. The temperature within the chamber is maintained at the desired value (± 2°F or 1 K) using a platinum resistance thermometer and a feedback circuit to control a heater that loads a constant cooling heat exchanger. The present operating range is 0 to 150°F (273 to 340 K).

Thickness Measurement

The thickness, L, in Eq 2 is the average, over the meter area, of the spacing between the hot and cold plates. The basic calibration method[1] involves measuring the hot-to-cold spacings at the outside edges of the cold plates at four equally spaced positions. The four spacings are correlated with a "known meter-area plate separation," which is determined with a direct measurement of the thickness in the center of the plates, using an independent set of temporarily mounted thickness transducers accurate to within 0.3 mils (7 μm).

The outside cold-plate positions are measured using four permanently mounted thickness transducers on each plate. These thickness transducers measure any change in position relative to the initial reference point. The calibration must be done for each plate orientation and for compressible and rigid samples.

These four permanently mounted thickness transducers are mounted on Invar bars to minimize error resulting from ambient temperature variation and measure the average spacing with a repeatability of 0.2 mils (5 μm). Thus, the thickness can be measured continuously during a test as temperature testing conditions change, an improvement over the procedure of measuring thicknesses only at the beginning and end of each test.

Plate Temperature Control

The plate temperatures are controlled with feedback circuits. Thermistors are used in these circuits because of their large change in resistance with temperature. A thermistor is located in each of the hot and cold plates. In addition, pairs of thermistors are used to control the temperatures between the gap and the outer guard. (The "gap" readout, however, is accomplished with a thermopile.) For the NBS/GHP apparatus the hot-plate temperature can be controlled to within a range of 2 mF (1 mK), the cold plate temperatures to within 12 mF (6 mK), and the average temperature difference across the gap to within 2 mF (1 mK). A microprocessor is used in conjunction with the feedback circuit to automatically bring the plate temperatures to a desired value. The use of thermistor control circuits makes it possible to achieve steady-state test conditions within 3 hours for low-density, 6-in. (150-mm) thick samples.

The steady-state value of apparent thermal conductivity is achieved in the constant hot-plate temperature mode, rather than a constant meter-area-heater power mode. This factor is important for the reduction of test times. Note that because the control range of the hot-plate temperature and the corresponding control range of the meter power is very small, the accuracy of the final steady-state value of the apparent thermal conductivity is not compromised by using the constant-temperature mode.

DATA ACQUISITION AND DOCUMENTATION

Automatic Data Acquisition

The control of plate temperatures and data acquisition is accomplished with a microprocessor. The selected plate temperatures are entered, and the computer reads temperatures as measured with platinum resistance thermometers. These values and a control algorithm are used to bring the temperatures to the desired values. Raw data consist of readings of a number of voltages. A scanner selects the voltage to be read by a digital voltmeter. When a complete scan is made of all the required voltages, the information is transmitted to a desk calculator-computer and stored on a cassette tape.

The desk calculator also produces plots of the important data as a function of time, such as plate temperatures or hot-plate power, Figs. 6-10. Note that the steady-state values on these figures lie within a narrow band (for example, 0.05% for the apparent thermal conductivity, λ). This short-term scatter is mostly due to the power change required by the meter-area heater to maintain the hot plate at a constant temperature. The hot plate is in turn responding to the short-term changes in the cold-plate baths, ultimately causing most of the short-term scatter in λ. However, the mean value of λ over several hours is known much better than within the 0.05% band (drifts in mean value of ~0.01% can be detected). Stated differently, the short-term scatter contributes a negligible amount to the uncertainty in λ, as long as the steady-state interval is several hours long. Rather, it is the data drifts over a period of about one day or more, as well as the systematic errors, that contribute significantly to the uncertainty in λ. The time plots are invaluable for ascertaining that the test is in steady state, meaning that there is no monotonic change over time in the measured mean value of λ.

Sample Report

A sample of reported data, shown in Fig. 11, illustrates the standard data that are transmitted to a user when an insulation standard is measured at the National Bureau of Standards. This includes information on sample identification and on test conditions that should be reproduced by the user laboratory undertaking equipment verification or calibration.

SUMMARY OF ERROR ANALYSIS

Method of Summing Individual Uncertainties

The apparent thermal conductivity and the thermal resistance of an insulation sample are calculated quantities based on several measured parameters. Each of these measured parameters has an associated uncertainty. In turn, this uncertainty has a random and a systematic part. It is possible to estimate the uncertainty of each parameter by an independent test. For example, the apparatus thickness readout can be compared with a thickness gauge placed between the plates. It is less straightforward to estimate the overall uncertainty of the calculated quantity, because there is usually not sufficient information on the breakdown between the random and systematic parts of the uncertainty for each individual parameter. In principle, it is possible to gather this information, but in practice it would be too time consuming.

A more simple and practical approach was used in this error analysis. The individual parameters, such as the thickness or temperature distribution over the meter area, were measured with an independent detector under test conditions. A comparison of the apparatus readout with these independent measured values made possible the estimate of the upper bound on the total uncertainty for each parameter. Since there is not sufficient information to assure that the measured values are randomly distributed about a "true" mean value, the upper bounds for each individual parameter are simply summed to arrive at the overall uncertainty. This approach differs from an alternative approach in which the uncertainties are treated as standard deviations that are then added in quadrature, i.e., the total uncertainty is the square root of the sum of the squares of the individual uncertainties. The method of simple addition results in a somewhat larger estimate of the overall uncertainty (by as much as 30%) as compared with the method to sum in quadrature), but it eliminates the need to make an inordinate number of check-up measurements to assure that there are no outlier values. This more conservative approach is thought by the authors to be appropriate for use by a national insulation standards laboratory.

The following philosophy was used with regard to the estimate of upper bounds. Even if an uncertainty might have been expected to be smaller, based on theoretical considerations and manufacturer specifications, the uncertainty value actually used was that of the detector making the independent check. For example, the plate temperature might very well be known within 10 or 20 mF (5 or 10 mK). The uncertainty value actually used--44 mF (22 mK)--was associated with the thermopile used independently to check the plate temperature.

It is possible to estimate the overall random uncertainty, as the range of values of repeated measurements on the same sample with the same apparatus. This range within a period of several months for the NBS 40-in. (1016-mm) GHP apparatus at a thickness of 4 in. (100 mm) was within 0.1%.

Generally speaking, the data on a single test are of two parts. The transient part at the beginning of the test shows an increasing or decreasing curve. When there is no monotonic trend, the steady-state condition has been achieved. There is still a scatter of data points, due mostly to the cycling of the bath temperatures. The scatter band is about 2 mF (1 mK) for the hot-plate temperature, 12 mF (6 mK) for the cold-plate temperatures, and 1 mW for the power. The scatter in the calculated λ-value is about 0.01% for a two-sided, 1 in. (25 mm) sample and 0.03% for a two-sided, 6-in. (150-mm) sample. The mean λ-value is known even better. The scatter in the data points, after the steady-state condition has been attained, is negligible compared to the estimated systematic errors in λ.

Individual Contributions to the Apparatus Uncertainty

Table 1 shows the contributions to uncertainty for the individual measured parameters such as the thickness or heat flow; the overall uncertainty values are also shown for various thicknesses. The methods of estimating these uncertainties are discussed in detail in Ref 10. This summary of uncertainties is for the case of compressible insulation samples at a mean temperature of 75°F (297 K) and a plate-temperature difference of 50°F (27 K). Note that at a thickness of 1 in. (25 mm), the temperature and thickness uncertainties are largest. At 6 in. (150 mm), the temperature is the only large uncertainty. At 12 in. (300 mm) the edge uncertainty is dominant. The gap-voltage uncertainty was kept small, even at 12 in. (300 mm), by using an 18-stage gap thermopile, low-thermal wiring, and a highly accurate voltmeter. The overall uncertainty value is about 0.3% up to a 6-in. (150 mm) thickness. At 12 in. (300 mm), it should be possible to decrease the uncertainty with further edge studies.

CONCLUSIONS

A description of the as-built NBS line-source guarded-hot-plate apparatus capable of measuring the thermal resistance of specimens of thermal insulation and building materials up to 15 in. (380 mm) thick is presented. The apparatus conforms to ASTM Standard C-177-76, "Standard Test Method for Steady-State Thermal Transmission Properties by means of the Guarded Hot Plate." Experience with the apparatus and the results of uncertainty analyses justifies the conclusion that the NBS apparatus is a viable means for measuring absolute values of thermal resistance to an uncertainty of ± 1%.

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TABLE 1

Percentage Estimate of Uncertainties in the Measured Apparent Thermal Conductivity for the NBS Guarded Hot Plate

Quantitative Value	Thickness			
	1 in. (25 mm)	3 in. (75 mm)	6 in. (150 mm)	12 in. (300 mm)
	Uncertainty, %			
Area (0.5 mil or 12 μm in radius)	0.01	0.01	0.01	0.01
Thickness (1.0 mil or 25 μm)	0.1	0.03	0.02	0.01
Meter power	0.04	0.04	0.04	0.04
Meter resistive Device (0.4 mW)	0.00	0.01	0.02	0.04
Gap heat flow (0.3 mW, or 0.5 μV in gap voltage)	0.00	0.01	0.02	0.03
Edge heat flow	0.00	0.00	0.00	0.50
Hot, cold-plate temperature difference (79 m°F or 44 mk)	0.16	0.16	0.16	0.16
TOTAL	0.31	0.26	0.27	0.79

* These values are for compressible, low-density, fiberglass insulation measured in the two-sided mode with a plate temperature difference of 50°F (28 K). Uncertainty values of less than 0.01% are reported as zero.

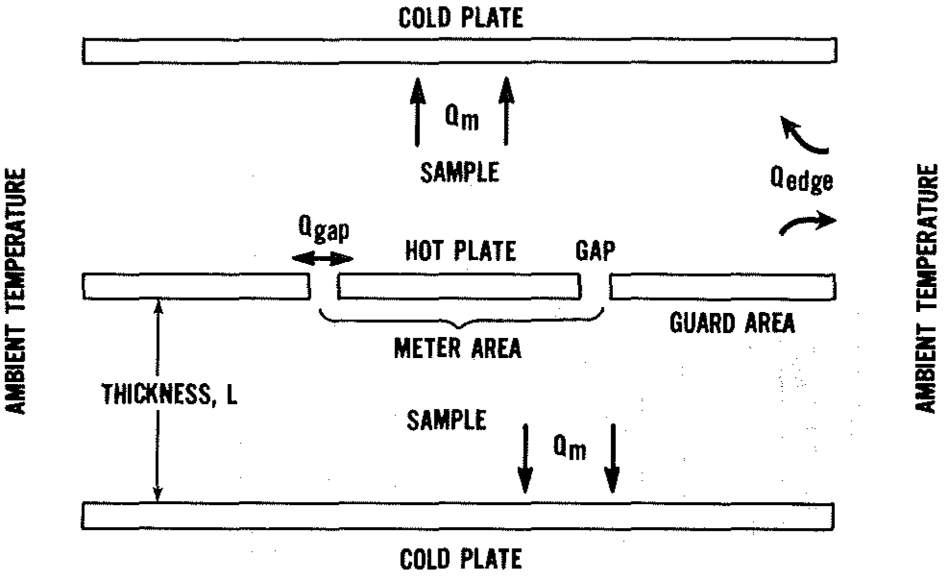

Figure 1. Principle of measurement

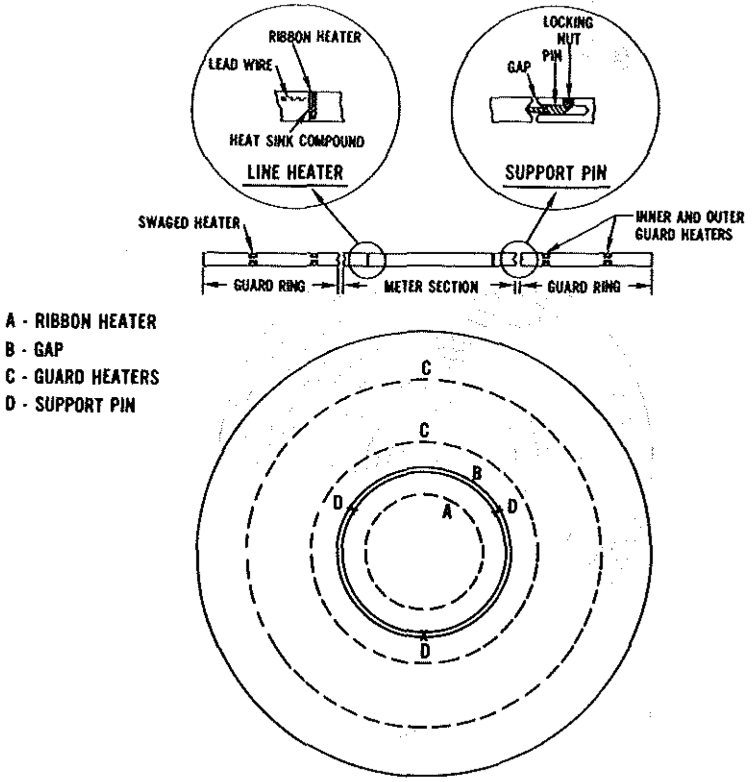

Figure 2. Hot plate

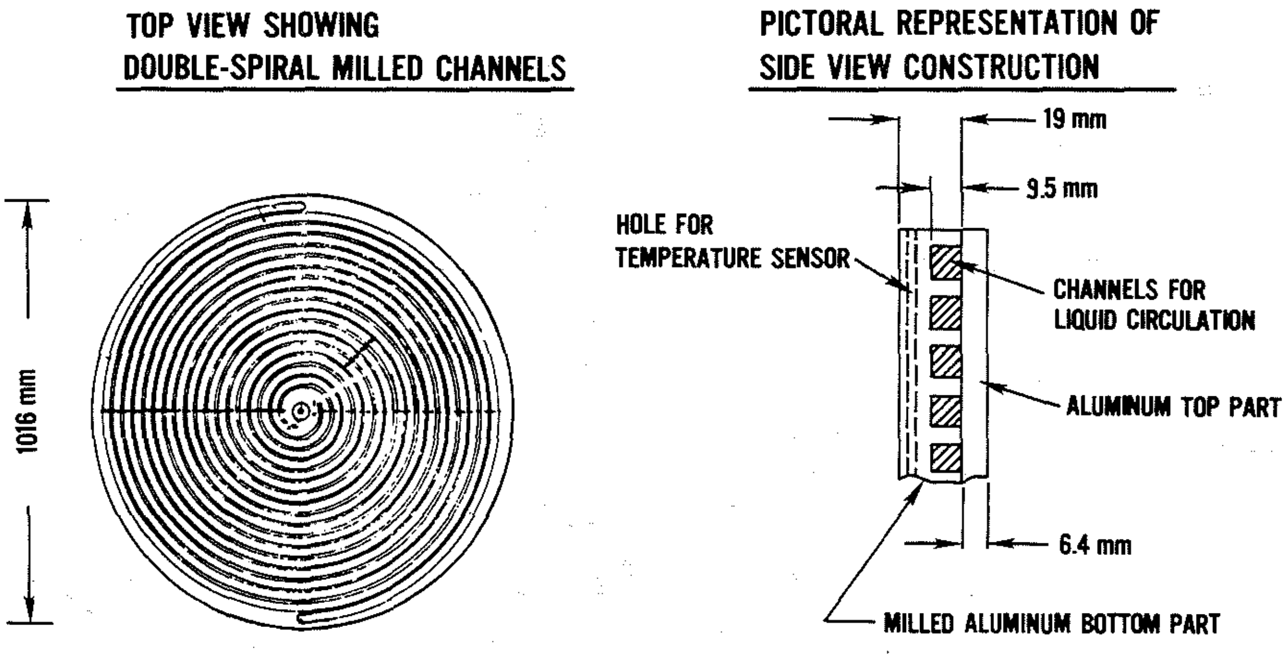

Figure 3. Cold plate

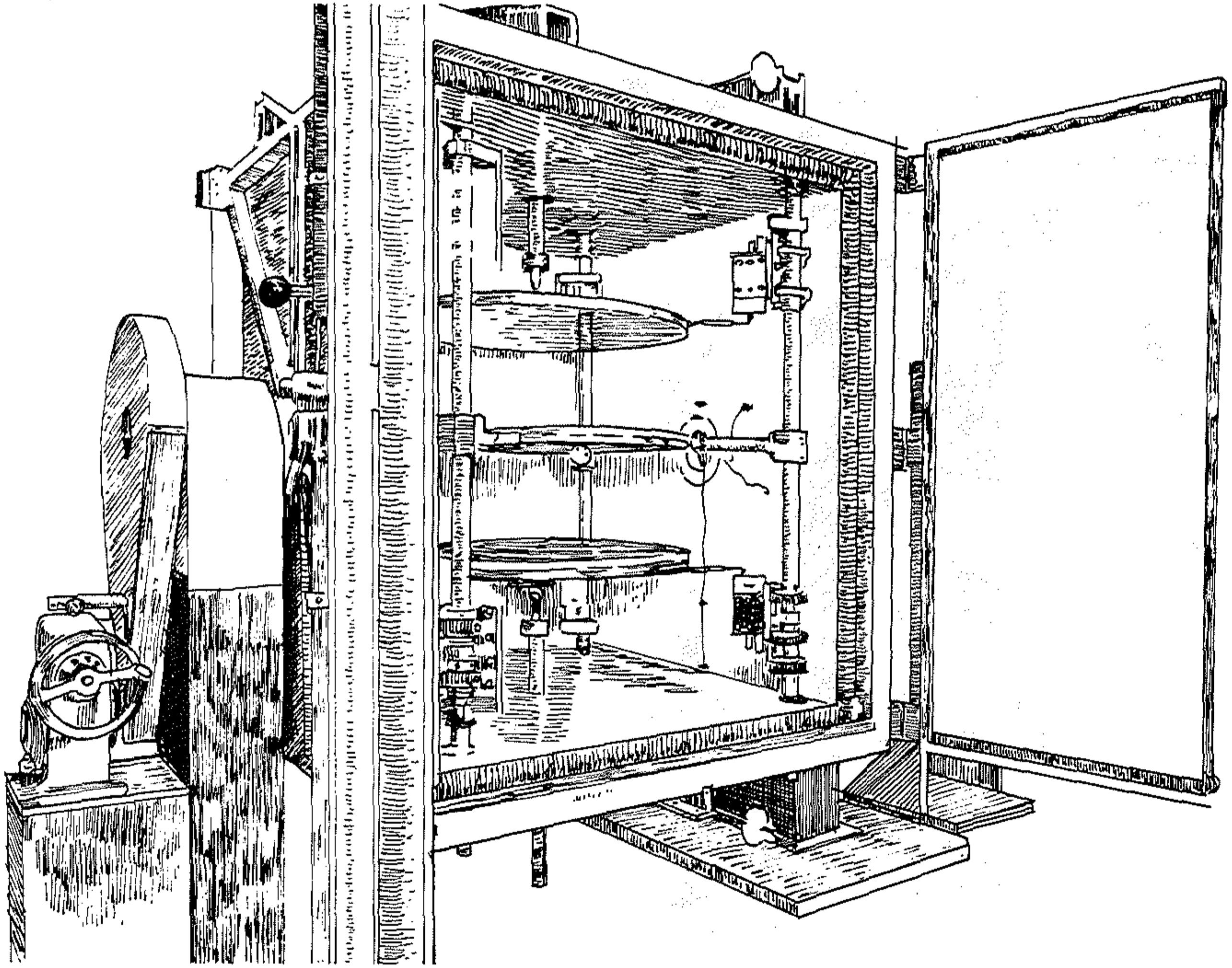

Figure 4. Support drawing

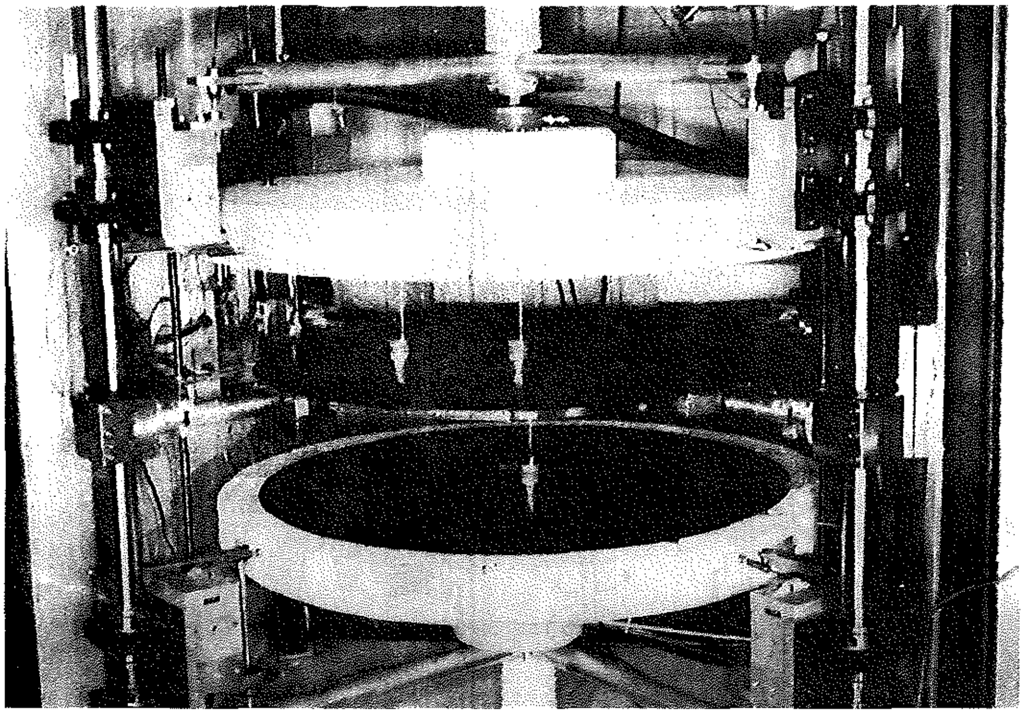

Figure 5. Support photo

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DATA ON HOT PLATE TEMP FROM 07/09 1981 AT 19:27:11 TO 07/10 1981 AT 08:57:11

ELAPSED TIME FROM FIRST TO LAST READING IS  13.50 HOURS

                              STATISTICAL DATA
MEAN            37.7761

MIN             37.7753
MAX             37.7777
RANGE             .0024            AS % OF MEAN   .006 %
NUMBER OF PTS      163
First record= 1  Last record= 163
```

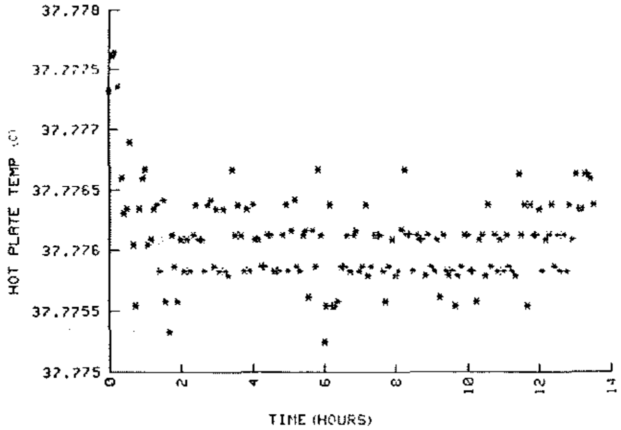

Figure 6. Hot plate temperature

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DATA ON UPPER COLD PLATE FROM 07/09 1981 AT 19:27:11 TO 07/10 1981 AT 08:57:11

ELAPSED TIME FROM FIRST TO LAST READING IS  13.50 HOURS

                              STATISTICAL DATA
MEAN              10.0018

MIN               10.0001
MAX               10.0044
RANGE               .0042            AS % OF MEAN    .042 %
NUMBER OF PTS       163
First record= 1  Last record= 163
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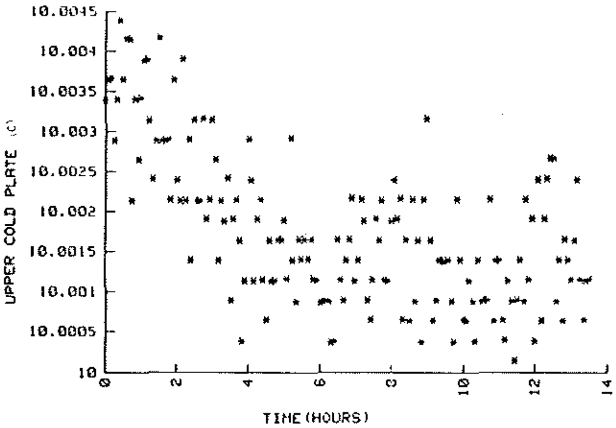

Figure 7. Cold plate temperature

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DATA ON POWER FROM 07/09 1981 AT 19:27:11 TO 07/10 1981 AT 08:57:11

ELAPSED TIME FROM FIRST TO LAST READING IS  13.50 HOURS

                              STATISTICAL DATA
MEAN              4.6024

MIN               4.5990
MAX               4.6035
RANGE              .0045             AS % OF MEAN    .097 %
NUMBER OF PTS      163
First record= 1  Last record= 163
```

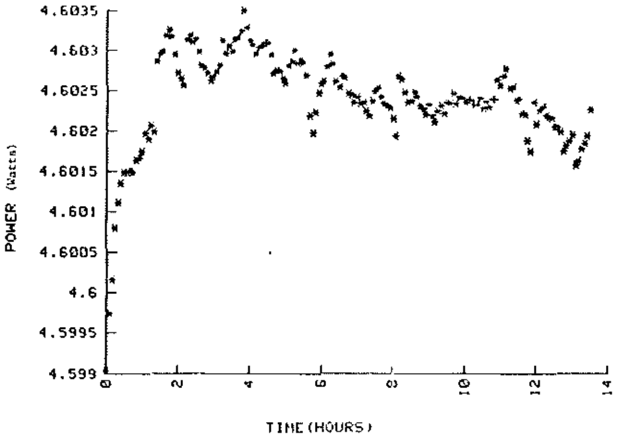

Figure 8. Meter-area power

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DATA ON GAP VOLTAGE FROM 07/28 1981 AT 17:09:07 TO 07/29 1981 AT 08:40:07

ELAPSED TIME FROM FIRST TO LAST READING IS  15.52 HOURS

                         STATISTICAL DATA
MEAN           .012380


MIN           -.280000
MAX            .460000


NUMBER OF PTS      134
First record= 1  Last record= 134
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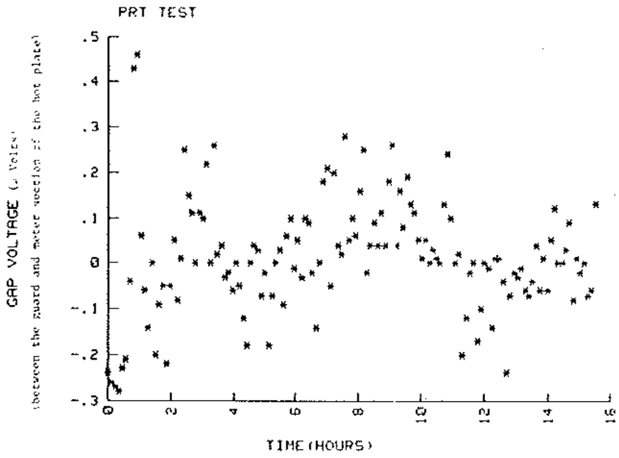

Figure 9. Gap voltage

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DATA ON K (Adj. Cond.) FROM 07/09 1981 AT 19:27:11 TO 07/10 1981 AT 08:57:11

ELAPSED TIME FROM FIRST TO LAST READING IS  13.50 HOURS

                         STATISTICAL DATA
MEAN           .048630

MIN            .048594
MAX            .048649
RANGE          .000055           AS % OF MEAN   .114 %
NUMBER OF PTS      163
First record= 1  Last record= 163
```

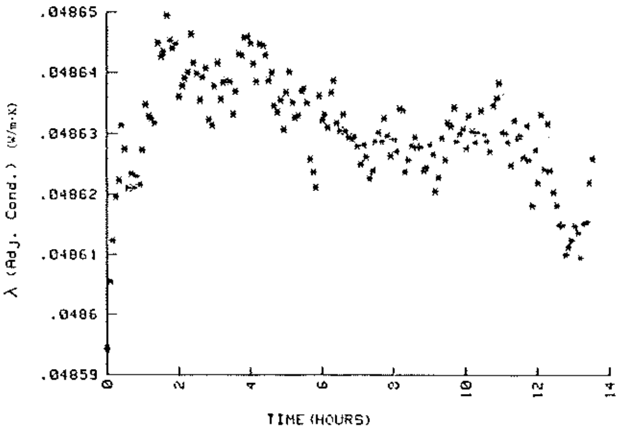

Figure 10. Apparent thermal conductivity

Test Results

Apparatus: NBS-GHP-1000

Table 1

Test No.		
Specimen identification no.		
Plate orientation during test		Horizontal
Direction of heat flow		Vertical (up)
Test Configuration		Cold Plate #1 Sample Hot Plate Sample Cold Plate #2
Test thickness (average)	mm	152.35
Thermal resistance a)	$(m^2 \cdot K)/W$	3.2554
Cold plate #1 temperature b)	°C	10.00
Hot plate temperature b)	°C	37.78
Cold plate #2 temperature b)	°C	37.78
Specimen (mean) temperature	°C	23.89
Ambient temperature	°C	24
Ambient humidity	% rh	30
Meter area	m^2	0.1299
Power input to meter area	W	1.108
Edge insulation thermal resistance c)	$(m^2 \cdot K)/W$	2.3

a) Last digit included for rounding

b) Emissivity of the surface at room temperature: 0.9
c) Nominal R-value of insulation around plates

The thermal resistance value in the above table was determined for that portion of the specimen within the meter area (central 406.4-mm diameter region) of the NBS-GHP-1000. The uncertainty in this thermal resistance value is estimated to be not more than ± 3/4 percent; this uncertainty includes apparatus systematic error and apparatus repeatability.

Figure 11. Sample report

Discussion

D.L. McElroy, Oak Ridge National Lab., Oak Ridge, TN: 1. Would you give the basis for the percent error in temperature?

2. Please indicate the repeatability and reproducibility for the apparatus.

F.J. Powell: 1. The estimate of the upper bound of the temperature difference is 44 mK. This is mostly due to the uncertainty of the thermopile device with which the plate surface temperature distribution was checked. The temperature difference is probably known much better, perhaps to within 15 mK, but, since we could not demonstrate this with an independent measurement, we do not claim it.

2. The repeatability is within 0.1% and the reproducibility within 0.1% to 0.3% depending on the material variability of the sample.

J.S. England, Department of Mechanical Engineering, Washington State University, Pullman: Please describe the temperature control system for the refrigerating system that cooled the cold plates.

F.J. Powell: The 45-liter, ethylene-glycol bath has constant cooling. The bucking heating is accomplished with a large programmable power supply controlled by a thermistor feedback circuit. The scatter of temperature is controlled to within 8 mK over a range of 0.40°C.