EVALUATION OF A 20-INCH GUARDED HOT-PLATE THERMAL CONDUCTIVITY APPARATUS RANGE -50°F TO +250°F

Chester W. Kaplar

June 1971

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

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PREFACE

This report presents an evaluation of the guarded hot-plate apparatus acquired in 1968 by the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) in support of Military Construction Investigations, Engineering Criteria and Investigations and Studies, Studies of Construction in Areas of Seasonal Frost; Project 48, Construction Materials in Cold Climates.

The Military Construction Investigations program is conducted for the Directorate of Military Construction, Office of the Chief of Engineers. This investigation was under the technical direction of the Engineering Division of this directorate, Civil Engineering Branch (Mr. F.B. Hennion, Acting Chief).

Mr. C.W. Kaplar, Research Civil Engineer, Applied Research Branch, conducted the study and prepared this report. The investigation was under the general direction of Mr. K.A. Linell, Chief, Experimental Engineering Division, and the immediate direction of Mr. A.F. Wuori, Chief, Applied Research Branch, USA CRREL.

Mr. William H. Parrott technically reviewed this report.

Mr. R. Atkins, Electronics Engineer, was consultant for this project in electrical and electronic matters.

The work of setting up and evaluating the apparatus was performed by Mr. Mark Greenberg, Mechanical Engineer, formerly of USA CRREL, and Mr. Richard Guyer, Technician, USA CRREL.

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

Lieutenant Colonel Joseph F. Castro was Commanding Officer/Director of USA CRREL during the publication of this report.
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EVALUATION OF A 20-IN. GUARDED HOT-PLATE THERMAL
CONDUCTIVITY APPARATUS, RANGE -50°F TO +250°F

by

Chester W. Kaplar

INTRODUCTION

The 20-in. guarded hot-plate (GHP) thermal conductivity apparatus was obtained as a replacement for an apparatus designed and constructed for the Arctic Construction and Frost Effects Laboratory (ACFEL)* in 1957. The older apparatus had been subjected to considerable hard usage and several physical moves. A survey at CRREL (Donovan, 1966) revealed undesirable temperature gradients in the hot plate and unsatisfactory cold-plate temperature control with the circulating brine system that had been incorporated into the system. It was concluded that repairs and modification of the apparatus would entail considerable time and cost and would require that the control and circulatory portions of the system, including temperature control of brine supply, be redesigned.

Because of this and the fact that the older apparatus did not have the desired temperature range, was bulky, and occupied about 50 sq ft of floor space in a very crowded laboratory, a new, compact unit was obtained. This unit requires about one-half the floor space of the former apparatus and was designed to operate in a wider range of temperatures, -50°F to +250°F. A special feature of the new apparatus is its capability for accommodating fairly large specimens, such as pavement slab sections, sandwich insulation panels, small wall panels, and frozen soil slabs, down to an average temperature of -50°F. It was constructed to conform in all respects to ASTM Specification C177-63 (ASTM, 1963), and to some additional requirements described in Appendix C, p. 35, of this report. It has one distinct advantage: materials containing moisture may be tested in the frozen state.

This report presents (1) apparatus design requirements, (2) salient construction details, (3) operating instructions, (4) results of thermal conductivity tests conducted on a specimen of gum rubber calibrated by the U.S. National Bureau of Standards, and (5) results of tests of a frozen sand containing moisture.

The new guarded hot-plate thermal conductivity apparatus adds to the capability of CRREL to fulfill the research requirements of the U.S. Army.

GUARDED HOT-PLATE THERMAL CONDUCTIVITY APPARATUS

Operating principle

By definition, the thermal conductivity of homogeneous material is the time rate of steady-state heat flow through a unit area for a unit temperature gradient perpendicular to an isothermal surface:

\[ k = \text{Btu in./sq ft hr°F}. \]

*ACFEL was merged with the U.S. Army Snow, Ice and Permafrost Research Establishment (USA SIPRE) in 1961 to form the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL).
A 20-IN. GUARDED HOT-PLATE THERMAL CONDUCTIVITY APPARATUS

The guarded hot-plate method of determining thermal conductivity utilizes the one-dimensional steady-state heat flow through a flat slab of test material. The equation governing heat flow is:

\[ Q = kA \left( \frac{T_2 - T_1}{X_2 - X_1} \right) \]  
(1)

or

\[ Q = kA \left( \frac{\Delta T}{\Delta X} \right) \]

Solving for thermal conductivity:

\[ k = \frac{Q}{A} \left( \frac{\Delta X}{\Delta T} \right) \]  
(2)

where

- \( k \) = thermal conductivity, Btu in./sq ft hr°F
- \( Q \) = time rate of heat flow, Btu/hr
- \( \Delta X = X_2 - X_1 \)
  - discrete distance through a material normal to the isothermal surface, in.
- \( \Delta T = T_2 - T_1 \)
  - temperature difference across the distance \( \Delta X \), °F
- \( A \) = area measured on an isothermal surface, sq ft.

To determine the thermal conductivity of a material, two identical test specimens of the material are placed one on each side of a flat-plate main heater unit.* The main heater unit consists of an inner or main heater surrounded by an outer or guard heater. The guard heater eliminates horizontal heat losses and forces the heat generated in the main heater to flow vertically in one direction through the two test specimens. To produce the desired temperature gradient through the specimens, liquid cooled heat sinks are placed adjacent to the outer surfaces of the specimens. For higher temperature operation, thermal resistance is provided between the specimens and their corresponding heat sinks by either insulating materials or auxiliary heaters, or by both. The test stack assembly (Fig. 1a) is surrounded by insulation within a refrigerant-cooled shroud (chamber) as shown in Figure 3.

Under normal operating conditions, the same temperature gradient is established through both specimens by matching their cold surface temperatures. The total heat flux through the test section of the two specimens is equal to the heat generated in the main heater section. To ensure that the heat flow from the main heater is one-dimensional, a matching temperature gradient is established in the guard heater section of the specimen. This matching temperature gradient is produced by operating the guard heater at a temperature equal to that of the main heater. The outer shroud is operated at a temperature at least 10°F lower than the cold plate surface temperature. When the test section has reached a steady-state condition, the temperature differences through the two specimens and the total heat generated in the main heater are used to calculate the thermal conductivity of the specimens in accordance with eq 2.

*Occasionally it is inconvenient to use two identical specimens; in this case, a single specimen may be used (See App A, Contractor's Operating Instructions, p. 27).
A 20-IN. GUARDED HOT-PLATE THERMAL CONDUCTIVITY APPARATUS

Figure 1. Cross section of stack assembly and thermocouple locations in plate surfaces.

General description

The guarded hot-plate thermal conductivity apparatus consists of two consoles connected by piping. Figure 2 shows the ensemble. The main console (Fig. 2b) is a 34 x 34 x 68-in. stainless steel cabinet, housing the specimen stack assembly in the upper portion and various electrical control devices, terminals, power packs, switches and transformers in the lower portion. The second console (Fig. 2a) contains two independent refrigeration units: one unit supplies coolant to the shroud around the stack, and the other supplies coolant to the two thick copper heat-sink cold plates in the stack.

Specimen stack assembly. The most important part of the apparatus is the specimen stack and its controls. To accommodate the 3-in. specimen thickness requirement specified by CRREL (see
4 A 20-IN. GUARDED HOT-PLATE THERMAL CONDUCTIVITY APPARATUS

a. Refrigeration units.  

b. Main console.

Figure 2. Guarded hot-plate apparatus (20 x 20-in. stack).

Figure 3. Stack assembly in position in refrigerant-cooled shroud (including two specimens) with front open and top cover off.
Design criteria and specifications, App. C) the contractor provided a 20 x 20-in. minimum size stack with a 12 x 12-in. central metered section guarded by a 4-in.-wide strip on all sides. Figure 3 shows the stack assembly containing a pair of specimens.

Because of the large size and weight of the specimens that may be placed in the apparatus, special provisions were made for placing them into and removing them from the stack and its enclosing shroud chamber. For test temperatures below freezing, the stack (including specimens, thermocouples, insulation sheets and/or gun rubber sheets) is assembled in a coldroom. The stack is then protected by a heat insulating blanket while being transported from the coldroom to the precooled chamber of the test apparatus located in an air-conditioned laboratory room. The bottom cold plate was made 22 in. long to provide a 1-in. extension on each side, thereby permitting a fork lift to raise and remove the cold plate and the stack above it. The shroud chamber was provided with two openings: one in front of the chamber to allow stack removal laterally and the other on top of the chamber to permit pouring of granular insulation around the stack assembly. These are shown in Figures 2 and 3.

Cold-plate temperatures. The refrigerant, Freon 502, is supplied unthrottled to two series-connected refrigerated copper heat-sink plates (see items 6, 7, 16, and 17, Fig. A1, App. A). The surface temperatures of the cold-surface plates adjacent to the specimens are regulated by interposing one or more thin layers of thermal insulation between the cold-surface plates and the refrigerated heat-sink plates and by applying auxiliary electric heating to obtain precise control. The temperatures of the two cold-plate surfaces are controlled separately to eliminate variations that might be caused by the series hookup. The control procedures are described in the Contractor's Operating Instructions, Appendix A (p. 19).

Shroud temperature. A refrigerant is also supplied continuously to the shroud cooling coils by a separate compressor; no temperature controls are used. For a test specimen temperature 10°F above the ambient temperature, refrigeration to the shroud is not needed and is turned off.

Hot-plate temperatures. The temperature of the warm side of the specimen is automatically controlled by the main heater and by the guard ring heaters at the temperature setting selected. Selection of the proper dial setting to obtain a given temperature at the hot-plate surfaces requires some experience but should be no obstacle to an experienced operator. This also pertains to the selection of the cold-plate surface temperatures.

Test temperature. All hot- and cold-plate surfaces have shallow thin grooves to permit instrumentation with sensing thermocouples to obtain plate-surface temperatures. The heater control balancing thermocouples are built-in. The specifications for main heater windings and the locations of plate-surface grooves are shown in Figures A3, A6 and A7. Specifications require that all plate surfaces be parallel and smooth to a tolerance of ±0.003 in.

The locations and identifications of various control knobs, gages, dials, terminals and other parts are shown in Figures A1 and A2. The items corresponding to the numbers on the figures are listed in Appendix A.

**COMPUTATION OF THERMAL CONDUCTIVITY**

When computing the coefficient of the thermal conductivity of tested specimens, the following information must be known: 1) the temperature differences through the specimens on each side of the hot-plate unit; 2) the total heat flow through the two specimens; 3) the metered area of the specimens; and 4) the thickness of the specimens between the hot and cold plates, or the distance between thermocouples if they are embedded in the specimens.*

*The user of the apparatus should refer to paragraph 4(h), ASTM Specification C177-63, for guidance in selection of procedure.*
A 20-IN. GUARDED HOT-PLATE THERMAL CONDUCTIVITY APPARATUS

Three of the test results slightly exceeded the desired ±2% variation from the values shown in Figure B1. However, with training and experience a technician should be able to obtain results within ±1% of NBS values for the gum rubber. Similarly accurate determinations should be possible on other materials suitable for testing in a guarded hot-plate apparatus.

Table I. Test results.

<table>
<thead>
<tr>
<th>Run no.</th>
<th>Avg specimen temperature (°F)</th>
<th>NBS k-value† (Btu in./sq ft hr °F)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>*</td>
<td>-43</td>
<td>1.124</td>
<td>-0.6</td>
</tr>
<tr>
<td>1a</td>
<td>+79</td>
<td>1.140</td>
<td>+1.5</td>
</tr>
<tr>
<td>1b</td>
<td>+79</td>
<td>1.153</td>
<td>+2.7</td>
</tr>
<tr>
<td>2a</td>
<td>+106</td>
<td>1.110</td>
<td>-1.0</td>
</tr>
<tr>
<td>2b</td>
<td>+106</td>
<td>1.101</td>
<td>-1.8</td>
</tr>
<tr>
<td>2c</td>
<td>+106</td>
<td>1.149</td>
<td>+2.5</td>
</tr>
<tr>
<td>2d</td>
<td>+106</td>
<td>1.140</td>
<td>+1.7</td>
</tr>
<tr>
<td>3a</td>
<td>+131</td>
<td>1.101</td>
<td>-1.7</td>
</tr>
<tr>
<td>3b</td>
<td>+131</td>
<td>1.095</td>
<td>-2.2</td>
</tr>
</tbody>
</table>

*No run number assigned.
†Interpolated or extrapolated from Figure B1.

CRREL frozen sand test results

Two 3-in.-thick, 20 x 20-in. specimens of a well graded sand were prepared in a shallow wooden box and then frozen from the top surface downward. The sand had a moisture content of 3.5 to 4.0% and was compacted to a unit dry weight of approximately 110 lb/cu ft. Two thermocouples were frozen into each specimen surface: one in the center and the other about 6 in. away, within the square-foot metered area. Figure 4 shows two large soil samples.

After freezing, the top surface was filed smooth and the bottom panel of the box was removed, leaving the 3-in.-wide wooden sides to contain the specimens. The test stack with the specimens was assembled in the coldroom; it was then protected by blanket insulation and transported by fork lift for placement in the precooled shroud chamber of the testing apparatus.

Testing was started at an average temperature of -47°F with a difference of approximately 10°F between hot- and cold-plate temperatures. Two other determinations were made at mean temperatures of approximately -10°F and +22°F. Table II gives results of thermal conductivity tests obtained in this series and other pertinent data.

Figure 5 shows the relationship between the thermal conductivity and the mean test temperature for the frozen sand. The curve shows that the thermal conductivity of the frozen sand increases with decreasing temperature (below freezing). These data and temperature relationships are consistent with data available in published literature (Wolfe and Thieme, 1964; Kersten, 1949).

A comparison of CRREL test data for Lebanon sand with Kersten's (1949, p. 158) data on a similarly graded sand for approximately the same water content (3.5%) and dry unit weight (110 lb/cu ft), and a test temperature of approximately 23°F, is shown in Figure 5. Also shown is a value from Kersten's (1949, p. 90) prediction chart for a sandy soil. The guarded hot-plate results lie in between Kersten's predicted results and his test data. It is, therefore, concluded that the guarded hot-plate apparatus produces results consistent with those obtained by other techniques.
A 20-IN. GUARDED HOT-PLATE THERMAL CONDUCTIVITY APPARATUS

Figure 4. Specimens of frozen sand. Each specimen weighed approximately 110 lb.

Figure 5. Thermal conductivity vs mean temperature for frozen sand.
A 20-IN. GUARDED HOT-PLATE THERMAL CONDUCTIVITY APPARATUS

Figure 6. Typical temperature distribution on plate surfaces during a steady-state test condition.
A 20-IN. GUARDED HOT-PLATE THERMAL CONDUCTIVITY APPARATUS

Table II. Results of thermal conductivity tests on frozen sand.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Date</th>
<th>Time (hr)</th>
<th>Avg hot-plate temp (°F)</th>
<th>Avg cold-plate temp (°F)</th>
<th>Avg specimen temp (°F)</th>
<th>ΔT (°F)</th>
<th>k-value (Btu in./sq ft hr °F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>19 June</td>
<td>1230</td>
<td>-40.15</td>
<td>-53.22</td>
<td>-46.74</td>
<td>13.17</td>
<td>10.43</td>
</tr>
<tr>
<td>1b</td>
<td>1430</td>
<td></td>
<td>-40.43</td>
<td>-53.47</td>
<td>-46.95</td>
<td>13.04</td>
<td>10.45</td>
</tr>
<tr>
<td>2a</td>
<td>22 June</td>
<td>1020</td>
<td>-5.54</td>
<td>-14.23</td>
<td>-9.89</td>
<td>8.69</td>
<td>8.19</td>
</tr>
<tr>
<td>2b</td>
<td>1120</td>
<td></td>
<td>-5.67</td>
<td>-14.35</td>
<td>-10.01</td>
<td>8.68</td>
<td>8.19</td>
</tr>
<tr>
<td>3a</td>
<td>26 June</td>
<td>910</td>
<td>+28.18</td>
<td>+15.10</td>
<td>+21.69</td>
<td>13.08</td>
<td>7.02</td>
</tr>
<tr>
<td>3b</td>
<td>945</td>
<td></td>
<td>+28.13</td>
<td>+15.19</td>
<td>+21.66</td>
<td>12.94</td>
<td>7.21</td>
</tr>
</tbody>
</table>

Typical record of temperature distribution across plate surfaces

Figures A6 and A7 show the locations of grooves made in each plate surface for installation of thermocouples to measure plate temperatures and gradients. During the acceptance tests copper-constantan thermocouples were installed in these grooves to measure uniformity of plate surface temperatures. Nine thermocouples were affixed to each surface, one in the center and a pair on each of the four sides of the foot-square metered area. As indicated in Figure 1b, all thermocouples were in congruent locations on each plate; thus, corresponding points were in a vertical line in the assembled stack. The paired thermocouples were separated by approximately ½ in. or ¼ in. on either side of the gaps in surfaces 2 and 3.

The plate surface temperature profiles thus obtained, at a steady-state condition during a test of 1-in.-thick NBS-calibrated gum rubber, at an average temperature of -40°F, for each of the four plate surfaces, are presented in Figure 6. The deviations of temperature from the average temperature on any plate were usually less than ½°F and this was considered acceptable.

LITERATURE CITED


BIBLIOGRAPHY


BIBLIOGRAPHY (Cont’d)


APPENDIX A. CONTRACTOR'S OPERATING INSTRUCTIONS

This appendix consists of the instruction manual furnished by the contractor with delivery of the instrument. The contractor's name and references to his model numbers have been omitted and other minor editorial changes have been made.

NOTICE

The operator should thoroughly read these instructions before proceeding with the installation and operation of the guarded hot-plate thermal conductivity instrument. It is a fine instrument which must be treated with care and operated only by personnel thoroughly familiar with its principles and operating procedures.
Figure A1. Front view of test console and cutaway view of stack assembly (see list on opposite page for parts identification).
Table AI. List of guarded hot-plate apparatus components.

<table>
<thead>
<tr>
<th>Item</th>
<th>Name</th>
<th>Item</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cold wall front cover slide</td>
<td>38</td>
<td>Cabinet screws</td>
</tr>
<tr>
<td>2</td>
<td>Front cover slide shoulder bolt</td>
<td>39</td>
<td>Cabinet front panel</td>
</tr>
<tr>
<td>3</td>
<td>Front cover flexible connection</td>
<td>40</td>
<td>Thermocouple selector switch</td>
</tr>
<tr>
<td>4</td>
<td>Top heat sink insulation protector</td>
<td>41</td>
<td>Potentiometer connection</td>
</tr>
<tr>
<td>5</td>
<td>Top heat sink support</td>
<td>42</td>
<td>DC power supply 36 v, 10 amp</td>
</tr>
<tr>
<td>6</td>
<td>Top heat sink cooling coil</td>
<td>43</td>
<td>Guard heater control</td>
</tr>
<tr>
<td>7</td>
<td>Top refrigerated heat sink plate</td>
<td>44</td>
<td>Bottom auxiliary heater control</td>
</tr>
<tr>
<td>8</td>
<td>Main heater</td>
<td>45</td>
<td>Bottom auxiliary heater voltage adjustment</td>
</tr>
<tr>
<td>9</td>
<td>Top hot plate</td>
<td>46</td>
<td>Top auxiliary heater voltage adjustment</td>
</tr>
<tr>
<td>10</td>
<td>Main and guard heater and guard unit</td>
<td>47</td>
<td>Top auxiliary heater control</td>
</tr>
<tr>
<td>11</td>
<td>Bottom hot plate</td>
<td>48</td>
<td>Top auxiliary control circuit breaker</td>
</tr>
<tr>
<td>12</td>
<td>Bottom specimen</td>
<td>49</td>
<td>Guard heater control</td>
</tr>
<tr>
<td>13</td>
<td>Bottom cold plate</td>
<td>50</td>
<td>DC power supply circuit breaker</td>
</tr>
<tr>
<td>14</td>
<td>Bottom auxiliary heater</td>
<td>51</td>
<td>Guard heater power supply circuit breaker</td>
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<tr>
<td>15</td>
<td>Bottom auxiliary heater insulation</td>
<td>52</td>
<td>Bottom auxiliary heater power supply circuit breaker</td>
</tr>
<tr>
<td>16</td>
<td>Bottom refrigerated heat sink plate</td>
<td>53</td>
<td>Top auxiliary heater power supply circuit breaker</td>
</tr>
<tr>
<td>17</td>
<td>Bottom heat sink cooling coil</td>
<td>54</td>
<td>Pilot lights 110 v</td>
</tr>
<tr>
<td>18</td>
<td>Bottom heat sink support</td>
<td>55</td>
<td>Bottom auxiliary heater power supply circuit breaker</td>
</tr>
<tr>
<td>19</td>
<td>Base plate</td>
<td>56</td>
<td>Reference junction circuit breaker</td>
</tr>
<tr>
<td>20</td>
<td>Bottom heat sink insulation protector</td>
<td>57</td>
<td>Guard heater power supply control</td>
</tr>
<tr>
<td>21</td>
<td>Bottom heat sink insulation (zero cell)</td>
<td>58</td>
<td>Guard heater power supply output meter</td>
</tr>
<tr>
<td>22</td>
<td>Test stack loading rods</td>
<td>59</td>
<td>Guard heater power supply current limiting control</td>
</tr>
<tr>
<td>23</td>
<td>Loading rod springs</td>
<td>60</td>
<td>Cold wall (shroud) refrigerant expansion valve</td>
</tr>
<tr>
<td>24</td>
<td>Test stack loading plate</td>
<td>61</td>
<td>Heat sink flexible connections</td>
</tr>
<tr>
<td>25</td>
<td>Top heat sink insulation (zero cell)</td>
<td>62</td>
<td>Refrigerant base plate feed thru</td>
</tr>
<tr>
<td>26</td>
<td>Top heat sink insulation (Vultra foam)</td>
<td>63</td>
<td>Heat sink refrigerant expansion valve</td>
</tr>
<tr>
<td>27</td>
<td>Cold wall top cover locking clamp</td>
<td>64</td>
<td>Guard heater power supply</td>
</tr>
<tr>
<td>28</td>
<td>Cold wall top cover</td>
<td>65</td>
<td>Reference junction power supply</td>
</tr>
<tr>
<td>29</td>
<td>Stack loading rod washers</td>
<td>66</td>
<td>Main power contactor</td>
</tr>
<tr>
<td>30</td>
<td>Stack loading rod nuts</td>
<td>67</td>
<td>Reference junction</td>
</tr>
<tr>
<td>31</td>
<td>Cold wall front cover stand pipe connections</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Top auxiliary heater insulation</td>
<td>68</td>
<td>Auxiliary heater relays</td>
</tr>
<tr>
<td>33</td>
<td>Top auxiliary heater</td>
<td>69</td>
<td>Precision resistor box</td>
</tr>
<tr>
<td>34</td>
<td>Top cold plate</td>
<td>70</td>
<td>Isothermal box</td>
</tr>
<tr>
<td>35</td>
<td>Cold wall (shroud) assembly</td>
<td>71</td>
<td>Cold wall (shroud) insulation</td>
</tr>
<tr>
<td>36</td>
<td>Main power switch DPST at 10 amp</td>
<td>72</td>
<td>Cold wall (shroud) insulation cover</td>
</tr>
<tr>
<td>37</td>
<td>Stack support cabinet</td>
<td>73</td>
<td>Over temperature control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>74</td>
<td>110-v receptacle</td>
</tr>
</tbody>
</table>

Note: Item number on list refers to identification numbers shown in Figures A1 and A2 and referred to elsewhere in this report.
APPENDIX A

PART A1. INSTRUMENT DESCRIPTION

1. General description of the instrument

The guarded hot-plate thermal conductivity instrument is illustrated in Figures A1 and A2. The instrument is contained in a single cabinet (item 37), containing the test section and all automatic control equipment, power supply and readout instrumentation.

In the test stack cabinet, the test section is mounted on a base plate (item 19). Nylon blocks (item 18) position the bottom heat sink block (item 16), while a block of Styrofoam (item 21) insulates it from the base plate. The bottom auxiliary heater (item 14) is located above the bottom heat sink block and separated from it by an inch of insulating paper. (If an auxiliary heater is not used, the insulating paper thickness is increased to create the desired thermal resistance between the sample and the heat sink block.) The bottom cold plate (item 13) is positioned directly above the bottom auxiliary heater and provides both a flat and isothermal cold surface for the bottom specimen (item 12), as well as a means of installing the specimens into the test stack.

The main and guard heater (item 10) is positioned above the bottom specimen. The main and guard heater has plates (items 9 and 11) on either side. These plates provide flat, isothermally heated surfaces for the warm side of the specimens. The arrangement in the upper half of the test stack is the same, but in the reverse order, above the main and guard heater unit. Exceptions to this are the top heat sink cooling coil (item 6) and top refrigerated heat sink block (item 7) which are attached to a stack loading plate (item 24). The stack loading plate is used to transmit a uniform load to the test stack. This load is applied to the plate by springs (item 23) and loading rods (item 22) which are attached to the base plate (item 19). Outside the entire stack assembly is a cooling shroud (item 35) supported by the base plate. This cooling shroud is used to retain the insulation around the test stack as well as maintain the outer surroundings of the test stack at a temperature 10 ° F or more lower than that of the specimen cold-plate surface temperature. All thermocouples and power leads are connected directly to terminal strips located in the front of the console.

All readout instrumentation and operating controls are located in the front of the instrument. At the top of the panel are a series of circuit breakers (items 48 to 56) which fuse each circuit in the instrument independently. These circuit breakers may be left on at all times. Adjacent to the circuit breakers is the main power switch (item 36) which energizes the main power contactor. The thermocouple selector switch (item 40) and output jacks (item 41) are located next to the main power switch.

Beneath the switches is the main heater control (item 42) which is a regulated direct-current power supply. This unit contains controls for voltage adjustment and approximate readings of the voltage and current. A system is provided for obtaining an accurate measurement of the specimen heater voltage and current, by reading on a potentiometer the voltage drop across precision resistors. This system is described in paragraph 2d.

Directly below the main heater control are the guard and auxiliary heater controls. The guard heater control consists of an automatic null balance controller (item 43) and the guard heater power supply (item 64) for supplying the proper amount of power to the guard heater. The power supply and controller are Barber Colman Models 621 and 354 respectively. The power supply adjustments (items 57 - 59) are located on the front panel for ease of operation. The auxiliary heater controls are used to control the temperature of the top and bottom auxiliary heaters. The control system consists of a fine proportioning controller (items 44 and 47) and a variable transformer (items 45 and 46). The controller establishes the operating temperature of the heater while the Variac establishes the amount of power supplied to the heater during the "on" cycle.
Figure A2. Back cutaway view of main test console (see list on p. 15 for parts identification).
2. Detailed description of certain components

This section provides a more detailed description of certain important features of the instrument. It is intended to provide the operator with a better understanding of the instrument, aiding him in its setup, operation and maintenance. In addition to the items described below, separate instruction manuals are available describing the functioning and care of the following equipment.

(1) Barber Colman Model 354 Null Balance Controller
(2) Barber Colman Model 621 SCR Power Supply
(3) Barber Colman Model 293 Temperature Controller
(4) Kepco Model SM M DC Power Supply
(5) Leeds and Northrup Model 8686 Portable Potentiometer.

These manuals should be read and thoroughly understood before operating the equipment.

a. Main and guard heater unit. The main and guard heater unit (item 10) consists of an inner or main heater surrounded by an outer or guard heater, both sandwiched between two flat plates (items 9 and 11). Four \( \frac{1}{4} \times 20 \) screws pass through both plates of the main and guard heater sections to hold the pieces together. The main heater is used to supply a measurable heat flux axially through the specimen. This heat flux is produced by the d-c power being dissipated in the heater. The guard heater, separated from the main heater by a \( \frac{1}{4} \)-in. gap, is operated at the same temperature as the main heater to eliminate radial heat exchange between the main and guard heaters. The guard heater is controlled so that the temperature of the specimen surface adjacent to the main heater is identical with that of the specimen surface adjacent to the guard heater. This ensures

Figure A3. Wiring diagram and specifications for main heater and guard ring heater.
Figure A4. Thermocouple and power wiring diagram.
that there is no radial temperature gradient in the specimen and therefore no radial heat flow. To minimize conduction between the main and guard heaters the $\frac{1}{4}$-in. gap must be maintained. A thermal balance is maintained between the main and guard heaters by use of a thermopile or differential thermocouple (see Fig. A3).

An eight-junction differential thermocouple is placed, with junctions alternating across the $\frac{1}{4}$-in. gap between the main and guard heaters. The junctions of the differential thermocouple are placed directly on the two heaters. A sheet of silicone rubber covers the thermocouple wire and insulates it from the adjacent plates. This differential thermocouple provides the guard heater controller with an error signal indicating a temperature imbalance between the main and guard heaters. Since the guard heater controller supplies heat when the signal is negative, a negative signal must be present when the guard is colder. To ensure this, first connect the thermocouple leads to the proper terminals on the elevated base plate, designated DIFF TC on the TC wiring diagram (Fig. A4). Then, with power on the guard heater and no power to the main heater, watch the indicator needle on the guard heat controller. The needle should move to the left of the set point; if it does not, reverse the connections on the elevated base plate.

b. Specimen cold surface temperature control. Two methods are used to produce the desired cold surface temperature of a specimen. One method employs auxiliary heaters; the other method uses insulating paper to produce a thermal resistance between the cold surface of the specimen and the heat sink block. In either case, metal plates (items 13 and 34) are used to provide a flat and isothermal working surface for the specimen cold face.

1) Auxiliary heater method. The auxiliary heaters (items 14 and 33) consist of continuous, wound heater wire encapsulated in silicone rubber (see Fig. A5). The heaters are separated from the heat sinks (items 7 and 16) by insulating paper. The insulating paper forms a small thermal resistance between the heater and the heat sink.
The control system for the auxiliary heater consists of an "on-off" temperature controller and an auto transformer. The auto transformer is used to adjust the voltage supply to heater so that the power dissipation of the heater does not cause large temperature fluctuations. The "on-off" temperature controller controls the heater to a prescribed temperature by closing and opening a relay. The temperature of the heater is sensed by a thermocouple located in the heater side of the cold plate (items 13 and 34).

2) Insulation method. When operating without auxiliary heaters, insulating paper is placed between the heat sink plate and the specimen cold surface. This insulating paper should be thick enough to produce a desired cold surface temperature for a given heat flux from the main heater. To calculate the required thickness of insulation necessary for a given test the following approximate equation may be used:

\[ X_{ins} = \frac{k_{ins} T_{avg} - T_{hs}}{k_s \Delta T_s} - \frac{1}{2} \Lambda X_s \]

where

- \( \Delta X_{ins} \) = thickness of insulation
- \( k_{ins} \) = thermal conductivity of insulation
- \( k_s \) = estimated thermal conductivity of specimen
- \( T_{avg} \) = average specimen temperature
- \( T_{hs} \) = temperature of heat sink
- \( \Delta T_s \) = desired temperature difference across specimen
- \( \Lambda X_s \) = thickness of specimen.

This expression is approximate since the thermal conductivity of the specimen is estimated.

Once a given thickness of insulation is established the range of operating temperature over which it can be used may be calculated. The range is fixed by the limits placed on the specimen temperature difference,

\[ T_{avg} = T_{hs} + \Delta T_s \frac{\Lambda X_{ins} k_s}{\Lambda X_s k_{ins}} + \frac{1}{2} \Lambda X_s \]

It is recommended that the temperature difference through the specimen be no less than 10°F (for high k-value material) and never greater than 100°F.

c. System for measuring main heater power. A system is provided for obtaining accurate measurements of the main heater current and voltage by reading on a potentiometer the voltage drop across precision resistors. This resistor network is shown in Figure A4. The current through the load resistor is determined by measuring the voltage drop across a 0.01-ohm precision resistor. To illustrate, when the potentiometer reads 1.0 mv (=0.01 volts) across the 0.01-ohm resistor, the current is determined by

\[ I = \frac{E}{R} = \frac{0.01}{0.01} = 1 \text{ amp.} \]

Thus, the millivolt reading on the potentiometer equals ten times the heater current in amperes.

To measure the voltage drop across the heater a 10-kohm resistor is placed in series with a 10-ohm resistor. The resistors are connected in parallel across the main heater as shown in Figure A4. The total resistance through the parallel leg is 10,010 ohms compared with the main heater
The resistance of approximately 4.3 ohms. The current flowing through the parallel leg is therefore less than 0.1% of the current through the load. Thus, the presence of this parallel leg does not introduce any appreciable error in the load current measurement described above. The voltage drop across the 10-ohm resistor $E_e$ is related to the load voltage drop $E_L$ as follows:

For 10 ohms

$$E_e = E_L \times \frac{10 \text{ ohms}}{10,010 \text{ ohms}}$$

$$= 0.001 E_L \text{ (within 0.1%).}$$

Thus, the voltage drop across the 10-ohm voltage resistor measured on a potentiometer in millivolts equals the voltage drop, in volts, across the main heater.

The resistors are arranged in a box (item 69) located inside the cabinet.

The potential taps for the heater voltage and current are connected to a switch (item 40) on the control rack. The readings are taken on a potentiometer connected to the potentiometer jack (item 41).

A few words of caution should be inserted here. Due to the small voltages being measured in this system, it is very important that the voltage tap connections to the precision resistors remain clean and tight. The circuit should be checked occasionally against a good wattmeter connected into the circuit as shown in Figure A4. If the precision resistors are removed for any reason, such as cleaning, replacement, etc., care should be taken to reinstall them exactly as shown in the wiring diagram (Fig. A4). In particular, the current taps (labeled $C_1$, $C_2$ in instrument) and the potential taps (labeled $P_1$, $P_2$) on the 0.01-ohm resistors should never be confused, since the precise value of resistance (0.01 ohm) applies only between the potential taps. The precision 10-kohm resistor should not be allowed to accumulate dirt on its surface (should be cleaned occasionally) since a slight dirt film shunting across its taps could change its resistance value somewhat and destroy the accuracy of the heater voltage measurements. With proper care this power measuring circuit should provide very satisfactory service for a long period of time.

d. Sample preparation. To run a standard test, two specimens of the same material are required. The thickness of the specimen depends on the thermal conductivity of the material and the temperature difference across the specimen. The temperature difference across the specimen should be between 10°F and 100°F. For best results a 50°F difference is recommended. This temperature difference is sufficient to render normal thermocouple inaccuracies negligible and small enough to permit consideration of linear temperature variations of thermal conductivity. The specimen should generally be between 1 and 3 in. thick. As a guideline, a 1-in.-thick specimen should be used on material having a thermal conductivity no greater than 1.0 Btu in./sq ft hr °F and 3-in.-thick specimens should be used on material having a thermal conductivity between 1.0 and 25 Btu in./sq ft hr °F.

Specimens should be machined so that their surfaces are flat and parallel to within 0.003 TIR. A minimum of four grooves should be cut across both surfaces of the specimen, two grooves into the center and two grooves 4 in. from the outside edge. These grooves are used for instrumenting the specimen with thermocouples. They should be sufficiently wide and deep to receive a $\frac{1}{2}$-in.-OD ceramic insulator (approximately 0.040 × 0.040). Each groove is instrumented with a direct reading thermocouple. The centrally located thermocouples are used for measuring the temperatures of each surface. The thermocouples outside the metered area are used to check the guard temperature produced by the guard heater.
A preferred method of instrumenting the specimen is to have three grooves across the central portion and two $\frac{1}{2}$-in. grooves outside the metered area. In this case, one of the central grooves on each surface is used for instrumenting with a differential thermocouple, from which the temperature difference across the specimen can be measured directly (in millivolts). This method eliminates errors produced by thermocouple calibration differences which show up when a temperature difference between two absolute readings is present. When it is difficult to place thermocouples in the specimen directly, the surface plates may be instrumented. The surface plates have been grooved to receive nine $\frac{1}{4}$-in.-OD sheathed thermocouples (see Fig. A6 and A7): one in the center and a pair across each of the four slots, or in corresponding positions in non-slotted plates. Any additional thermal resistance between the specimen surface and the surface plates introduces an error in the calculated value of the specimen conductivity. Therefore, when using the instrumented surface plates, intimate contact between the specimen and surface plate must be assured. Assurance of intimate contact between surfaces is not too difficult to obtain with nonrigid specimens. Therefore, the use of instrumented surface plates in general should be limited to compressible specimens of low thermal conductivity. They may be used for rigid specimens of high conductivity when no other means of instrumentation are possible; however, this is not recommended as a general practice.

Normally, a full 20-in.-sq specimen is used in this instrument. However, for a material having a thermal conductivity greater than 1.0 Btu in./sq ft hr °F separation of the metered area from the guarding area is recommended.

If the amount of specimen material is limited, an acceptable method is to use the specimen material in the central, or metered, section and to use another material of similar conductivity to form the guard ring portion. This method is not recommended in the general case; it is considered acceptable only if the standard method is not possible.

When instrumenting the specimens, bare thermocouple wire should be used. The smallest wire compatible with temperature limits, calibration drift and strength requirements should be used (normally 20 to 30-gage wire). The two wires forming the thermocouple should be welded to each other. A two-hole $\frac{1}{4}$-in.-OD ceramic tube should be slid over each wire up to, but not covering, the welded junction. The tube should be long enough to extend from the center to the outside of the specimen. The thermocouple inside the tube is placed inside the grooves provided in the specimen. The tubes are then cemented to the specimen using Astroceram cement. When the cement has dried, a razor blade should be used to clean excess cement from the surface of the specimen. Care should be taken to make sure that the surfaces of the specimen are left completely flat after the instrumentation is installed. The thermocouple wires extending from the specimen should be long enough to reach the base plate terminal strip (approximately 18 in.). The leads should be covered with ceramic beads, or suitable sleeving.

e. Liquid cooling system. The instrument contains two refrigerated cooling systems. One system supplies the top and bottom heat sink plates (Fig. A8) which are connected in series; the other supplies coolant to the stack chamber wall. The compressor units for both systems are contained in a cabinet located adjacent to the instrument cabinet. Both systems are charged with refrigerant F-502.

Installation for the compressors requires 208/3/60 electrical service with the 30-psi cooling water supply having the following flow rate:

<table>
<thead>
<tr>
<th>Flow rate</th>
<th>Water temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 gal/hr</td>
<td>80°F</td>
</tr>
<tr>
<td>55 gal/hr</td>
<td>70°F</td>
</tr>
<tr>
<td>40 gal/hr</td>
<td>60°F</td>
</tr>
</tbody>
</table>
Figure A6. Details of thermocouple grooves in hot-plate surfaces.

Figure A7. Details of thermocouple grooves in cold-plate surfaces.
In operation both systems are turned on by the indicated switch located on the compressor cabinet. The heat sink system remains on at all times during operation of the instrument. The cold wall system is used for testing below room temperature; for testing above room temperature this system should be turned off.

1. **Thermocouple and power wiring layout.** The thermocouple and power wiring layout is illustrated in detail in Figure A4. A few additional remarks here will help describe the system.

Provision is made for using copper-constantan thermocouples for temperature sensing. Lead wires are installed for accommodating up to 20 thermocouples. In addition there are 2 pairs of copper leads for use with differential thermocouples when required. The thermocouple leads are terminated in the front of the cabinet on suitable terminal strips numbered in accordance with the code shown on the wiring diagram. The thermocouples used are connected to the thermocouple lead wire at this point.

Outside the test section the thermocouple lead wires are connected to terminal strips located inside the right side panel, before being run to the positive side of the selector switch. The constantan leads are interconnected in an isothermal box. A common constantan lead leaves the box and is referenced to copper in an automatic ice reference junction before being run to the negative side of the selector switch. Copper wire is used to connect both the positive and negative sides of the selector switch with the thermocouple jacks.

The numbers on the selector switch correspond to those in the outside terminals and correspond to the following schedule:
<table>
<thead>
<tr>
<th>Terminal no.</th>
<th>Test stack location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bottom specimen bottom center</td>
</tr>
<tr>
<td>2</td>
<td>Bottom specimen bottom center</td>
</tr>
<tr>
<td>3</td>
<td>Bottom specimen bottom guard</td>
</tr>
<tr>
<td>4</td>
<td>Bottom specimen bottom guard</td>
</tr>
<tr>
<td>5</td>
<td>Bottom specimen top center</td>
</tr>
<tr>
<td>6</td>
<td>Bottom specimen top center</td>
</tr>
<tr>
<td>7</td>
<td>Bottom specimen top guard</td>
</tr>
<tr>
<td>8</td>
<td>Bottom specimen top guard</td>
</tr>
<tr>
<td>9</td>
<td>Top specimen bottom center</td>
</tr>
<tr>
<td>10</td>
<td>Top specimen bottom center</td>
</tr>
<tr>
<td>11</td>
<td>Top specimen bottom guard</td>
</tr>
<tr>
<td>12</td>
<td>Top specimen bottom guard</td>
</tr>
<tr>
<td>13</td>
<td>Top specimen top center</td>
</tr>
<tr>
<td>14</td>
<td>Top specimen top center</td>
</tr>
<tr>
<td>15</td>
<td>Top specimen top guard</td>
</tr>
<tr>
<td>16</td>
<td>Top specimen top guard</td>
</tr>
<tr>
<td>17</td>
<td>Bottom heat sink</td>
</tr>
<tr>
<td>18</td>
<td>Top heat sink</td>
</tr>
<tr>
<td>19</td>
<td>Cold wall</td>
</tr>
<tr>
<td>20</td>
<td>Bottom specimen differential</td>
</tr>
<tr>
<td>21</td>
<td>Top specimen differential</td>
</tr>
<tr>
<td>22</td>
<td>Guard heater controller</td>
</tr>
<tr>
<td>23</td>
<td>Top auxiliary controller</td>
</tr>
<tr>
<td>24</td>
<td>Bottom auxiliary controller</td>
</tr>
</tbody>
</table>

The only exception to the thermocouple description is on thermocouples no. 22, 23 and 24, which run directly to the automatic controllers.

The power circuit is also shown in Figure A4. It contains eight subcircuits each of which is independently fused with a circuit breaker located on the front panel. These subcircuits are fed from a main contactor which is energized by a switch on the front panel. The main circuit should be connected to a 110-v, 40-amp, 60-Hz supply.

Following are the current breaker numbers and circuit descriptions:

<table>
<thead>
<tr>
<th>Circuit breaker no.</th>
<th>Circuit description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB 1</td>
<td>Top auxiliary heater</td>
</tr>
<tr>
<td>CB 2</td>
<td>Bottom auxiliary heater</td>
</tr>
<tr>
<td>CB 3</td>
<td>Guard heater</td>
</tr>
<tr>
<td>CB 4</td>
<td>Main heater</td>
</tr>
<tr>
<td>CB 5</td>
<td>Guard heater controller</td>
</tr>
<tr>
<td>CB 6</td>
<td>Top auxiliary heater controller</td>
</tr>
<tr>
<td>CB 7</td>
<td>Bottom auxiliary heater controller</td>
</tr>
<tr>
<td>CB 8</td>
<td>Automatic reference junction</td>
</tr>
</tbody>
</table>
PART A2. INSTRUMENT INSTALLATION

The following list of instructions is given to aid installation of the instrument. When using these instructions, reference should be made to the general assembly drawing (Fig. A1).

1. Install with sufficient space behind the unit to allow direct access to all components.

2. There is no need for special room air conditioning; the unit operates in normal ambient air temperature. The thermocouple reference junction box requires an air temperature not in excess of 90°F. If the ambient temperature becomes too warm, this is detected by a failure of the indicator light to cycle. Operating with the air temperature in excess of 90°F does not harm the reference junction; it merely prevents the unit from establishing the usual 32°F thermocouple reference temperature. Do not allow the instrument to stand in an air temperature below 32°F. Freezing of the thermocouple reference junction causes permanent damage.

3. Once the instrument has been placed in the desired permanent laboratory location, the inlet and outlet water lines should be connected to the compressor cabinet. A water supply at normal line pressure (30 to 50 psig), possessing the following flow rates, should be used:
   - 90 gal/hr at 80°F
   - 55 gal/hr at 70°F
   - 40 gal/hr at 60°F.

4. After connecting the water lines, connect the electrical supply to the instrument. The instrument contains two circuits, the test section and the refrigeration section power. The test section should be supplied with 110 v, 60 Hz, 40 amp; the refrigeration cabinet should be connected to two 208-v, 60-Hz, 3-phase, 10-amp supplies.

5. The instrument has been shipped with the meters of each controller shunted to avoid damage during shipment. The shunt wires for each controller are tagged at their location. These shunt wires must be removed before operating the instrument.

PART A3. TEST STACK ASSEMBLY

The test stack is assembled according to the stack assembly drawing (Fig. A1). The bottom auxiliary heater (item 14) is placed on top of approximately ½ in. of insulation (item 15) above the bottom heat sink plate (item 16). The bottom specimen, instrumented in the manner described in Part A1, paragraph 2d, is placed on the bottom cold plate. The specimen should then be checked to be certain that flatness and contact are maintained between it and the plate surface. The main and guard heater assembly (items 9, 10, 11) is placed on the bottom specimen, again checking for flatness. The top specimen is placed on top of the main and guard heater assembly followed by the top cold plate (item 34) and top auxiliary heater (item 33). Caution: All mating surfaces must be clean, flat and in good contact with each other.

With both specimens in position, the thermocouples are connected to the proper terminals on the elevated base plate (see Fig. A4). The selection of the terminal should be made in accordance with the schedule in Part A1, paragraph 2f. The main, guard and auxiliary heater leads are then connected to the correct terminals at the front of the cabinet (see Fig. A4).

When the thermocouples and power leads are connected, they should be checked for shorting. With one end of the ohmmeter connected to a plate the other end of the ohmmeter should be connected consecutively to the terminals of the thermocouples adjacent to that plate. This
procedure is performed with each plate and its adjacent thermocouples. The heater leads should then be checked for shorting against the plates and each other. To check shorting of the heater leads a procedure similar to that for checking the thermocouples should be followed. If, in checking, either a thermocouple or a power lead is shorted out, it should be fixed immediately and rechecked.

When the thermocouple and power leads are properly checked out, the top heat sink (item 7), insulation (item 25) and stack loading plate (item 24) are lowered over the test stack being positioned by the stack loading rods (item 22). Springs and nuts are placed on the stack loading rods and each tightened with equal pressure to produce a uniform loading over the entire test stack. These springs produce a total loading of 200 lb when fully compressed.

With the test stack secure, the front cover of the cooling shroud is closed and locked. Granular insulation is then poured in from the top, taking care not to damage the delicate thermocouple wires. The insulation should entirely fill the vacant space between the test stack and cooling shroud up to the test stack loading plate.

After insulation is in place, the thermocouple circuit is checked. To do this a complete set of thermocouple readings should be taken on the potentiometer and recorded. If all thermocouples are good, the test procedure may commence.

If only one specimen is available, the same test stack and assembly procedure is followed except that a ½-in.-thick Fiberfrax insulating paper is used in place of the second specimen.

**PART A4. TEST PROCEDURE**

To operate the instrument the following steps should be followed:

1. Turn on the refrigerant to the heat sinks and cooling shroud.

2. Turn the current limiting switch (item 59) located on the front panel to minimum current.

3. Set the auxiliary heater control (items 44 and 47) to room temperature.

4. Turn on the main power switch (item 36).

5. Turn on the reference junction switch (item 56). It takes approximately 10 min for the junction to reach reference temperature. When reference temperature is reached the light will flash bright to dim.

6. Turn on the DC power supply switch (item 42) and set the desired main heater power. The setting is determined as the product of the current and voltage readings shown on the DC supply. This setting is rough; further refinement of the setting to yield the desired sample temperature difference will be necessary. The adjustments on the DC power are made as the test stack approaches thermal equilibrium.

7. Set the auxiliary heater controllers (items 44 and 47) to the desired temperature in millivolts. Adjust the Variacs to provide sufficient voltage for the desired temperature. The voltage can be set roughly and adjusted if it is found too small to reach temperature or too large causing temperature cycling. Refined adjustments on the controller action can be made in the manner described for the Barber Colman Model 259. If only a single specimen is being used the auxiliary heater adjacent to the dummy specimen should be adjusted so that the temperature difference across the dummy specimen is less than 1°F.
8. Adjust the guard heater controllers (item 43) as described in the Barber Colman Manuals 354 and 621, making certain to adjust the current limiter to the proper setting. To maintain the accuracy limits, the controller should be adjusted to yield a temperature difference no greater than 1°F between the main and the guard heater.

9. Thermocouple and main heater power readings should be taken and recorded every half hour. The thermocouples are read out on positions of the TC selector switch (item 40). The current and voltage are read out through positions 27 and 28 of the TC selector switch.

10. When the values of conductivity as calculated do not change more than 1% between two readings, thermal equilibrium is considered attained and the final point may be taken. However, a detailed procedure of operation is described in the ASTM Specification C-177-63. This procedure should be followed whenever results obtained are to be published.
APPENDIX B. NBS CALIBRATION OF GUM RUBBER STANDARD

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON 25, D.C.

NATIONAL BUREAU OF STANDARDS
REPORT OF TEST

on
Thermal Conductivity
of
Gum Rubber


Material

Two pieces of commercial gum rubber 12 inches by 12 inches by 1 inch in size, approximately, were supplied by [contractor] for thermal conductivity determinations for use as calibrated thermal conductivity reference specimens.

Procedure

The average thermal conductivity of the specimen pair was measured in an 8-inch guarded hot-plate apparatus conforming with the requirements of Standard Method of Test ASTM C177.

Results

<table>
<thead>
<tr>
<th>Test No.</th>
<th>HC12667</th>
<th>HC12567</th>
</tr>
</thead>
<tbody>
<tr>
<td>421.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean temperature of specimens, °F</td>
<td>19.0</td>
<td>130.0</td>
</tr>
<tr>
<td>Thermal conductivity,* Btu/hr ft² (deg F/in.)</td>
<td>1.127</td>
<td>1.120</td>
</tr>
<tr>
<td>Thickness, as tested, in.</td>
<td>1.006</td>
<td>1.032</td>
</tr>
<tr>
<td>Density, as tested, lb/ft³</td>
<td>61.7</td>
<td>60.1</td>
</tr>
<tr>
<td>Temp. gradient in specimens, deg F/in.</td>
<td>45.4</td>
<td>40.0</td>
</tr>
</tbody>
</table>

* Corrected for a plate-contact thermal resistance of 0.012 deg F per (Btu/hr ft²) determined by simultaneous solution of uncorrected values for 1/2 inch and 1 inch gum rubber.
Neither the contents of this report nor the fact that the tests were made at the National Bureau of Standards shall be used for advertising or promotional purposes.

For the Director,

H. E. Robinson, Chief
Environmental Engineering Section
Building Research Division, LAT

February 6, 1967
Test Folder No. 191263
TWWatson; trw
Figure B1. Thermal conductivity vs average specimen temperature of gum rubber based on NBS data.
APPENDIX C. DESIGN CRITERIA AND SPECIFICATIONS

DESIGN REQUIREMENTS

General

A set of specifications was prepared which essentially incorporated all of the requirements of American Society for Testing and Materials (ASTM) Specification C-177-63, with some modifications. The apparatus was to be designed to take flat square slabs of material up to 3 in. thick and over a range of $k$-values from 0.1 to 30 Btu in./sq ft hr °F within the specified temperature range. The complete applicable technical specifications are presented below:

1. The guarded hot-plate system is to be used for testing flat slabs of materials, up to 3 in. thick, ranging from lightweight insulating boards to Portland cement concrete and frozen sand and gravel containing stones up to 2 in. in diameter. The $k$-values of the materials to be tested in this apparatus will range from 0.1 Btu in./sq ft hr °F for the insulating board to about 30 Btu in./sq ft hr °F for the frozen high-density saturated sand and gravels.

2. The minimum temperature to be achieved and maintained in this apparatus is -50°F in the cold plate to +250°F in the hot plate. The apparatus must be capable of operating and being maintained at any desired temperature between these limits with a minimum difference of 10°F between hot and cold-plate surface temperatures.

Technical specifications

The guarded hot-plate system required under these specifications shall conform in every essential requirement with ASTM Specification C-177-63 (see 1965 Book of ASTM Standards, Part 14, Thermal Insulation, etc.), except as modified below for the specific applications at USA CRREL:

1. Maximum thickness of test specimens: 3 in.
2. Test plate geometry: Square
3. Surface plate temperature uniformity: Surface temperatures of the hot plate and the cold plates must not differ more than $\frac{1}{4}$°F between any two points on the same surface.*
4. Restriction of heat losses: Heat losses from the outer edges of the hot-plate guard section shall be restricted by controlling the surrounding air temperature within the specimen enclosure to a dew point temperature 10°F or more lower than that of the cold plate and by insulation.
5. Testing position, etc: The specimens must be tested in a horizontal position. The design of the plates and supporting structure must be adequate to support the weight of 3-in.-thick material having a unit weight of 170 lb/cu ft.
6. Overall size: The complete unit must be constructed as compactly as possible and may be in functional sections as necessary. The unit must be neat and of good workmanship, with dials and gages, controls, etc., mounted in convenient and accessible locations. All sections must fit through a standard doorway (33 in. wide and 76 in. high).

*This requirement was relaxed when rigid compliance could not be met.
7. **Power requirements:** The system will operate at 110 v, 60 cycle, except that any motors of 1 hp or more shall be 208 v, 3 phase.

8. **Plate temperature selection:** The apparatus shall be equipped with temperature selector switches conveniently mounted which will enable the selection of the temperature desired in the hot plate and the required differential not exceeding 40°F, in the cold plates, within ±2°F of selected value.

9. **Automatic power regulation:** Input power to central heater shall be automatically regulated.

10. **Loose fill insulation around assembly in specimen chamber:** The contractor will furnish the loose fill insulation required. It will be of a granular non-dust type, treated to resist moisture absorption or be moisture resistant. A sufficient amount shall be furnished to fill the assembly container when empty.

11. **Commercial gum rubber:** Four sheets of \( \frac{1}{8} \)-in.-thick commercial gum rubber (30 to 45 Durometer floating stock, Federal Specification MIL-R-880A) of sufficient size, shall be furnished as part of this procurement.

12. **Standard test specimens:** The contractor shall furnish a certified National Bureau of Standards test specimen of appropriate material (to become property of CRREL), which will be used to check the accuracy of the apparatus as required in the temperature range specified.

13. **Demonstration and performance requirement:** Acceptance of the apparatus shall be based on a demonstration of its performance at contractor's plant in the presence of the Project Officer. The apparatus must meet all requirements of ASTM Standard C177-63 and specified requirements; it must accurately reproduce k-values of NBS-certified standard specimens; it must operate efficiently and be trouble free in every respect within its specified operating temperature range.
APPENDIX D. NOTES AND OBSERVATIONS BY CRREL PERSONNEL ON OPERATION OF NEW GUARDED HOT-PLATE INSTRUMENT

1. Determination of main heater power level
   a. Using formula, solve for power $P$:

   $\text{Power} = \frac{k(A)\Delta T}{\Delta X} \cdot \frac{2}{3.415}$

   $k = $ assumed conductivity constant, Btu in./sq ft hr °F
   $A = $ area of test section, sq ft
   $\Delta T = $ temperature difference, °F
   $\Delta X = $ thickness of specimen, in.

   b. Adjust power level until $EI$ product equals calculated power; a wattmeter speeds this operation.

2. Temperature settings and stabilization
   a. The auxiliary heater temperatures are set on their respective meters; they stabilize in about an hour.
   b. The main heater temperature is affected by:
      1) the main heater power input
      2) the $k$-factor of the specimen
      3) the temperature gradient, possibly by imbalance of guard heater
      4) the fluctuations in power furnished to main heater power supply, etc. It takes 18 to 24 hours for sufficient stabilization of temperature.
   c. The setting of the main heater guard is a rather intricate operation. First, note that the limit and bias controls have been transposed from what the operation manual calls for; however, they are correct as labeled. It is desired to get the indicator needle to assume a neutral position on the meter. Experience shows this requires patience.
   d. It is wise to have a graphical recorder attached to the various plates so that changes can be observed as they occur.
   e. Considerable time can be saved by heating or cooling the various surfaces by individual applications of heating or cooling to obtain the approximate temperatures desired before the entire system is turned on for stabilization.
   f. Experience has shown that the auxiliary heater’s plate temperature may disagree with the controller setting by several degrees Fahrenheit; these controllers can be calibrated. Also, Variacs can cause excessive overshoot. It is desirable to have “on time” equal to “off time.”
g. The GHP apparatus terminal board provides for measuring only 19 of the 36 existing plate thermocouples. This is not enough if close checking of plate temperature uniformity is needed. There are generally several erroneously reading thermocouples due to shorts, etc. A short, in a thermocouple lead, causes a summation reading rather than a direct reading of either the short or the thermocouple.

3. Shutdown process

a. Due to the extreme cold temperature and considerable mass of the cold sinks, they maintain their cold temperature for considerable time (24 to 36 hours). This causes excessive frosting when the machine is shut down. The moisture from the frost, in turn, delays the next test. This problem can be lessened by shutting off both cooling units and allowing the heaters to continue at a high setting long enough to warm the cold sinks.

b. The top door should be opened first and the environmental insulation removed before it has a chance to come in contact with the inherent frost.

c. The main door of the GHP apparatus should not be opened until sufficient time has been allowed for the flexible plastic refrigerant lines to warm. This takes only a short time after the environmental insulation (Pelspan) has been vacuumed out. Rubber stoppers are visible in the bottom of the chamber when the main door is opened. These stoppers should be removed to allow any excess condensate to drain into the drip pan. This water has been a source of a number of problems and an effort should be made to remove it as soon as possible.

4. Precautions

a. Check voltage, current and resistance values for compliance with Ohm’s law. Some malfunctioning (now corrected) has been observed in previous testing.

b. A difference in initial and stabilized power level can be attributed to a change in thermal resistance of the main heater as there is generally a sizeable difference in room temperature and operating temperature.

c. Place polystyrene insulation in holes in top door facing; also tape all door seams to reduce frosting.

d. Be extremely careful in handling the stack to prevent damage to thermocouples, heaters and their respective leads.

e. Make sure cooling water is turned on before refrigeration system is turned on.

f. Use nylon bolts in securing the main door. Their frosting characteristics are not nearly as objectionable as those of steel bolts.
EVALUATION OF A 20-IN. GUARDED HOT-PLATE THERMAL CONDUCTIVITY APPARATUS, RANGE -50°F TO +250°F

A new custom-made guarded hot-plate thermal conductivity test apparatus capable of accommodating two 20 x 20-in. specimens up to 3 in. thick is described. The apparatus was designed for testing materials ranging from thin, rigid, foamed thermal insulations to 3-in.-thick pavement sections of asphaltic or portland cement concrete, with a 1-ft-square metered area. The effective temperature range of the apparatus is from +250°F to -50°F. Some performance test data on a calibrated gum rubber specimen and results of evaluation tests on a frozen wet sand are presented. The k-values obtained for the frozen sand compare well with those obtained by other techniques.

Key Words:
- Soil tests
- Testing equipment
- Thermal conductivity tests
- Thermal insulation tests