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DISSERTATION

Presented in Partial Fulfillment of the Requirements for
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By

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* * * * * *

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PUBLICATIONS


TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>ACKNOWLEDGMENTS</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>VITA</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>vii</td>
</tr>
</tbody>
</table>

Chapter

| I. INTRODUCTION   | 1 |
| II. EQUIPMENT     | 6 |

2.1 Operation of a Guard Ring Thermal Conductance Cell
2.2 Design Considerations for the Experiment
2.3 Temperature Measurements for the Experiment
2.4 The Top Half of the Cell
2.5 The Bottom Half of the Cell and Gas Jacket
2.6 Vacuum and Gas Handling Systems
2.7 Thermometer and Heater Circuits
2.8 Carbon Resistance and Heater Connections

III. MEASUREMENTS

3.1 Primary and Secondary Calibrations
3.2 Balance of Guard Ring and Active Center
3.3 Measuring the Thermal Resistance of the Cell

IV. THE KAPITZA BOUNDARY RESISTANCE

4.1 Primary Calibration: The Carbon Resistance Thermometer
4.2 Cell Conductance
Chapter | Page
--- | ---
4.3 The Copper Correction | 49
4.4 Contributions to Cell Resistance | 54
4.5 Sources and Magnitude of Experimental Error | 63

V. ANALYSIS OF RESULTS | 69

5.1 Different Approaches to Understanding the KBR | 69
5.2 The Adsorbed Layer | 80
5.3 Previous Indications of a KBR in Caseous Helium | 82
5.4 Discussion of Results | 84
5.5 Evidence for a Possible Phase Change in the Adsorbed Layer | 87
5.6 Low Pressure Measurements of the KBR | 91
5.7 Comparison Between $^3$He and $^4$He | 93
5.8 Future Directions of Research | 94

APPENDIXES

A. SPACER CONSTRUCTION AND GAP THICKNESS MEASUREMENTS | 96
B. THE TEMPERATURE REGULATOR | 101
C. THE POWER AMPLIFIER | 109
D. PRELIMINARY STEPS IN MAKING A RUN | 113
E. ADJUSTMENT AND OPERATION OF THE TEMPERATURE REGULATOR | 115
F. DETAILED STEPS FOR BALANCING HEAT INPUT TO GUARD RING AND ACTIVE CENTER | 124
G. SOLUTION FOR FINDING THE CONSTANTS OF THE FIVE CONSTANT FORMULA | 127
H. INTERPOLATION WITH THE SECONDARY CALIBRATION AS EXAMPLE | 134
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Measuring the Thermal Resistance of the Cell</td>
<td>40</td>
</tr>
<tr>
<td>2. Types of Overload</td>
<td>117</td>
</tr>
<tr>
<td>3. Operation of Temperature Regulator</td>
<td>119</td>
</tr>
<tr>
<td>4. Balancing Heat Input to Guard Ring and Active Center</td>
<td>125</td>
</tr>
</tbody>
</table>
LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Schematic Diagram of Conductance Cells</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>The Cell</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>Vacuum and Gas Handling Systems</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>Block Diagram of Electrical Equipment</td>
<td>28</td>
</tr>
<tr>
<td>5</td>
<td>Circuits for Carbon Resistances and Heaters</td>
<td>31</td>
</tr>
<tr>
<td>6</td>
<td>Channel #2 Chart Recorder Data</td>
<td>39</td>
</tr>
<tr>
<td>7</td>
<td>Flow Diagram of Measurements and Calculations of Cell Conductance</td>
<td>46</td>
</tr>
<tr>
<td>8</td>
<td>Corrected Cell Conductance</td>
<td>52</td>
</tr>
<tr>
<td>9</td>
<td>Relative Contribution to Cell Resistance as a Function of Temperature</td>
<td>58</td>
</tr>
<tr>
<td>10</td>
<td>The Kapitza Boundary Resistance</td>
<td>61</td>
</tr>
<tr>
<td>11</td>
<td>The Kapitza Boundary Resistance for Low Pressures</td>
<td>65</td>
</tr>
<tr>
<td>12</td>
<td>Density Profile of He II Adjacent to a Copper Wall (6)</td>
<td>74</td>
</tr>
<tr>
<td>13</td>
<td>Variation of the KBR with Pressure (6)</td>
<td>77</td>
</tr>
<tr>
<td>14</td>
<td>Various Measurements of the KBR for He II on Copper (18)</td>
<td>79</td>
</tr>
<tr>
<td>15</td>
<td>Specific Heat for Intermediate Coverage (&lt; 1 layer) of $^3$He and $^4$He</td>
<td>90</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>16.</td>
<td>Optical Paths for Gap Thickness Measurements</td>
<td>98</td>
</tr>
<tr>
<td>17.</td>
<td>Bridge Circuit for Temperature Regulator</td>
<td>103</td>
</tr>
<tr>
<td>18.</td>
<td>T vs. Output Voltage of Temperature Regulator Bridge</td>
<td>106</td>
</tr>
<tr>
<td>19.</td>
<td>Circuit for the Power Amplifier</td>
<td>111</td>
</tr>
<tr>
<td>20.</td>
<td>Contour Plot of Percent Errors of Five Constant Formula, (Equation 2)</td>
<td>130</td>
</tr>
<tr>
<td>21.</td>
<td>Carbon Resistance Thermometer Data Where One Branch of Contour Plot is Missing</td>
<td>133</td>
</tr>
<tr>
<td>22.</td>
<td>Example of Interpolation Scheme</td>
<td>136</td>
</tr>
<tr>
<td>23.</td>
<td>((\log R_3 - 2)^{-1}) vs. Channel #1</td>
<td>139</td>
</tr>
</tbody>
</table>
CHAPTER I

INTRODUCTION

The process of heat transfer between solid surfaces and liquid helium was first studied in detail by Kapitza (1) who noted the presence of a thermal resistance at the interface between a solid and liquid He II. The discovery of a similar effect (2) in liquid $^3$He (which does not exhibit superfluid behavior) showed that the Kapitza resistance is not closely related to the phenomenon of superfluidity. Subsequent measurements (3),(4) have shown that the magnitude and temperature dependence of the Kapitza resistance depend as much on the nature of the solid as on the state (density and isotopic constitution) of the liquid in contact with it. Recent theories of the Kapitza resistance have concentrated, therefore, on the mechanism of energy transfer between solid and liquid, rather than on a supposed connection with superfluidity. The most incisive approach was that of Khalatnikov (5) who considered the processes of emission and adsorption of thermal vibrations by the surface of the solid, treating the solid and the liquid as elastic continua. Unfortunately, this direct approach gives resistance values too large by one or two orders of magnitude, and cannot account for the various kinds of temperature dependence observed. Nor has any conspicuous success been achieved in later attempts to
modify the theory, (a) by taking into account (6) the improvement in acoustic impedance matching between liquid and solid that results from the formation, by van der Waals' forces, of a layer of highly compressed helium at the solid surface, or (b) by considering (7) the interaction of the electrons in a metallic solid with phonons at the liquid helium surface, or directly with the helium atoms.

This dissertation describes an effort to measure a thermal resistance to a small heat current passing perpendicular to the interface between copper and various phases of the two isotopes of helium over the temperature range of 1.5°K to 4.5°K. These measurements confirmed a suspicion (8) that the Kapitza boundary resistance (KBR) is greater by an order of magnitude in He I than it is in He II. This fact shows that theory has a great gap in it, since no effort has been made to compare the behavior of the KBR in He I and He II. Indeed, Khalatnikov (5) asserts that the KBR should exist only in superfluid helium.

In an attempt to provide a different starting point for discussion of the Kapitza effect, it has been suggested (4) that the adsorbed layer of helium atoms at the solid surface plays an important part in the heat transfer. This idea, which still awaits theoretical development, bears the immediate implication that the Kapitza resistance should not be greatly dependent on the density of the bulk liquid, or even on the phase (solid, liquid, gaseous)
of the helium. Unfortunately, experimental data for fluids other than superfluid He II is scanty because of the difficulty of distinguishing the surface resistance from bulk resistive effects in the fluids, which are themselves poor conductors of heat above 1.5°K. The work done for this dissertation was an effort to extend experimental data on the KBR into as large a range of temperature, pressure, phase, and isotope as practical. In addition, refinement was sought over earlier measurements (9) (see section 2.2) to discover structure in the KBR, if any, with respect to any of the above variables. Earlier indications (10) of KBR in gaseous helium have indeed proved true, and in addition new effects have been discovered.

For the reader unfamiliar with the KBR, the rest of this chapter consists of a short description of important aspects of a simplified mechanism giving rise to the KBR. The temperature jump caused by passing a heat current across a copper-helium interface is limited to a very narrow region whose thickness is of the same order of magnitude as the range of the Van der Waals' forces, i.e., a few angstroms. The dominant mechanism of heat transfer at helium temperatures is by phonons. Each phonon carries energy hv at the speed of sound in the direction of propagation, where v is the frequency and h is Planck's constant. Phonons may be scattered by other phonons, by impurities, or by the boundaries of the medium through which the phonon is traveling. Thus the more often a phonon is scattered, the lower will be the thermal conductivity of the medium. The reflection of a phonon at the interface
between two substances will occur when the acoustic impedances of the two substances are not equal. The acoustic impedance is $Z = \rho c$ where $\rho$ is the density and $c$ is the speed of sound. In the case of a heat current passing across an interface, many phonons on the high temperature side will be reflected. Thus the energy density of phonons on the high temperature side will be greater than the density of phonons immediately on the other side of the interface due to this reflection. The density of phonons is a direct measure of the temperature (11); thus a difference in the density of phonons across an interface indicates a difference in temperature.

There is an additional factor in the case of a copper-helium interface which influences the transmission of phonons across the interface. This is the existence of a higher density layer of helium adsorbed on the surface of the copper by Van der Waals' forces. This layer of denser helium, having an acoustic impedance intermediate between that of bulk helium and the copper, serves as an acoustic matching layer, just as the inclusion of a short length of transmission line having intermediate electrical impedance will greatly reduce the reflection of a radio frequency signal transmitted down a line having a step change in impedance.

Because of the tremendous acoustic mismatch between copper and helium, it is easy to see that the more dense adsorbed layer of helium plays a very important part in the magnitude of the KBR. One might well expect
that a change in pressure or temperature could affect the thickness of the adsorbed layer of its phase. Any such change in the adsorbed layer could have a large effect on the thermal boundary resistance at the interface between the helium and copper.
CHAPTER II

EQUIPMENT

Section 2.1: Operation of a Guard Ring Thermal Conductance Cell

All measurements of the KBR in this research were made using a thermal conductance cell with a guard ring to prevent heat leaks outside the sample area. Figure 1a shows a simple conductance cell without a guard ring. A heating coil in the top piece generates heat, at a rate $\dot{Q}$, which passes through the sample and the lower piece into the heat sink, which is held at a constant temperature. The temperatures on either side of the sample space are measured with resistance thermometers $T_1$ and $T_3$. Assuming the copper to be a perfect conductor of heat, the temperature drop across the sample is $\Delta T = T_1 - T_3$. The sample fluid is contained by a sample jacket and the cell is insulated by a vacuum. In such a cell it is difficult to make satisfactory corrections for that part of the heat current that does not pass through the sample, but reaches the heat sink by conduction in the sample jacket or in the heater and thermometer leads. This difficulty is circumvented by using a "guard ring".

A conductance cell with a guard ring is shown in Figure 1b. In the guard ring cell, the ratio of the power inputs to the guard heater $\Pi_G$ and to the active center heater $\Pi_C$ is adjusted so that the temperatures, $T_1$ and $T_2$, of the
Figure 1

Schematic Diagrams of Conductance Cells:

(a) Simple Conductance Cell

(b) Conductance Cell with Guard Ring
guard ring and the active center remain equal when a heat current is passed through the cell. Then there is no heat transfer between the active center and the guard ring, and all heat generated at $H_C$ passes through the sample.

**Section 2.2: Design Considerations for the Experiment**

Design considerations for this experiment depended upon the magnitude of the quantities to be measured. Other important design considerations were the number of points that had to be taken, and the reduction of errors as much as practical. The KBR for helium which this experiment has measured is equivalent to the resistance of a layer of bulk gas at most ten microns thick. Since the ratio of the thermal conductivity of bulk helium gas to that of oxygen free high purity copper is about $1 : 100,000$ at $4°K$, the KBR is equivalent to about 1 meter of this copper.

It is clear that the gap between the copper surfaces containing the sample gas must be ten microns or less in order to make good measurements of the boundary resistance. Also the thermometers $T_1$ and $T_3$ used to measure the thermal conductance of the gap should be as close as possible to the gap in order to minimize temperature corrections due to thermal gradients in the copper. By placing the two thermometers effectively about one cm. apart it was possible to keep corrections for thermal gradients in the copper to about one percent or less for helium gas and normal liquid.
Since the measurements extend over a wide range of pressures and temperatures many hundreds of measurements had to be made. It was further necessary that these measurements be made as accurately as practical since any possible reduction of error might reveal more structure in the KBR. To decrease the time required for a measurement, an effort was made to automate to some extent the electrical equipment used to make these measurements. In partially automating the measurements, it was further found possible that several important sources of error could be either eliminated or minimized. This would not have been possible otherwise.

The first special electronic device used was a temperature regulator bridge. The cell was decoupled from the main helium bath by a thermal standoff and the temperature set and maintained at the desired value by a negative feedback system. This regulator almost completely eliminated temperature fluctuations arising in the main helium bath. It also allowed the temperature of the cell to be set at any new temperature from 1.5°K to 4.5°K in a few seconds by the adjustment of a single potentiometer knob, whereas pumping or warming the main helium bath would have been inefficient in the use of helium and time consuming. A special feature (Section 2.3 and Appendix F) of the temperature regulator allowed the guard ring and active center of the top half of the cell to be thermally balanced without knowing the calibration of the carbon resistance thermometers. This fact allowed reduction of the number of points that needed to be taken by a factor of 2.
Another special feature of the temperature regulator bridge was the generation of an electrical signal proportional to the temperature of the cell. This was recorded along with the cell conductance measurements on a dual trace chart recorder. Also the temperature of the cell could be seen at a glance, and even spacing of the measurements with respect to temperature was facilitated over the entire range of temperatures.

Cell conductance measurements were made by recording the off-balance signal of an ac resistance bridge. By recording a measurement on a chart recorder, many measurements could in effect be made in one inch of recorded trace, and averaged to reduce the error (Figure 6, Section 3.3). Further, the ac resistance bridge could be calibrated quickly for each point. Thus the speed of making a measurement was limited only by the equilibrium time of the cell and the amount of noise in the signal, which could be removed by an averaging technique as mentioned above. By using the dual trace chart recorder all data for each conductance measurement was recorded at the same location on the chart. This eliminated the time that would be necessary to collate the data, and possible errors associated with that process.

The thermal conductance cell shown in Figure 2 is the heart of the experimental apparatus, and it was with this cell that all actual measurements on helium were made for this dissertation. The conductance cell consists of three main parts: the upper half, the lower half, and the gas jacket. The upper and lower halves of the cell were machined from oxygen free, high
Figure 2

The Cell
conductivity (OFHC) copper which was used to achieve the lowest possible thermal gradient in the copper. In addition the top half of the cell was designed to be free standing to avoid differential thermal contraction problems. The strong gas jacket would allow possible future measurements on solid helium. The design also minimized the effect of thermal gradients in the copper. The surfaces and geometry of the gap were designed for the very narrow width of 8 µ which could later be reduced to as little as 0.5 µ.

Section 2.3: Temperature Measurements for the Experiment

Before the thermal conductance cell of Figure 2 is described in detail, it is appropriate to consider all temperatures that had to be measured for the experiment. Measurements of temperatures and temperature differences were the most important design consideration in the experiment.

There are four carbon resistance thermometers shown in Figure 2 labelled T₁, T₂, T₃, and T₄. T₁ and T₃ were calibrated directly against the vapor pressure of the main helium bath while in good thermal contact with it. This is called a primary calibration. T₄ was calibrated against T₃ (for reasons described later in this section) during what will be referred to as the secondary calibration. A primary calibration was performed every time the cell was cooled down from room temperature. The secondary calibration was easier to do, and it was performed more often as required. All but T₂ had to be calibrated. (T₂ did not have to be calibrated because of a special feature
of the temperature regulator described later in this section, (Section 3.2 and Appendix B). Since the carbon resistors used for the thermometers were selected as a matched set from a group of fifty, their temperature characteristics were very similar, although not identical. (At liquid helium temperatures, variations of resistance, of about 1% were noted within the matched set.)

The thermometers were carbon resistors whose values varied rapidly with temperature, so their resistances were read with an ac resistance bridge for each bath temperature. The bath temperature was found from its measured vapor pressure by appropriate tables (13). Eleven primary calibration temperatures were used: 4.2, 3.5, 2.8, 2.5, 2.2, 2.0, 1.8, 1.65, 1.5, 1.4, and 1.3°K.

Temperature differences could also be measured by the ac resistance bridge by reading the resistance difference between two carbon resistance thermometers (Section 2.8). Thus at each primary calibration temperature the resistance of \( T_3 \) and the resistance difference between \( T_1 \) and \( T_3 \) were measured by the ac resistance bridge.

Carbon resistance thermometer \( T_4 \) always remained connected to the temperature regulator for the cell. As mentioned earlier, the temperature regulator could maintain the temperature of the cell at some desired value above the bath temperature because of a thermal standoff between the cell.
and the main bath. The value of thermal resistance of this standoff was fairly critical since it had to be small enough to keep the cell in good thermal contact with the bath for the primary calibration (with the regulator turned off), but not so small that too much power would be required to raise the cell to a desired temperature above that of the main bath. (1/4 watt was required to maintain the cell at 4.5° while the bath was at 1.5°C) The temperature regulator generated a dc signal derived from the regulator setting, which thus indicated the cell temperature as long as the regulator was working and in balance.

The secondary calibration consisted of reading the value of $T_3$ on the ac resistance bridge versus the dc signal indicating the setting position of the temperature regulator knob displayed on channel #1 of the dual trace chart recorder. This secondary calibration allowed for any mismatch between $T_3$ and $T_4$. From the primary calibration, the temperature of $T_3$ could be found for any resistance measurement of $T_3$ by the ac resistance bridge. From the secondary calibration just described, the resistance of $T_3$ could be found for any channel #1 pen position on the chart recorder, provided the temperature regulator was in operation at the time. Hence the channel #1 pen position was used to record the temperature of $T_3$ when the temperature regulator was in operation, which was true whenever the cell conductance was being measured.

The secondary calibration was performed at least once a day during the time measurements were being taken because of a small long term drift.
probably in the battery used in the temperature regulator. Regular secondary calibrations were also carried out as a precaution against any other long term effects that might occur.

During the measurements of cell conductance two additional steps were necessary involving temperature measurements of parts of the cell. The first step was the adjustment of the ratio of power to the guard and active center heaters described before in Section 2.1. A special feature of the temperature regulator, used only for this adjustment of the guard-active-center power ratio, was its capability to lower the temperature of the bottom half of the cell by a small reproducible, adjustable increment at the instant the top heaters were turned on.

Lowering the temperature of the bottom half of the cell would tend to lower the temperature of the top half of the cell as well. On the other hand, turning on the top heaters would tend to raise the temperature of the top half of the cell. If the correct value of heater power were used, these two effects on the temperature of the top half of the cell would cancel and the temperature of the top half of the cell would remain unchanged.

To use this feature of the temperature regulator for adjusting the power ratio of the top heaters the ac resistance bridge was set to measure $\Delta R_{12}$, the difference in resistance between the two carbon resistance thermometers in the guard ring and active center. The off balance signal of the ac resistance bridge was rectified internally by a phase detector and then
displayed on Channel #2 of the chart recorder. When the top heaters were turned on (but the temperature of the top half of the cell kept unchanged), the heater power ratio was adjusted so that $\Delta R_{12}$ was also unchanged. This meant that the temperature difference between $T_1$ and $T_2$ was unchanged when the top heaters were turned on. Since $T_1 = T_2$ before the top heaters were turned on, $T_1 = T_2$ afterwards also, which is the desired adjustment of the guard ring.

The cell conductance required the measurement of the temperature drop across the sample gap. This was done by setting the ac resistance bridge to measure $\delta (\Delta R_{13}) = \delta R_H$, the change in the resistance difference between $T_1$ and $T_3$ as the top heaters were turned on (described in Section 3.3). Since the bottom half of the cell was kept at a constant temperature by the temperature regulator when conductance measurements were made, $T_3$ remained unchanged and $\delta R_H$ was the change in the resistance of $T_1$ caused by the temperature drop across the sample gap.

From the primary calibration the relation between $T_1$ and $R_1$ is known. Let $T_{1H}$ and $R_{1H}$ be the temperature and resistance of $T_1$ with the heaters turned on. Let $F$ represent the formula relating $R_1$ to $T_1$ such that $F(R_1) = T_1$. Then $R_{1H} = R_1 + \delta R_H \cdot F(R_{1H}) = T_{1H}$. Finally, $\delta T_H$, the temperature drop across the sample gap equals $T_{1H} - T_1$, and $T = T_1 + \frac{\delta T_H}{2}$.
Since $T$ and $T'$ are basic to any conductance, their derivation was outlined briefly above. This section has not discussed other measurements such as heater voltage, which are discussed elsewhere. A flow diagram showing how the various temperature measurements fit into the calculation of cell conductance is shown in Figure 7 and described in Section 4.2.

**Section 2.4: The Top Half of the Cell**

The top half of the cell consists of two parts, an active center and a guard ring. The guard ring is included in the cell so that when $T_1$ and $T_2$ are equal, the active center is shielded from stray heat currents; and all heat generated in the active center by its heater must pass downward across the eight micron gap into the bottom half of the cell. The entire top half of the cell may be disassembled so that should any electrical element fail it may be replaced without having to rebuild the top half of the cell. Thermometers $T_1$, $T_2$, $T_3$, and $T_4$ in the top and bottom halves of the cell were Allen Bradley 1/4 watt carbon resistors with a nominal room temperature resistance of 180 ohms and five percent tolerance. These four carbon resistors were picked from a set of fifty similar resistors on the basis of having most similar low temperature behavior. The three heaters on the top and bottom halves of the cell were made of $\#40$ evenohm wire insulated with nylon, and all heaters had a resistance of about 150 ohms. The active center of the cell contains its heater and thermometer, $T_1$, both of which are totally enclosed and potted in Apiezon N grease.
In the design of the cell great care was taken to (a) heat sink heaters and carbon resistance thermometers to the copper, and (b) totally enclose heaters and thermometers in copper, especially in the active center where stray heat currents would have their worst effect. (a), of course, insures that the carbon resistance thermometers will always be at the same temperature as the copper. (b) prevents power from escaping the active center to the guard ring, or even worse, passing directly to the thermometer above it and causing a false reading.

The active center of the cell is supported solely by an annulus of stycast, 1/16" in thickness, which bonds it at the bottom to the guard ring. Stycast was chosen because it has a coefficient of expansion equal to that of copper, and an unusually low thermal conductivity due to the fact that the stycast is filled with sand. Tiny threads were machined on the copper to provide firm bonds, preventing any possibility of the active center and the guard ring moving with respect to each other.

The top half of the guard ring may be unscrewed allowing access to the active center. The cell is divided in the middle by an eight micron gap which is maintained by three spacers around the edge of the gap. The spacers were attached to the guard ring. Notice that the guard ring stands only on the three spacers and is free of the gas jacket.
Appendix A describes how the spacers were made and the measurement of the thickness of the gap. In fabricating the top half of the cell the bottom surface was machined as flat as possible after the active center had been joined to the guard ring by the stycast. The bottom surface, which forms the top half of the eight micron gap, was then polished optically flat using standard optical polishing techniques (12). This polishing was done by using successively finer grinding powders, suspended in a vehicle of metal polish which itself did not contain any abrasive except rouge.

Section 2.5: The Bottom Half of the Cell and Gas Jacket

The bottom half of the cell contains two carbon resistors. The upper one, T3, was sealed in place with brass plugs which were soldered in the ends of the hole containing the carbon resistor in order to prevent helium leaking from the sample space. The cell then sat on a thermal standoff which in turn rested on the bottom of the vacuum jacket. The thermal standoff was composed of a two mill thickness of mylar.

The gas jacket which encloses the upper two-thirds of the cell was made from stainless steel for corrosion resistance and strength. The cell was designed to withstand a pressure of about fifty atmospheres with a large safety factor of 100 percent at room temperature and considerably greater at helium temperatures, since the strength of stainless steel increases as the temperature is reduced. The diameter of the bottom half
of the cell increases just above the gas jacket flange attached to it, thus making it virtually impossible for this joint to fail. As mentioned above, the top half of the cell stands completely free of the gas jacket. This is necessary to prevent the gap width in the cell being changed by differential thermal contraction between the stainless steel and the copper. The electrical leads from the carbon resistance thermometers and heaters were led out through #40 copper wires attached to the electrical feedthrough indicated in Figure 2. This electrical feedthrough was made by potting the wires and the end of the tube from which they emerge in epibond 100A and is vacuum tight even to superfluid helium. At the bottom of the cell below the gas jacket is the thermometer, $T_4$, and a heater right next to it. The heater is used to create a temperature rise across the thermal standoff. The current input to the heater is regulated by negative feedback from $T_4$ so that the temperature at the bottom of the cell remains constant and is thus decoupled from temperature fluctuations in the main bath.

Section 2.6: Vacuum and Gas Handling Systems

Figure 3 is a schematic diagram of the vacuum and gas handling systems. The cell described above is enclosed in a brass vacuum jacket. This vacuum jacket has a false bottom (i.e., double walled) so that all heat generated in the cell must pass out the side of the vacuum jacket into the liquid helium bath. This prevents the possibility of helium gas bubbles forming directly
Figure 3

Vacuum and Gas Handling Systems
under the cell and causing violent temperature fluctuations in the cell. The vacuum jacket is suspended by its pumping tube inside a double Dewar system. The inner Dewar contains liquid helium and the outer Dewar liquid nitrogen. The inner Dewar is sealed by a silicone rubber gasket to a large copper pumping line leading to a large vacuum pump. Thus the helium bath pressure may be lowered to a desired value which in turn maintains the helium bath at a desired temperature as indicated by the vapor pressure tables for $^4$He. A static pressure line leads from the main bath to the manometers where the pressure of the main bath may be precisely read to determine the temperature with sufficient accuracy to calibrate the carbon resistance thermometers.

The vacuum jacket is pumped by a 1/2" line from the top of the vacuum jacket. Directly above the vacuum jacket inside the 1/2" pumping line is a simple spiral radiation trap. The 1/2" vacuum line then extends upward out of the Dewar system and past a high quality valve into a nitrogen trap and then to a high vacuum diffusion pump. The purpose of the nitrogen trap is to prevent any oil vapor from streaming backward from the diffusion pump, and to increase the pumping speed of the vacuum system for water and for low vapor pressure organic materials. The diffusion pump is then backed by a standard mechanical pump.
The gas feedline is a 1/8" stainless steel tube also leaving the top of the vacuum jacket and extending upward out of the Dewar system. This gas line continued to a manifold connecting to several $^3$He storage bottles and to a Consolidated Vacuum Corporation, diaphragm-type, vacuum gauge reading pressure at constant percentage error from 1 to 350 Torr.

**Section 2.7: Thermometer and Heater Circuits**

Figure 4 is a block diagram of the electrical support and measurement equipment. This diagram may be divided into two main parts. The top half consists of a temperature regulating bridge and amplifier used to maintain the cell at constant temperature above that of the main helium bath temperature. The details of the temperature regulator and power amplifier are described in detail in Appendixes B and C respectively. The bottom half of the block diagram shown in Figure 4 consists of the electrical equipment used to measure the temperature of the carbon resistors and regulate current from the batteries to the heaters. All carbon resistor and heater leads go through a shielded cable from the cryostat to a switch box so that the resistance of any heater or resistance thermometer can be measured on an ac bridge, and so that the potential drop across each heater that is switched on can be measured with a potentiometer. The records of off-balance output from the regulating bridge and the ac resistance bridge, displayed on a dual-channel chart recorder, constitute most of the direct raw experimental data.
Figure 4

Block Diagram of Electrical Equipment
THERMAL NEGATIVE FEEDBACK

CARBON RESISTOR

BRIDGE → PREAMP → LOCK-IN → POWER AMP. → HEATER

SWITCH BOX

MALAKER BRIDGE → DUAL TRACE RECORDER

BATTERIES

POTENTIOMETER

HEATERS
Section 2.8: Carbon Resistance and Heater Connections

Referring again to Figure 4 the circuits for reading the carbon resistance thermometers and the resistance of the heaters, and for putting current into the heaters, will now be discussed. The details of these circuits are shown in Figure 5. In this figure the ac resistance bridge appears at the bottom with leads labelled 1, 2, and 3.

The inset in Figure 5 shows the bridge and the three lead systems connecting to the remote carbon resistance thermometer. Since leads 2 and 3 are in opposite arms of the bridge, the resistance of lead 2 compensates for that of lead 3. Thus if $R_2$ is inserted in series with lead 2, only the difference between $R_2$ and $R_3$ will be read on the bridge.

In Figure 5 for example, switches $S_2$ and $S_3$ are set so that the ac resistance bridge will measure the difference between carbon resistors $T_1$ and $T_2$. Should the difference between the two resistances be negative, $S_1$ may be used to reverse the two leads and make this differential resistance positive as the reading of this differential resistance appears on the ac resistance bridge. Should the differential resistance between two resistors be nearly zero, $S_4$ may be used to switch in the 200 ohms, $R_1$. This would make the total differential resistance 200 ohms, which then may be subtracted from the reading after it has been taken, to give the true differential resistance between the two resistors being measured. The 100 pfd capacitors,
Figure 5

Circuits for Carbon Resistances and Heaters
5 millihenry chokes, and ferrite beads immediately above the ac resistance bridge are for the purpose of filtering out radio frequency interference.

The total resistance of just one carbon resistance thermometer may be read by setting one of the switches $S_2$ or $S_3$ on $G'$ and the other on the carbon resistance thermometer whose resistance is to be read. In like manner by switching $S_2$ to $G'$ and $S_3$ to a heater on the active center or on the guard ring, the resistance of this heater may be read at helium temperatures. In reading these heaters $S_5$ is opened and decade box #2 disconnected.

Current to the heaters is supplied by a nine volt battery which passes through a voltage regulator $R_2$ and $D_1$. The current through both the active center and the guard ring heaters is regulated by decade box #1. The voltage across the guard ring heater is then read by the potentiometer.

Resistor $R_3$ and $R_4$ constitute a voltage divider network since in some cases the voltage across the guard ring heater exceeds the voltage range of the potentiometer.

The ratio of the currents through the guard ring heater and the active center heater is regulated by decade box #2. Once this ratio has been established, the power dissipated in both heaters is regulated by decade box #1 and read on the potentiometer. Resistor $R_5$ and switch $S_6$ are used during the experiment to maintain a constant load on the battery, when the heaters are switched off.
CHAPTER III
MEASUREMENTS

Section 3.1: Primary and Secondary Calibrations

The procedures for preparing to make a run are described in Appendix D. The first measurement usually made at liquid helium temperatures was the primary calibration of the carbon resistance thermometers $T_1$ and $T_3$ inside the cell as shown in Figure 2. ($T_4$ is calibrated against $T_3$ during the secondary calibration.) The main helium bath was pumped down to the desired pressure and temperature while the mercury manometer was open to it. The vapor pressure corresponding to a given temperature was determined from the "1958 4He Scale of Temperatures" (13). A particular pressure of the main helium bath was then regulated by a manostat. The resistance of one of the carbon resistors was monitored with the off-balance signal of the ac resistance bridge produced on the chart recorder. This dc off-balance signal was generated by a phase detector inside the bridge. The voltage and sign of the dc signal depends linearly on the amount and direction of imbalance. When the temperature stopped changing everything had come to equilibrium so measurements could be made. The resistance of each carbon resistor at the set temperature was then measured with the ac resistance bridge.
The details of the operation of the temperature regulator used for the secondary calibration and cell conductance measurements are described in Appendix E. The secondary calibration of carbon resistance thermomter $T_3$ was performed to provide a chart record of temperatures for each measurement. In Figure 17, Appendix E, one output of the regulator is labelled "To the chart recorder" and is a differential output from points C and D. This differential voltage is proportional to the temperature at which the voltage regulator is set provided $S_1$ is closed. In displaying this signal on the chart recorder it was found most convenient to adjust the variable gain and the variable zero point of the chart recorder so that in sweeping from "zero" to "seven" as indicated on the knob of the bridge temperature control, the recorder pen would sweep from edge to edge of the chart. Since diode $D_1$ compensates for the drift of diode $D_2$, caused by changes in the ambient temperature, the output signal to the chart recorder is fairly stable. However, over a long period of time some drift may be observed, usually a few percent. For this reason it is important to check every half hour, after initial stabilization, that the recorder pen sweeps from edge to edge of the chart under appropriate settings as the bridge temperature control knob moves over a predetermined convenient range. (The variable gain and zero point of the chart recorder were set so that the experimental range of temperatures (1.5 to 4.5°K) could just be accommodated on the chart.)
The secondary calibration refers to calibrating the position of the chart recorder pen against the value of carbon resistor \( T_3 \) shown in Figure 2. In effect the resistance of \( T_3 \) (read on the Malaker ac resistance bridge) was recorded for a given position of Channel #1 of the chart recorder. This was done every third of a degree over the range of 1.5°K to 4.5°K. Comparisons of various runs on different days shows that interpolations between these secondary calibration points are quite consistent from run to run.

Section 3.2: Balance of Guard Ring and Active Center

The heat input to the guard ring and active center must be balanced so that the two are at exactly the same temperature. Otherwise an undesirable heat current would flow between them making cell conductance measurements inaccurate. A neat trick was employed in accomplishing this balance. When heat was put into the top half of the cell, the temperature regulator was made to lower the temperature of the bottom half of the cell just the right amount so that the temperature of the top half remained unchanged. Therefore the calibration of carbon resistance thermometers \( T_1 \) and \( T_2 \) need not be known to make this balance adjustment. The detailed steps for balancing the guard ring and active center are given in Appendix F and summarized in Table 4 of the appendix.
It is emphasized that in contrast to the above procedure, during the actual measurement of the thermal resistance of the cell, the top half of the cell rises in temperature typically by a few hundredths of a degree (0.1°K at most). The bottom half of the cell is kept constant in temperature by the temperature regulator. This is assured by adjusting the bias control of the power amplifier so that the meter on the lock-in detector returns to zero after the top heaters are turned on.

Balancing the guard ring and active center was accomplished by adjusting decade box #2 (see Figure 5). The adjustment of #2 decade box had to be made for every measurement, and typically measurements were made every 0.2°K. A test was made at different temperatures and pressures to see how carefully the balancing procedure (Table 4, Appendix F) had to be done. After making the balance at some particular temperature and pressure, decade box #2 was changed a given amount and a measurement was made. It was found that decade box #2 could be changed by an amount ten times greater than the finest adjustments that could be made during the balancing procedure before any detectable changes could be observed in the measurements. In other words the heat input to the guard ring and active center by the top heaters could be balanced ten times better than necessary to make the measurements within the limit of error arising from other sources.
Until the behavior of the cell was well understood, the balancing procedure was followed for each point. This was especially important at the lower end of the temperature range where the balance setting changed rapidly with temperature.

**Section 3.3: Measuring the Thermal Resistance of the Cell**

Table 1 lists the appropriate steps for measuring the thermal resistance of the cell. Channel #2 of the chart recorder was used to make a record of the off-balance phase detected signal of the ac resistance bridge which was adjusted to look at the resistance difference between $T_1$ and $T_3$ ($R_{13}$). The Channel #2 recorder pen trace for a typical data point is shown in Figure 6a. In this figure the earliest time is at the right; time moves left and the last section of the recorder pen trace is on the left. Events that occurred as this trace was made are labelled with numbers which increase with time. First the bridge was set about 50 Ω off balance with the bridge ohms dial (1). Next the bridge ohms dial was changed by exactly 100 Ω so that the bridge was about 50 Ω out of balance in the opposite direction (2). Then the ohms dial was returned to its original position and the top heaters of the cell turned on (3). The power input to the top heaters was adjusted (4) so that the trace was almost exactly at the same height as in event #2, which thus serves as a calibration of Channel #2 for each data point.
Figure 6

Channel #2 Chart Recorder Data for δ T of Cell Conductance Measurements

(V_H, Decade box #2 setting, δ R_C, and time noted on chart adjacent to Channel #2 data for point.)
Finally the top heaters were turned off allowing the trace to return to its original height, the same as in event #1 (5). Other pertinent data were recorded on the chart paper.

The discussion of the steps in Table 1 will now be continued.

### TABLE 1

**MEASURING THE THERMAL RESISTANCE OF CELL FOR GIVEN TEMPERATURE AND PRESSURE**

1. Look at \((T_1, T_3)\) with the resistance bridge and display output signal of bridge on channel #2 of chart recorder. (Make sure that T bypass switch used in Table 4 is closed.)

2. Change the setting of the ac resistance bridge from one side of balance to the other by an amount \(R_C\) as large as convenient (\(-10\%\) of \(T_1\)). Then return to original setting.

3. Turn on top heaters and adjust their currents (decade box #1, Figure 5) so that the off balance signal of the ac resistance bridge changes in the same direction and about the same amount as in Step 2 as seen on the chart recorder.

4. Record on the chart paper: the time, heater voltage, setting of decade box #2, and \(R_C\) of Step 2.

5. When equilibrium has been reached turn off top heaters and wait for equilibrium again, before stopping chart recorder.
In Step 2 the ac resistance bridge is operated out of balance. However, for reasonably small departures from balance the bridge is quite linear. Linearity was measured by changing the resistance bridge setting by successive 10 Ω increments and comparing the pen motion for each increment. Maximum nonlinearity was 10% with 1% a typical figure. The bridge balance point should be near the middle of the pattern (as indicated in Figure 6a) to allow the greatest swing in the resistance being measured without exceeding the linear region of the bridge. Any error due to the small nonlinearity that may remain can be made negligible by Step 3 in which the heat input to the top half of the cell is adjusted so that the height of the recorder pen is almost the same as in Step 2.

The purpose of Step 5 is to check for any drift in the temperature of the cell. Any error due to such drift, provided the drift is constant, can be greatly reduced in the usual manner by making measurements from a base line, shown in Figure 6a as a dotted line. Figure 6b shows an extreme example of temperature drift where the cell temperature was not regulated. Notice that even here the temperature drift of the cell contributed negligible error to the measurements. This figure also illustrates a case where considerable noise is present in the signal. By drawing a dotted line through the recorded trace, in effect an average of many measurements is made, so that errors due to noise are greatly reduced.
CHAPTER IV

THE KAPITZA BOUNDARY RESISTANCE

Many sources of data reduced by many different calculations were required in the course of this research to arrive at the corrected values of the KBR. This chapter describes in detail most of these calculations, the reasons for them and any peculiarities they may have. In addition to the cell conductance and the KBR, calibrations, interpolations and corrections are of special interest in this chapter.

Section 4.1: Primary Calibration, The Carbon Resistance Thermometer

The use of an ordinary 1/4 watt carbon resistor as a thermometer has several advantages: low cost, small size, and great sensitivity. One serious disadvantage is a change of as much as several percent in value at a given temperature every time the resistor is cycled up to room temperature and back. This means that the carbon resistance thermometer must be calibrated every run. (Calibration data for the carbon resistors consisted of 11 measurements of resistance versus vapor pressure of the main helium bath, which was converted to the equivalent temperature (13).

Since the thermometers were being used to measure small temperature differences, it was important that the calibration yield good values of
\[ \frac{1}{T} = \frac{A}{\log R} + B + C \log R \]  

(1)

which has the advantage of being nearly linear (see below). Making a least squares fit to Equation (1) with the data for the carbon resistors used in this research showed that Equation (1) was only accurate to several percent in some cases. For this research the slope of the curve of resistance versus temperature was even more important than knowing the temperature itself, since measuring the thermal resistance of the cell directly involves \( \frac{dR}{dT} \). Unfortunately, the slope of a curve fitted to a set of measurements is more difficult to find accurately than a point on the curve. This may be seen by connecting the measured points by straight lines. Intermediate values are well defined by this method, but the slope is not. In Equation (1) the constant \( A \) is usually much smaller than \( B \) or \( C \); thus Equation (1) is nearly linear, that is, \( \frac{d}{dT}(1/T)/\log R \) is almost constant. This means that the slope of the curve of Equation (1) is relatively insensitive to temperature when plotted as \( 1/T \) against \( \log R \). However an error in \( \frac{dR}{dT} \), arising from the limited accuracy with which Equation (1) can be fitted to the carbon resistance calibration data, will cause the same percentage error in the calculations of \( \delta T \) used to arrive at the thermal conductance of the cell.
In an effort to reduce the slope error in fitting the carbon resistance data, Equation (1) was modified to include an additional two adjustable constants:

\[
\left( \frac{1}{T} \right)^Y = \log X R \left( A + B \log R + C \log X R \right) = \log^2 R \cdot P (\log R)
\]

In this equation, \( P \) stands for parabola. Notice that this equation reduces to Equation (1) if \( Y = 1 \) and \( X = -1 \). Details of the method adopted for finding these five constants are given in Appendix G.

Section 4.2: Cell Conductance

The rather elaborate Equation (2) performed essentially the task of interpolating the data of the primary calibration of carbon resistance thermometer \( T_1 \) with the special result of carefully preserving the slope. Many other interpolations were necessary in the course of calculating the cell conductance as shown later in this section and in the calculation flow diagram, Figure 7. A simple example of an interpolation where slope was not so important is conversion of the helium bath vapor pressures into the equivalent temperatures. It was found convenient to do this and all other required interpolations (except the primary calibration) with a simpler interpolation scheme on the computer. The exact procedure for this interpolation scheme is shown in Appendix II.
Figure 7

Flow Diagram for Measurements and Calculations of Cell Conductance

\[ V_{VP} \] vapor pressure
\[ R_3 \] resistance of \( T_3 \)
\[ \Delta R_{13} \] difference of resistance between \( R_1 \) and \( R_3 \) with no heat current
\[ C_{h1} \] channel 1 of chart recorder
\[ C_{h2} \] channel 2 of chart recorder
\[ \delta R_H \] change in resistance of \( T_1 \) due to heat current only
\[ V_H \] active center heater voltage
\[ W_H \] active center heater power
\[ T \] temperature of bottom half of cell
The cell conductance was derived from data taken during a run by a fairly long sequence of calculations and interpolations. The entire sequence from the beginning of measurements to the final step in obtaining the corrected cell conductance is shown in the flow diagram in Figure 7. (Variables are defined on the figure title page.) Measurements for the primary calibration, secondary calibration, and the thermal conductance data for various pressures and temperatures were taken during the run. The various calculations and interpolations were performed later on the computer for the sake of accuracy and speed. With the exception of the 5 constant formula, all could have been done by the use of tables and desk calculator.

The measurements for the primary and secondary calibrations were used for inputs to the interpolations and to the five constant formula described in Section 4.1. Each interpolation is shown in the flow diagram as an inverted triangle and appears on the upper part of the figure; double lines extend downward from it to a transistor-like symbol intersecting flow lines of the appropriate data variables upon which the interpolation is performed. Special discussions of the variables $\delta R^r_H$, $W^r_H$, gross cell conductance, and the copper correction among others will be pursued in the following paragraphs and section.
In the measurements for the primary and secondary calibrations, carbon resistance thermometer \( T_3 \) was used as the primary calibration carbon resistor because, being in the same piece of copper as the temperature regulator, its resistance showed the greatest stability. The other resistances were then measured relative to \( R_3 \), e.g., \( R_1 = R_3 + \Delta R_{13} \). Since \( R_1 \) and \( R_3 \) will be in opposite arms of the bridge (see Figure 5), and since they are closely matched, temperature fluctuations in them will nearly cancel.

On the other hand, \( R_1 \) is used to calculate temperatures with the five constant formula in the flow diagram. This is because only \( R_1 \) changes since \( R_3 \) is held constant during the thermal conductance measurements by the temperature regulator (as opposed to the operation of balancing the guard ring against the active center, where the regulator is made to lower the temperature of the bottom half of the cell and the temperature of the top half of the cell is thus maintained constant as described in Section 3.2).

The primary data for the calculation of the gap temperature drop (\( \delta T \)) was taken from the graphical record of the second channel of the chart recorder (Section 2.7). The change in thermometer resistance (\( \delta R_H \)) produced by switching on a heater (i.e., by changing the temperature) is obtained by comparison with a calibrated resistance change (\( \delta R_C \)) produced by manipulating the resistance bridge. Referring to Figure 6:  

\[
\frac{\delta R_H}{L_H} = \frac{\delta R_C}{L_L}.
\]
The heat current passing across the cell gap from the active center is the variable in the calculation of cell conductance, and it is this variable that is controlled independently by the decade boxes and heater circuit as was shown in Figure 5. In this figure all the resistances in series with the active center heater between the potentiometer and heater had to be measured. They were the line resistance $R_L$ (3 $\Omega$) heater resistance $R_H$ (153.7 $\Omega$) and resistance of the decade box #2 ($R_{D2}$). The decade box #2 resistance was recorded with each data point on the chart paper.

The current through the active center heater circuit is

$$I = \frac{V_T}{R_{D2} + R_L + R_H}$$

where $V_T$ is the total voltage across the heater circuit at the potentiometer. Then the power developed in the active center heater is:

$$W_H = R_H I^2 = \frac{R_H V_T^2}{(R_{D2} + R_L + R_H)^2}$$

Section 4.3: The Copper Correction

Some means must be found for applying a correction to the gross cell conductance to account for the effects of temperature gradients in the copper end pieces between the thermometers and cell faces. The gross cell conductance is simply $S_{cell} = W_H / \delta T$ where $\delta T$ is the temperature drop.
across the gap for a given power input, \( W_H \), to the heater in the active center. From Figure 8 it can be seen that the cell conductance observed during these experiments ranged over two orders of magnitude. Therefore the correction for temperature gradients in the copper could be relatively insignificant (1-2%), or very large (50%) depending on whether \(^4\text{He}\) gas or superfluid liquid were in the cell.

Fortunately in this case one can deduce from internal evidence what the copper correction has to be. If the thermal resistance of the copper is assigned too high a value, the gross temperature drop of the cell would be less than the calculated temperature drop. Because of this the cell conductance measurement for \(^\text{He II}\) just below the lambda point in the copper for that particular heat current places an upper bound on the thermal resistance of the copper, making the 2% correction to the gross cell conductance for gaseous \(^4\text{He}\) mentioned above about the maximum possible correction. Hence, the copper correction is not very important for measurements of the KBR in gaseous helium.

Referring to Figure 8 one can see that the values of cell conductance for \(^\text{He II}\) cover an order of magnitude. This means that a change in the thermal resistance of copper will affect the highest temperature conductance for \(^\text{He II}\) ten times more than the lowest temperature conductance. In fact, small changes in the copper thermal resistance will have very little effect on the
Figure 8

Corrected Cell Conductance
position of the lowest two points, or on the slope of a line drawn between them. This fact is the basis for a criterion for setting a specific value on the thermal resistance of the copper used in the cell for the purpose of making the copper correction: let all the cell conductance points for He II fall on a straight line in Figure 8. If the thermal resistance for the copper is increased slightly, that line will bend upwards to infinity. Similarly, if the copper resistance is lowered, that line will bend over and become flat at the high temperature end.

The details of how the copper correction was made involve the temperature dependance of the thermal conductivity of copper and its magnitude. The thermal resistivity ($\rho$) of copper is inversely proportional to temperature for pure copper in the range of temperatures of this experiment.

The relation between the resistivity of copper and the resistance of the copper between carbon resistance thermometers $T_1$ and $T_3$ (see Figure 2) is

$$\rho = \frac{A}{L} \times \frac{R}{T} \frac{\text{cm} \, \cdot \, ^\circ K}{\text{W}}$$

where $\rho$ is the resistivity of copper inversely proportional to temperature, $A$ is the cross sectional area, $1.268 \, \text{cm}^2$, of the active center at the gap, $L$ is the distance, $1.27 \, \text{cm}$, separating $T_1$ and $T_3$, $R$ is the resistance at $1^\circ K$ of the configuration of copper between $T_1$ and $T_3$, and $T$ is temperature. Notice that $A/L = 0.998$ so $\rho = R$ at $1^\circ K$.

The inferred value for the thermal resistance of the copper in the cell is $R = 0.326 \frac{\text{cm} \, \cdot \, ^\circ K^2}{\text{W}}$ so that $\rho = 0.325/T \frac{\text{cm} \, \cdot \, ^\circ K}{\text{W}}$ which is a typical value
for OFHC copper. This value of R made the points for He II in Figure 8 fall on a straight line. Above the lambda line at 2.18°K the cell conductance for the liquid drops sharply since the conductivity of He I is only four times larger than that of the gas.

Section 4.4: Contributions to Cell Resistance

When the copper correction has been made the corrected cell conductance is in its final form, shown in Figure 8. The general character of the differences between data for He II, He I and $^4$He gas is reminiscent of the behavior of the bulk fluids. One would expect a high cell conductance for He II, smaller for He I and smaller still for $^4$He gas, although the flattening of the lower curves near 4°K is hard to explain in terms of the conductivities of the bulk fluids.

The cell conductance for $^3$He gas is also shown in Figure 8 so it can be compared with $^4$He. It is larger than that for $^4$He since the bulk conductivity is larger by a factor of two. One important difference is that the $^3$He curve continues to increase at the high temperature end rather than becoming flat.

This fact has important implications which will be discussed in the next chapter.

The thermal resistance of the cell can be written as the sum of three terms, $R(\text{cell}) = R(\text{gas}) + 2R(\text{Knudsen}) + 2R(\text{Kapitza})$, if it is assumed that at
each cell face there is a gas-kinetic temperature jump introducing a resistance \( R(\text{Knudsen}) \) between the bulk gas and a layer of adsorbed helium. \( R(\text{Kapitza}) \) is then the boundary resistance between the adsorbed layer and the copper surface. In heat transfer at the interface between a gas and a solid, a surface resistance is expected from kinetic theory. This resistance is conveniently described in terms of the Knudsen (or Smoluchowski) temperature jump distance, \( g \), which is the thickness of a layer of gas of equivalent resistance. Kinetic theory gives, per unit area of the surface, \( R(\text{Knudsen}) = g / K \), where \( K \) is the conductivity of the bulk gas, and (15)

\[
g = \frac{2 - \alpha}{\alpha} \left( \frac{\gamma - 1}{\gamma + 1} \right) \frac{K}{P} \left( \frac{2 \pi T}{R} \right)^{1/2}
\]  

(4)

in which \( \alpha \) is the accommodation coefficient, \( R \) is the gas constant (per gram), \( \gamma \) is the ratio of gaseous specific heats, \( P \) is the pressure, and \( T \) is the temperature of the gas at the wall. Since \( g \) varies inversely as the pressure, \( R(\text{Knudsen}) \) vanishes at sufficiently high pressures. In Figure 8, the downward displacement of the cell conductance curve for the \(^4\)He gas pressure of 1.5 mm Hg. displays the Knudsen effect as the mean free path in the gas becomes comparable with cell width. To correct for the Knudsen effect in the low-pressure data, a value for \( \alpha \) in Equation (4) was chosen that removed the pressure dependence from the data. The value thus obtained for the
accommodation coefficient was $\alpha = 0.79$ for $^4\text{He}$ and $1.0$ for $^3\text{He}$. There was no detectable variation of $\alpha$ with temperature.

After correcting for the Knudsen effect, which in any case is negligible at higher pressures, it was found that the thermal resistance of the cell could not be accounted for in terms of the resistivity of the bulk gas. There was always a positive residue which has been referred to in Chapter I as the Kapitza Boundary Resistance (KBR).

Figure 9 shows the relative contributions of these resistances for a gas pressure of 1.5 mm. Hg. (at which the Knudsen effect is still appreciable). As is shown, the bulk gas resistance decreases as the temperature is raised, although the cell resistance flattens out. That is, the residue (KBR), appears to increase at the highest temperatures. As mentioned in Chapter II, the cell width of about 8 $\mu$m was chosen to make this residue an appreciable fraction of the total cell resistance. In Figure 9 the KBR constitutes about one half the total cell resistance at 1.5°K, and one third the total at 4.5°.

When the other contributions to cell resistance are subtracted away, the remaining term is the KBR,

$$R_{1,K} = 1/2 \left( \frac{A}{S_{\text{cell}}} - \frac{2g + Y_0}{K} \right)$$

The factor of $1/2$ appears in front of the brackets because two surfaces were involved in the measurements. The first term inside the brackets is the total
Figure 9

Relative Contributions to Cell Resistance as a Function of

Temperatures for a Pressure of 1.5 mm. Hg.
$\text{He}^4 \text{ GAS AT } 1.5 \text{MM. HG.}$

**Diagram:**

- **Cell Resistance (°K/Watt)**
- **Temperature (°K)**

- **Curves:**
  - Bulk Gas
  - Knudsen
  - Kapitza

The graph shows the relationship between cell resistance and temperature for different gas pressures and conditions.
resistivity of the cell, where \( A \) is the area of the active center. The middle term is calculated from Equation (4). In the last term, \( Y_0 \) is the gap width, 8.2 \( \mu \). Both \( g \) and \( Y_0 \) are distances, so dividing them by the conductivity of the gas of liquid \( K \) (16,17) results is a resistivity.

Figure 10 shows the measurements of the KBR for liquid and gaseous \(^3\)He and \(^4\)He at various temperatures. The points for \(^4\)He can be separated into three main curves. The highest KBR were measured for the gas. Notice here that for gas pressures ranging over 2 1/2 orders of magnitude, correction for the Knudsen effect places all the measurements on the same curve. This shows independence of the KBR from pressure for gaseous helium.

The KBR for the normal fluid behaves very much like that of the gas except that it is smaller by a factor of 1.5. A comment is in order here about the reproducibility of the measurements of the KBR. KBR measurements in general are notoriously non-reproducible (18). However, all comparisons in this research among the gas and liquids were made during the same run and are highly reproducible. (One run lasts as long as the cell remains below 90°K.) This kind of comparison shows that the KBR in He II is about an order of magnitude less than it is in He I near the \( \lambda \) point. And, in He II, its temperature dependence is much stronger.
Figure 10

The Kapitza Boundary Resistance
In Figure 10 there are two sets of points for normal and superfluid helium. For the superfluid the squares represent measurements using a 1/8" fill tube which constitutes so large a heat leak that even the guard ring could not completely remove it. Thus at the lowest temperatures where cell resistance gets large, the fill tube heat leak caused quite noticeable errors in the KBR while the data taken with the capillary does not show this, since these points continue in a straight line. Except for the heat leak problem, these two sets of measurements compare very well even though the cell was warmed up to room temperature to change the fill tube. Then for the measurements at lower temperatures, the KBR for $^4\text{He}$ gas goes approximately as $20T^{-2.2} \frac{\text{cm}^2 \text{e}^\circ \text{K}}{\text{W}}$ and for $^3\text{He}$ gas and the normal liquid, $13T^{-2.2} \frac{\text{cm}^2 \text{e}^\circ \text{K}}{\text{W}}$. For the superfluid a formula of $17T^{-5} \frac{\text{cm}^2 \text{e}^\circ \text{K}}{\text{W}}$ is suitable.

At the low temperature end the points for $^3\text{He}$, both liquid and gas, fall on the same curve. Beyond the critical temperature at $3.326^\circ\text{K}$ the fluid was treated as a gas, and at the highest temperatures its KBR returns to the curve for the gas at other pressures. Since the thermal conductivity of $^3\text{He}$ is not known in the critical region, values for the thermal conductivity far away from this region had to be used. This deficiency is responsible for the jump in the liquid curve for the KBR in the critical region, and this jump should not be construed as real discontinuity. In comparing the curve for $^3\text{He}$ with those for $^4\text{He}$, the curve for $^3\text{He}$ would fall on top of that for the normal liquid $^4\text{He}$ in the region of 2.2 to 3°K. The plots for the two isotopes were separated to avoid confusion in the figure.
Figure 11 shows the KBR for the lowest gas pressures measured, and includes the lowest pressure $^4$He results from Figure 10. The departure of the KBR, at low pressures, from the general pattern established by the high pressure data, will be discussed in the next chapter.

Section 4.5: Sources and Magnitude of Experimental Error

The description and estimate of various types of errors occurring in these measurements have already been done for some cases, such as the uncertainty of the copper corrections (Section 4.3). An important error, the uncertainty from all causes in the gap width, is described in Appendix A. The sensitivity of the measurements to surface conditions arising from different methods of preparation of the surface will be discussed in Section 5.2. The irreproducibility of surfaces in different cells makes it difficult to compare the absolute magnitude of the measurements of different experimenters (Figure 14).

It is the purpose of this section to discuss the effect of error in each item entering into the calculation of the KBR, where it has not been discussed elsewhere in the context of a special topic. The first item of consideration is the cell conductance, $S = W / \delta T$. The voltage on the active center heater could be read to an accuracy of 0.1% so the error in the power, $W$, was 0.2%. The temperature changes, $\delta T$, are proportional to $\delta R_H$, the resistance changes of $R$, which could be measured (Section 3.3) to 0.2%.
Figure 11

The Kapitza Boundary Resistance for Low Pressures
The major source of error which caused the observable scatter in the measurements was the uncertainty in the temperature derived from the temperature regulator and recorded on channel #1. The value of $\delta T$ calculated from $\delta R_H$ (Section 2.3) depends strongly on the temperature at which $\delta R_H$ was measured. From points taken only a few hundredths of a degree apart for test purposes, it could be calculated that $\partial (\delta T) / \partial T$ was about 4 for the five different temperatures where double measurements were made. $T$ could be measured to an accuracy of 0.2% which contributed an error of 0.8% to the determination of $\delta T$. Adding the percent error attributable to $W$, $\delta R_H$, and $T$, one must expect a total error contributing to the scatter of the cell conductance of 1.2%.

The maximum error in the various primary calibrations for the different runs was about 0.3% (Appendix G). This could cause a systematic error in $\delta T$ of as much as 1.2% but would not contribute to scatter in the data. Total maximum error of all sorts in the cell conductance is 2.4% but the actual error is probably less.

In making the measurements, it was observed that occasionally strong radio frequency interference would cause the chart recorder channel #2 to deviate several percent. When this was observed, the point was taken again. It is probably that some cases of this interference were not caught, and would be responsible for a few points (less than 1% of the total number of points) having larger than normal scatter.
Finally, the temperature regulator was not effective at the lowest temperature for a particular pressure, probably because the cell temperature was too close to the bath temperature and the temperature regulator could not completely decouple the cell from the bath. Also very small power inputs had to be used to both the top and bottom heaters, further restricting full operation of the system and reducing accuracy.

On the average about 2/3 or 3/4 of the cell conductance is subtracted away to account for the conductivity of the bulk gas in calculating the KBR. This would increase the error in the KBR by a factor of 3 or 4 which amounts to scatter and deviation between pressures of 7 to 10%. This is sufficient to account for the scatter actually observed in the KBR data of Figure 10.

In Appendix A all sources of error in the measurement of the cell spacing were discussed and the error in the gap width was estimated at 10%. This would cause a systematic error in the KBR of about 6%. This was verified by comparing calculation of the KBR for $Y_0 = 8.2 \mu$ and $7.1 \mu$. Error bars are inserted in several places in Figures 9 and 10 to show the effect of this systematic error in gap width for different pressures. For fluids with higher bulk conductivity, the effect was proportionally less. For example in the measurements for $^3$He the scatter is visibly less than for $^4$He since the thermal conductivity of $^3$He gas is 2 to 3 times greater than that of $^4$He.
Another error not yet discussed is the magnitude of possible heat leaks along the electrical leads or the fill tube. The electrical leads from the top of the cell consisted of 6 #40 copper wires with a total cross sectional area of about $10^{-5}$ in.$^2$. The effective length in copper of the sample gap with $^4$He gas in it is about 15 in. and about the same as the length of the electrical leads, but the cross sectional area is about 1 in. Thus the ratios of the thermal resistances of electrical leads and the sample is $10^5$, so a negligible amount of heat would flow through the leads to the main helium bath.

The pressure for each sample of helium had to be read on the manometers. For high pressures (greater than 1 Torr.) this could be read to 0.5% or less. For $^3$He a CVC gage was used and calibrated against the manometers. Hysteresis limited the accuracy of these readings to about 1%. Finally low pressures were read on a MacLeod gage with an accuracy of about 5% and where necessary corrected for the thermomolecular effect (24).

The pressure is of little importance in cell conductance until reduced to 1 Torr. or less where the Knudsen effect becomes comparable to the KBR. In the low pressure region of 100 μ and less where pressure was least accurately measured, the KBR loses identity to the accommodation coefficient $\alpha$ which is poorly understood. Only the variation of the measurements with temperature will be of interest in the lowest pressure region.
At the time of this writing, many experiments have been performed on different materials to measure the KBR. In several instances an investigator would emphasize a particular aspect of the measurement which resulted in an advancement in the understanding of the mechanisms involved. However, no theoretical treatment gives satisfactory agreement with the measurements. In this chapter important work by other investigators will be discussed to the extent it is relevant to the measurements presented in this dissertation. These measurements, of course, will be discussed in detail, and speculation as to the direction future research might take will be presented.

Section 5.1: Different Approaches to Understanding the KBR

The various contributions of different investigators are all founded on Khalatnikov's basic mechanism (5) of acoustic mismatch across the interface between the solid and helium. The most significant improvement of this basic theory was that of Challis, Dransfeld, and Wilks (6), who investigated the improved matching associated with the adsorbed layer of helium. Another
interesting but relatively unimportant mechanism in the transmission of heat across the interface, is the role of the interaction of conduction electrons with helium atoms (7). One possible mechanism suggested for the transfer of energy across the interface is adsorption and desorption of atoms from the copper surface. This idea remains undeveloped.

Khalatnikov in his basic theory examines the various acoustic waves present in a solid and their coupling to the superfluid helium. Of considerable importance is the behavior of the phonons at the interface, and the approximation is made that the surface of the solid may be treated as if it were in a vacuum because of the very low density of helium. An exception to the vacuum approximation is the extension by Little (19) concerned with the effects of quantized surface waves (called epiphonons). Such waves would arise when a phonon in the helium approached the surface of the solid at such an angle that it would be refracted to propagate parallel to the surface. Such a wave would have an unusually large amplitude and resultant larger probability of coupling to the helium. However, the total solid angle containing such waves approaching the interface in the helium is very small, so the effect is not important since the directions of propagation of phonons in the copper are nearly uniformly distributed.
Khalatnikov calculates that the heat flow $\dot{Q}$ between a solid at temperature $T$ and liquid helium at temperature $T - dT$ is given by

$$\frac{\dot{Q}}{A} = \frac{16\pi^5 k^4}{15 h^3} \frac{F}{\rho_s c_t^3} \rho c T^3 dT$$

where $A$ is the surface area, $k$ is Boltzmann's constant, $h$ is Planck's constant, $\rho$ and $\rho_s$ are the densities of the helium and the solid, $c$ is the velocity of sound in the helium, and $c_t$ the velocity of transverse waves in the solid. $F$ is a function of the ratio of the velocities of longitudinal and transverse waves in the solid, and for most materials has a value of about 1.5. Although this equation yields values of the KBR two orders of magnitude less than experimental values it did succeed in giving the right temperature dependence, which agreed with Kapitza's results. The reason for the $T^3$ temperature dependence is that the energy density of phonons, discussed in Chapter I, varies as $T^4$ for a normal solid at low temperatures.

The most important modification of the Khalatnikov theory was by Challis, Dransfeld, and Wilks, (CDW) (6), and their results go far in bringing theory closer to experimental results. Their modification also explains very well the insensitivity of the KBR to density changes in the helium, which is very important with respect to the measurements of this dissertation.
To calculate the input acoustic impedance at the copper surface to the matching layer of adsorbed helium, CDW used the usual expression from electromagnetic transmission line theory, \( Z_i = X_i + j Y_i = \)

\[
\frac{Z_0}{Z_0 + j(X + jY) \tan (2 \pi \nu x/C)}
\]

Here the input impedance \( Z_i \) to a lossless line of length \( x \) and characteristic impedance \( Z_0 \) is terminated by an impedance \( X - j Y \); \( \nu \) is the frequency of the sound waves and \( C \) the velocity in the line. Starting with the impedance of the bulk liquid (\( X = \rho \sigma, Y = 0 \)), CDW performed the calculation in twenty steps by computer over the variation of the density profile shown in Figure 12. The profile becomes flat at 4 Å because under the influence of the van der Waals forces the helium density will attain a value limited by the size of the atoms. Also the step occurring at about 10 Å is smoothed out because zero point motion of the helium atoms over this short range would tend to make the phase boundary between the liquid and solid indistinct. In this figure the interesting assumption is that the density at the copper helium interface is the same for two quite different densities of the bulk liquid corresponding to 0 and 20 atmospheres pressure. The result of this assumption is that the difference in \( X_i(T) \) over the range of 0 to 20 atmospheres is only 50% at .5°K and only 15% at 2°K.
Figure 12

The density of liquid helium at 0°K under the saturated vapour pressure and under 20 atm pressure as a function of the distance, x, from a copper wall. The calculated values are given by the dashed lines, and smoother values by the full lines (6).
Specifically CDW's modification was to replace $\rho$ in Equation (5) with $\frac{d \ln X_1(T)}{d \ln T}$. According to this modification one would expect a small, but measurable change in the KBR with pressure. CDW made measurements at the same temperature but different pressures to search specifically for this 15% to 50% change in the KBR with the density of the helium. Their results as shown in Figure 13 fail to show more than 1 or 2% change in the KBR. Therefore, CDW did not go far enough; a theoretical method is needed for removing all of the pressure dependence of the KBR.

Another prediction of this modification is that the KBR would vary more rapidly with temperature. This is because the frequency at which the maximum energy is emitted gets higher at higher temperatures, or the dominant phonon wavelength becomes shorter. Hence for shorter wavelength the adsorbed layer matching unit is effectively longer and therefore more efficient. Figure 14 shows a comparison of the results of Equation (5), the CDW modification, and most of the measurements on copper for superfluid helium, (the measurements of this dissertation have been added to the figure taken from a review article by Frederking (13)). From Figure 14 it can be seen that the experimental values of the KBR are one to two orders of magnitude less than the prediction of Khalalnikov's theory, but CDW's modification is an improvement of one order of magnitude.
Figure 13

The variation of the thermal boundary resistance between liquid helium II and copper at four spot temperatures as a function of the pressure over the helium (6).
Figure 14

Various Measurements of the KER for He II on Copper (18)

Large Crosses: Current Measurements with 1/8" Fill Line

Large Circles: Current Measurements with Capillary Fill Line
A third mechanism for transmission of energy across the copper helium interface has not been discussed yet. This is the contribution to the Kapitza conductance ($1/KBR$) between a metal and liquid helium II which arises through coupling between the surface modes and the conduction electrons. Challis and Cheeke (7) have written a very nice article comparing the various cases for this coupling undertaken by other authors and showing under what conditions they are equivalent. The importance of this contribution to the KBR may be measured on a superconducting metal by comparing it with the normal state when the metal is under a magnetic field. The largest ratio observed by Challis and Cheeke was 2.0 although ratios of 1.3 or less are much more common. Thus this contribution to the KBR is relatively unimportant to the current measurements in this dissertation.

Section 5.2: The Adsorbed Layer

Returning to the discussion of the adsorbed layer, various authors have examined different aspects of it and made measurements to find out more about it. The main theoretical work on this problem by CDW has been discussed above. They also made measurements designed to test their modification as opposed to the predictions of Equation (5). Specifically they used different solids so as to change the $\rho_f c_i^3$ term of Equation (5), and also the $\rho c$ term by changing the density of the liquid helium as mentioned above. Little variation
was found by changing the density of the liquid helium. A definite variation was found when measurements on copper, quartz and lead were compared, but even greater variations resulting from different surface conditions of the same material (see Figure 14) obscured the results and prevented any conclusions from being drawn.

From these and other measurements it was clear that the KBR depended strongly on surface conditions and that measurements were notoriously unrepeatable in this respect. A dramatic demonstration of this fact occurred in measurements by Johnson and Little (4) where they measured the KBR on one specimen of copper machined under liquid helium to prevent contamination and then after being oxidized in air. The change in the KBR was 75%. Figure 14 shows that surface condition of copper can cause a variation in the KBR of copper of about an order of magnitude.

CDW and others have investigated the possible effects of amorphous layers or Deilby layers (produced, for instance, by polishing the surface) by comparing measurements of etched and unetched materials. For one specimen of copper CDW found a difference of greater than 50%.

An important paper by McCormick, Goodstein, and Dash (20) recently published considers the effects of depositing layers of volatile substances on the metal surface and the resulting change in the adsorbed layer of helium.
One particular result was that by plating the copper surface with argon atoms, much more reproducible results were achieved with respect to the adsorbed layer of helium. This was attributed to a "smoothing" action the argon atoms might have since they would tend to condense preferentially in depressions and cracks. The measurements in this paper were of helium adsorption isotherms and the heat capacity of thin helium films. Some of the results of these measurements tend to confirm a new effect discovered in the current measurements (see Section 5.5).

**Section 5.3: Previous Indications of a KBR in Gaseous Helium**

The first indication of a KBR in gaseous helium was in measurements of its heat conductivity by Fokkens, Taconis and de Bruyn Ouboter (21). Their conductivity cell included a guard ring and a mechanism for changing the spacing of the cell to a width as small as 300 μ. By taking measurements over a range of 800 μ to 300 μ and extrapolating to 0 spacing, they were able to detect a residue which they attributed to a gaseous KBR.

Another conductivity experiment by Challis and Wilks (8) was designed to measure the conductivity of ³He liquid using a very small amount of it. To test their cell, they made measurements on ⁴He I and compared it with other measurements in much larger cells where any KBR could be ignored. They found the measurements to be 15% too small. From this and the geometry of
their cell they deduced that, "Although the scatter on the points is such that a
detailed estimate of the boundary resistance is hardly possible, the magnitude
of the resistance just above the lambda point seems to be three to six times as
great as that just below it."

An interesting result of attempting a theoretical description of the
process of heat transfer in gas-filled powders (10) was the necessity of
including a gaseous boundary resistance. This changed the theory for higher
gas pressures and smaller powders by as much as an order of magnitude and
brought the theory to within the limit of error of the measurements. The
magnitude of the boundary resistance at 4°K was comparable with other
measurements just below the lambda point, but the temperature dependence
was too small, being between $T^{-1}$ and $T^{-2}$.

The first actual measurements of the KBR of gaseous helium (9) were
made with a simplified version of the cell used for the current measurements.
This cell contained all the drawbacks that the current cell has avoided as
described in the introduction to Chapter II. Because of the absence of a guard
ring the high temperature results tended to be obscured by heat leaks when the
KBR became sufficiently small. However, because of its simplicity, this cell
had the advantage that it could be cleaned in an ultrasonic cleaner with
appropriate solvents without the danger of removing spacers or damaging other
parts. The fact that the measurements on this first cell were twice as large
as the current KBR measurements can probably be explained by the cleaner
copper surface.
Section 5.4: Discussion of Results

It is most likely that the presence of organic materials in the cell would cause a thin layer of these materials to be plated onto the surfaces of the gap when the cell was cooled down. Such condensed organic material would act as an additional matching layer because its acoustic impedance would be considerably less than that of copper but greater than solid helium. This confirms, as has been noticed many times previously, the extreme sensitivity of the KBR to surface preparation. However, if the copper surface is kept cold no oxidation can take place nor can any other subtle ageing of the surface occur. Thus it is very important to note that all the comparisons of work in this dissertation among the gas and liquids were made during the same run and are highly reproducible.

If the KBR of the current measurements for He II, shown in Figure 14 as the large circles and crosses, were increased by a factor of two as suggested in the previous section, they would fall right in the middle of other measurements on copper, at least at the low temperature end. (The crosses contain an error caused by superfluid heat leak along the 1/8" fill tube.) Notice that the parameter plotted in Figure 14 is \(1 / (\text{KBR} \times T^3)\).

The measurements in this dissertation are the first to make a quantitative comparison between the KBR for He I and He II, and note that the KBR jumps by a factor of 10 upon crossing the lambda point into the He I region. This
factor of 10 multiplied by the factor of two arising from the organic layer on
the surface of the copper would put the measurements for He I almost on top
of the extrapolation of the CDW modification of the Khalatnikov model. For
this reason the CDW modification can be said to agree fairly well with the
measurements for He I. Unfortunately the irreproducibility of copper
surfaces prevents any more detailed comparison from being made. The
relative success for the CDW modification in the He I region cannot be taken
to imply that all is well with the theory. Aside from the complete inability of
the theory to account for the discontinuous change in the KBR at the lambda
point by a factor of ten, the theory was designed for and takes its
assumptions from the superfluid state. It is sufficient to quote Khalatnikov
at the end of his development where he says:

It is opportune to indicate also that the entire analysis in the
present paper is valid only for the case of the boundary between
a solid body and a quantum liquid. In ordinary liquids it is not
possible to speak of separate excitations. In the case of heat
exchange between a solid body and an ordinary liquid there are
no causes which could restrict the exchange of energy.
Consequently, at the said boundary a temperature jump is
absent.

Returning again to Figure 14, one interesting aspect of the current
values measured for the KBR is the greater temperature dependence which
does not agree with any of the other data. (The CDW modification comes
closer to agreement with this increased temperature dependence.) The
explanation probably lies in a combination of the following three considerations.
Already discussed is an uncertainty in the conductivity of the copper and the sensitivity of the highest temperature points to this factor. This would not change the slope of the low temperature section very much. Another effect influencing the slope is the presence of the organic film whose matching properties, like that of the adsorbed helium film, would be better at higher temperatures, thus tending to increase the slope of the line. Finally the cell used for the current measurements has a gap narrower by one or more orders of magnitude than the cell used for the other measurements in Figure 14. Perhaps the narrowness of the gap could begin to influence the values of the KBR observed, especially when one observed that within the temperature range of the current measurements, the mean free path length of the phonons becomes comparable to the width of the cell (22).

One of the most positive contributions of the current measurements is to give even stronger support to CDW's prediction that the KBR should be relatively independent of density. In fact this prediction can now be extended to include relative independence of KBR to phase or isotope, with the exception of the transition of He I to He II. As pointed out in Section 4.4, the gaseous KBR is completely independent of pressure for $^4\text{He}$ and almost completely so for $^3\text{He}$ as one can see from Figure 10. An exception to this which will be discussed later is the KBR for pressures less than 1 mm. Hg.
The liquid $^3$He data in Figure 10 falls directly on top of that for the $^3$He gas. The only deviation from complete independence of pressure is the He I result which is a factor of 1.5 less than that of the $^4$He gas. Again, the validity of these comparisons from the measurements can be made because as appropriate both $^3$He and $^4$He or the liquid and the gas were measured in the same run, thus insuring that the surface remained unchanged.

Section 5.5: Evidence for a Possible Phase Change in the Adsorbed Layer

A remarkable and initially perplexing feature of the KBR measurements for high temperature $^4$He is the existence of a broad minimum between 3°K and 3.5°K for both the liquid and the gas. This minimum was viewed with great suspicion. The most obvious question was whether this minimum was instrumental. As was previously pointed out, the measurements within the same run were highly reproducible, and considerably so even between runs on the same surface which was carefully protected from contact with the atmosphere.

The minimum cannot be attributed to an error in the values of the bulk conductivity of the gas because the normal liquid shows the very same behavior, even though the correction for the bulk conductivity of the normal liquid was based on an entirely different set of data. The most compelling argument against instrumental error as a source of this minimum is the KBR measurements taken for $^3$He during the same run. These gave comparable values of the KBR but without any sign of a minimum as shown in Figure 10.
One indirect indication that this flattening of the KBR temperature
dependence for $^4$He had been observed before was given by Brodie and Mate (10).
They found the temperature dependence of an apparent gaseous boundary
resistance to be too small, and as small as $T^{-1}$ as mentioned in Section 5.3.

Recent studies of the specific heat of monolayer and submonolayer films
of $^3$He and $^4$He by McCormick, Goodstein, and Dash (20) has shed much light
on the minimum in the KBR temperature dependence. Their results, shown
in Figure 15, give the specific heat for intermediate coverage of layers of
$^3$He and $^4$He. A very obvious broad maximum to the specific heat of a .62
layer coverage of $^4$He occurs between 3°K and 3.5°K, exactly where the
minimum in the current measurements is. They suggest, "that this is due to
a diffuse melting transition between a disordered solidlike and a liquidlike
surface phase." They furthermore detect a linear term in the heat capacity
of both $^3$He and $^4$He (Figure 15) suggestive of the heat capacity of two-
dimensional Bose and Fermi gases at low temperatures.

Why would such a partial monolayer effect be observed in the current
measurements at relatively high pressures and even in the liquid? This is
very good independent evidence that the KBR resides mostly in the mismatch
between the first adsorbed layer and the copper surface. Even the change
from a gas to a liquid makes very little difference in the shape of the
minimum, although the magnitude of the KBR changes, showing that some
additional mismatch occurs in going from the liquid to the gas. This is not
Figure 15

Specific Heat for Intermediate Coverage (< 1 layer) of $^3$He and $^4$He
unexpected, since the density profile shown in Figure 12 changes gradually and asymptotically to the bulk density. This is probably a fairly accurate description of what happens in the gas as well.

If one reasons in the opposite direction about the minimum, one could conclude that the transition from a gas to a liquid would change all parts of the adsorbed layer except that part right next to the copper. Since the shape of the minimum is hardly changed in this transition, the first atomic layer of the adsorbed helium is probably responsible for the minimum. This piece of deductive evidence gives considerable strength to the conclusion that the minimum is caused by the same phenomena responsible for the maximum in the intermediate-coverage specific heat of Figure 15, which is known to be caused by the first monolayer.

If one accepts the suggestion of McCormick, Goodstein and Dash that some kind of melting is occurring between 3°K and 3.5°K, then the fact that the KBR increases beyond this point supports this suggestion. The KBR would increase upon melting of part of the adsorbed layer because a liquid has a lower acoustic impedance than the more rigid solid. In addition the liquid cannot support shear waves.

Section 5.6: Low Pressure Measurements of the KBR

It was shown in Section 4.4 that the effects of pressure on the cell conductance could be attributed to the Knudsen gas-kinetic temperature jump,
and that a single choice of the accommodation coefficient would remove all pressure dependence from the KBR. As Figure 11 shows, this no longer works for pressures less than about 1mm. Hg. Here it appears that the KBR increases rapidly with decreasing pressure, although it retains its temperature dependence, which will be discussed presently.

One interpretation of the low pressure measurements is that the matching layer gradually gets thinner and thinner until its thickness becomes comparable with the wavelength of the dominant phonon frequency at which stage the matching layer quickly becomes much less effective. Another description of the same measurements would imply that as most of the adsorbed layer is removed, more and more of the impinging gas atoms see the bare copper and bounce off without coming to equilibrium, which is another way of saying the accommodation coefficient begins rapidly changing with pressure. Since it no longer makes sense to talk about phonons in sufficiently rarefied helium, the gas-kinetic description of the low temperature measurements is the more appropriate. Unfortunately, no theory exists for the calculation of the accommodation coefficient.

Even though the domain of the gas-kinetic description is entered for low pressure measurements, the minimum remains that was discussed in the previous section. An explanation immediately suggests itself which tends to support the idea that the first monolayer undergoes a phase change in $^4$He
at about 3.2°K. If the monolayer melts in some manner, it presumably would have a higher vapor pressure for a given fraction of coverage. For an increase in temperature at constant pressure the fraction of coverage would rapidly grow smaller above the melting point causing the accommodation coefficient to decrease at the same rate. Thus, the low pressure measurements might still be considered a valid indicator of any phase change.

Section 5.7: Comparison Between $^3$He and $^4$He

Bekarevich and Khalatnikov (23) have developed an expression for the KBR of liquid $^3$He analogous to the expression for He II, but which unfortunately has no better agreement with experiment than the latter. In Figure 10, comparison of the measurements for the gases of the two isotopes show that they differ by a fraction of 1.5, and have the same temperature dependence at lower temperatures. The factor of 1.5 presumably has something to do with the fact that the liquids in the adsorbed layer obey different statistics. Further evidence along this line may be the fact that for $^3$He the KBR for the gas and liquid are not different (except near the critical temperature).

The striking difference between the two isotopes comes at higher temperatures: $^3$He has no minimum. An examination of the low pressure data for the two isotopes in Figure 11 shows again for .1 mm. Hg. they are about the same in temperature dependence at lower temperatures and in this case
even have about the same values. But as the temperature increases the values for \(^3\text{He}\) turn upward even sooner than for \(^4\text{He}\) at about 2.2° as opposed to 3.2°K for the latter. If the assumption is made that the \(^3\text{He}\) adsorbed layer shares some similarities with \(^4\text{He}\), one might suspect that this minimum for \(^3\text{He}\) could be indicative of a possible change of phase in the adsorbed layer similar to that of \(^4\text{He}\) at 3.2°K. With a bit of imagination one could perhaps see a slight bulge in the curve for \(^3\text{He}\) in Figure 15, or even in Figure 10. However, the best that can really be said for the minimum for \(^3\text{He}\) in Figure 11 is that it would be a hopeful area of investigation in the future.

**Section 5.8: Future Directions for Research**

The resolution of the data presented in this dissertation would have benefited by increased accuracy and better resolution. This could be accomplished in the future by two means: first, decrease the cell spacing to less than one micron, (the polished surfaces are sufficiently flat to do this without contact, but the geometry would be less certain). This would reduce the correction for the bulk gas to a minor item. Second, the surfaces might be made more reproducible by preadsorption of argon (20) or by better cleaning techniques. Perhaps gold or some other material like sapphire would be an improvement.
A change or greater range of variables could yield more information. Perhaps decreasing the cell spacing as described above would show there was a dependence of the KBR on the gap width for sufficiently small distances.

Another interesting extension would be to go to higher temperatures and see if the KBR for $^4$He reached a maximum and then decreased again. It ought to do this because of its strong basic dependence on a negative power of $T$. The observed increase in the KBR for $^4$He would allow it to be observed to a much higher temperature than previously thought possible. Finally the whole field of mixtures lies waiting. With increased resolution many new structural details might be seen in the measurements.
The three spacers were placed on the guard ring after polishing was complete. The spacers were deposited using a micro-syringe. Each spacer was made by depositing about two micro-liters of GE varnish solution diluted about 50:1 with GE varnish solvent over an area 5 mm. in diameter. The solvent evaporated almost immediately but the varnish itself took about half an hour to dry. While the seven micron spacers were still soft, an optical flat was placed on them. An interference pattern was caused by light being reflected back and forth between the surface of the optical flat and the copper surface. The appearance of the fringes indicated when all three spacers were at the same height. If one spacer appeared too high it was squeezed down to the proper height by pressing down on that part of the optical flat above it. After half an hour all three spacers had dried and were then permanently all the same height.

Interferometry was used to measure the thickness of the spacers. Figure 16a shows the surface of the copper, the spacers on it, and the surface of the optical flat. Light incident perpendicular to the surface will be reflected
Figure 16

Optic Paths and Geometry in the Interferometric Measurement of Gap Thickness
from both the copper and the surface of the optical flat 8.2 \( \mu \) above the copper.

The relative phase of the two reflected beams will remain unchanged if \( D \), the thickness of the spacers, is changed by one half of a wavelength. The path length difference between the two rays is then changed by one wave length or by one interference fringe.

If an observer is looking at the surface reflection with sodium light reflected normally, and then moves to observe the reflected light at a greater angle of incidence, he will observe the surface growing lighter and darker as interference fringes pass by. This is because an increased angle of incidence will increase the path difference between the two reflected rays as shown in Figure 16b. The beam splits at point \( I_1 \) and the two beams, \#1 and \#2, are compared at \( P \) and \( I_3 \) for the path length difference which is \( \Delta L = 2\Pi - \Lambda \).

From the geometric constructions in Figure 16b one can see that \( \Delta L \) forms one side of the right triangle \( I_3 \ P_2 \ P_3 \). Hence for two different thetas the two equations for \( \Delta L \) are:

\[
\Delta L_0 = 2D \cos \Theta_0 = n_0 \lambda
\]
and
\[
\Delta L_1 = 2D \cos \Theta_1 - n_1 \lambda
\]
or
\[
2D (\cos \Theta_0 - \cos \Theta_1) = (n_0 - n_1) \lambda
\]
and
\[
D = \left( \frac{n_0 - n_1}{\cos \Theta_0 - \cos \Theta_1} \right) \frac{\lambda}{2}
\]
where $\lambda$ is the wavelength of sodium light and $n$ the number of wavelengths in $\Lambda L$. With $n_0 - n_1 = 6$, $\Theta_0 = 0$, $\Theta_1 = 37^\circ$ and $\lambda = 5900 \text{Å}$; $D = 8.8 \mu$. In four tries, $\Theta_1$ was measured with a maximum difference between measurements of $1^\circ$.

The interference pattern actually observed was a mosaic of light and dark areas, since the surface of the copper was only flat to within one wavelength of light. It was found experimentally that sufficiently noticeable changes in the mosaic interference pattern could be observed to determine to within one degree when exactly six fringes had passed in going from $0$ to $37^\circ$, even though in going from $36^\circ$ to $37^\circ$ $\Lambda L$ changed by considerably less than one wavelength.

$\pm 1^\circ$ accuracy is equivalent to 5% accuracy in determination of the gap width or $\pm 0.4 \mu$. Most plastics contract between 1 and 2% in going from room temperature to helium temperatures, so the spacers would be 0.1 $\mu$ less when cold. It was observed that by pressing down on the optical flat on top of the spacers with a pressure equivalent to the weight of the top half of the cell, two fringes passed by. This means that the weight of the top half of the cell probably compressed the spacers by 0.5 $\mu$. With all the above considerations and their uncertainties, the gap width is $8.2 \pm 0.8 \mu$ or to an accuracy of 10%.
APPENDIX B
THE TEMPERATURE REGULATOR

Figure 17 shows the schematic diagram for the bridge used in the temperature regulator. The carbon resistor used as thermometer $T_4$ forms the lower right hand arm of the bridge and points A and B are the output terminals of the bridge. The lower left arm of the bridge is the field effect transistor TR1 whose resistance may be varied to the desired value by adjusting the voltage on its gate. The distinguishing characteristic of the field effect transistor as used in this application is that the source-to-drain resistance of the field effect transistor varies as the exponential of the gate voltage. This means that a simple linear potentiometer can vary the output resistance of the field effect transistor evenly over several orders of magnitude.

It is convenient to make the voltage output signal from the bridge to the chart recorder, points C and D in Figure 17, proportional to the temperature. This can be achieved by taking the logarithm of the voltage on the gate of the field effect transistor. This may be done electrically by placing the voltage on the gate of the transistor across the elements $D_2$ and $R_2$. The voltage across $D_2$ is then the logarithm of the voltage on the gate of the field effect
Figure 17

Bridge Circuit for Temperature Regulator
5 KC SIGNAL IN, FROM LOCK-IN

BURGESS 24

6V

(USED AT 4.5 VOLTS)

100,000Ω 100Ω 33Ω 10Ω

2N3277 (FAIRCHILD)

R(T) IS 3K TO 100K

TO POINTS B, A OF BRIDGE

140 pfd

390 pfd

120 pfd

1000 pfd

TO CHART RECORDER

QUADRATURE ADJUSTMENT
transistor, TR2. A plot of T versus the voltage appearing between points C and D (output to chart recorder) is given in Figure 18. It can be seen that this plot is remarkably close to a straight line, which made it very easy during the experiment to note the temperature of the cell. The linearity of the plot also made it very convenient to space data points evenly with respect to temperature.

Since the voltage across D2 also depends on ambient room temperature, D1 and R3 are included as a temperature compensation network. Thus the voltage appearing between points C and D will be, to the first order, independent of ambient room temperature; and a change in this voltage is proportional to the change in the logarithm of the voltage on the gate of the field effect transistor. D3 is a zener diode which, in conjunction with R4, regulates the voltage from the six volt battery. R5 and C1 serve to filter out any noise generated by changing potentiometer R1.

Also included in the lower left hand side of the bridge of Figure 17, is a series of carbon resistors whose values vary by factors of three from 10 to 100,000 ohms. Using S2, resistance values of 10, 43, 143, 473, . . . . 147773 Ω may be inserted in this arm of the bridge. S1 may be used to short out this extra resistance. If with the bridge in balance, S1 is opened, increasing the resistance of the lower left hand arm of the bridge, then the feedback network will adjust the temperature of the cell until the resistance of
Figure 18

T vs. Output Voltage of Temperature Regulator Bridge
PEN POSITION ON CHART RECORDER (CHANNEL #1)
T₄ has changed enough to rebalance the bridge. Thus, opening $S_1$ causes the temperature regulator to decrease the temperature of the cell by an amount $\Delta T$ whose value has been preset at $S_2$. If $S_1$ is then closed the temperature of the cell will return exactly to its original value which is, of course, determined by the setting of the potentiometer, $R_1$.

In series with the number 2 lead from carbon resistor $T_4$ to the bridge is a five millihenry choke which has been included to filter out radio frequency interference from transmitters operating at about one megacycle. The capacitance network connected between points A and B (see insert, Figure 17) serves to balance the quadrature caused by the reactive components of the bridge, namely the five millihenry choke and the distributed capacitance of the lines going to the cryostat.

Referring again to the temperature regulator, in Figure 17, the output of the bridge just described goes to the preamplifier which is a Princeton Applied Research, low-noise, differential amplifier Model CR4. The output of the preamplifier goes to the Model 120 lock-in detector, also made by Princeton Applied Research. The lock-in detector operates in the following manner: an audio oscillator inside the lock-in detector generates a signal of 5 kHz. Part of the signal is used to drive the bridge. The amplified off-balance signal from the bridge is fed into the input of the lock-in detector, a phase detector which compares the returned signal and the signal generated
by the local oscillator, both with respect to phase and amplitude. The dc output of the phase detector is then passed through a filter with the desired time constant. The result is a dc signal whose polarity and amplitude depend respectively upon the direction and amount of bridge imbalance. This dc error signal is then amplified and transmitted to the heater at the base of the cell. It is this heater that maintains the cell at the required temperature above that of the main helium bath temperature.
APPENDIX C

THE POWER AMPLIFIER

Figure 19 shows a schematic diagram of the power amplifier. The input at the left goes through a choice of two resistors, which vary the sensitivity of the power amplifier, to the first transistor $T_1$ which amplifies the signal by a factor of several hundred. The output is connected directly into the base of the transistor $T_2$ where the signal is again amplified by a factor of about a hundred. The output of transistor $T_2$, the collector, then goes to the load, the other end of which is grounded. The output may be switched ($S_2$) from the load to a 150 ohm dummy load for testing purposes. The power supply for the power amplifier is a standard fullwave rectifier circuit supplying $\pm 20$ volts at about 1.5 amperes. The current used by transistors $T_1$ and $T_2$ is regulated by zener diode $D_1$. Additional regulation for the power supply is provided by zener diodes $D_2$ and $D_3$. A bias current control $R_1$ provides a fixed current which passes through $R_2$ and is added to the signal at the base of transistor $T_1$. Thus the current to the heater may be set at any desired value by $R_1$. The input signal will then increase or decrease this current as the negative feedback requires. $D_4$ and $D_5$ are protection diodes. $D_4$ prevents a
Figure 19

Circuit for the Power Amplifier
signal of inverse polarity from putting too much reversed bias voltage on transistor $T_1$. Diode $D_5$ prevents too much inverse voltage from being applied across the electrolytic capacitor $C_1$. 
APPENDIX D

PRELIMINARY STEPS IN MAKING A RUN

Preparations for making a run were made several days in advance. These consisted mainly of pumping the various vacuum and gas spaces to remove low vapor pressure materials and to clean up the system. (Whenever the conductance cell itself was pumped, the liquid nitrogen trap was used to prevent back streaming of oil vapor from the oil vapor diffusion pump.) Another desirable procedure preparatory to making a run was a complete test for leaks in various parts of the system. Finally the space between the double walls of the helium Dewar was evacuated to remove any helium gas that might have diffused through the glass during the previous run. This space was then filled with air at a pressure of about 1 Torr.

A run was actually begun the night before measurements were to be taken. At this time liquid nitrogen was put in the liquid nitrogen Dewar and left over night in order to cool down the helium Dewar. Before filling the nitrogen Dewar with liquid nitrogen, one atmosphere of helium gas was put in the cell. Pure dry nitrogen gas was put in the helium Dewar and in the vacuum space around the cell. These various gasses served to transfer the heat from the cell eventually to the liquid nitrogen Dewar.
The morning of the run liquid helium was put in the helium Dewar. Before this was done, various spaces within the helium Dewar were checked again for leaks in case any had developed in being cooled down to liquid nitrogen temperatures. Next the electronics were turned on so that components could come to thermal equilibrium, and various batteries adjusted to the load they would be under the duration of the run.

All the nitrogen gas had to be pumped from the helium Dewar and the vacuum space. The helium Dewar and vacuum space were then filled with helium gas: the helium Dewar was filled to a pressure of one atmosphere and the vacuum jacket to 1 Torr. Next, since the contents of the vacuum jacket cooled rapidly, liquid helium was transferred into the helium Dewar. The exchange gas was pumped from the vacuum jacket by the diffusion pump. This was generally completed in ten to fifteen minutes, and measurements could then be started.
APPENDIX E

THE ADJUSTMENT AND OPERATION OF THE TEMPERATURE REGULATOR

Before describing the actual steps necessary to put the temperature regulator into operation, it is appropriate at this time to discuss various types of subtle overload situations that can degrade the performance of the various components of the temperature regulator. To recapitulate, the temperature regulator bridge operates by amplifying an error signal in the bridge containing the carbon resistance thermometer. This error signal passes through several amplifiers, is phase detected, and finally powers the heater on the bottom of the cell. If one of the amplifiers in this series should overload, clipping will result, and the output will be a square wave in which the peaks of the output signal will have been clipped off. It has been observed that overloading will not stop operation of the temperature regulator, but will degrade its performance. The reason for this is that the phase detector will still operate on a square wave as well as the undistorted signal itself. But necessarily some information carried by the signal is lost due to the clipping so the sensitivity of the temperature regulator will be decreased.
(Table 2 lists the types of distortion that can occur in the temperature regulator and may be used as a check list.) The first component considered in Table 2 is a Princeton Applied Research preamplifier. When the bridge is in balance the only signal at the input preamplifier will be noise or radio frequency interference picked up by the leads. Radio frequency interference has been minimized as explained in Chapter II. To be completely in balance the bridge must be balanced not only with respect to the signal but with respect to any quadrature induced by reactive components of the bridge. Since the lock-in phase detector is insensitive to quadrature signals, the preamplifier may be overloaded by a large quadrature signal and this effect not be noted on the output of the lock-in. Quadrature imbalance of the bridge may be adjusted to some extent by viewing the output of the lock-in detector before phase detection (i.e., with the "meter/monitor" switch set to "signal"). If this output is viewed on an oscilloscope, signal distortion such as clipping due to overload or second harmonic generation can also be viewed. However, the tuned amplifier at the front of the lock-in will tend to round a square wave and attenuate second harmonics. For most critical adjustment, the output of the preamplifier should be examined.
**TABLE 2**

**TYPES OF OVERLOAD**

<table>
<thead>
<tr>
<th>A. Preamplifier Overload</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Out of phase component too large</td>
</tr>
<tr>
<td>2. rf interference, rectified; may produce interference at signal frequency.</td>
</tr>
<tr>
<td>3. Noise</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B. Lock-in</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Input too large (varies according to sensitivity).</td>
</tr>
<tr>
<td>2. Phase detector</td>
</tr>
<tr>
<td>a). out of phase component may be too large</td>
</tr>
<tr>
<td>b). noise at nearly 5 KC may overload input even though long time constant keeps meter on scale</td>
</tr>
<tr>
<td>3. Filtered DC too large, meter off scale.</td>
</tr>
</tbody>
</table>

The ac amplifier of the lock-in may also be overloaded in the same manner as the preamplifier. This problem is reduced somewhat because the preamplifier will have removed much of the noise and interference at a frequency considerably different from that of the signal frequency. However, one subtle distortion due to radio frequency can survive. If severe radio frequency interference is present on the input of the preamplifier, it will be rectified due to the slight non-linearity of the transistors in the preamplifier.
This rectified signal may have frequency components close to that of the signal and thus will survive not only the selectivity of the preamplifier but also that of the tuned stage of the lock-in detector. At any rate care must be taken not to overload the ac amplifier of the lock-in detector. The phase detector part of the lock-in may be overloaded if the out of phase component of the signal due to quadrature is sufficiently large. Finally the phase detector may be overloaded by great amounts of noise even though the final output may not drive the meter to its limits due to a large time constant. All these types of overload conditions are described in greater detail in the appropriate manuals for the preamplifier and the lock-in.
TABLE 3
OPERATION OF TEMPERATURE REGULATOR

1. Tune up lock-in by manual, set rolloffs on preamplifier to pass 5 kHz, and set input of preamplifier to "III Z differential".

2. Set 5 kHz input to bridge at moderate level and set lock-in mode on internal.

3. Balance bridge by adjusting R, of Figure 17, the bridge temperature control, looking at output of ac amplifier of lock-in with a monitor oscilloscope by setting "monitor/meter" switch of the PAR 120 lock-in amplifier to signal (power amplifier is off).

4. When minimum is found balance the out-of-phase signal component using C₂ and S₂ in Figure 17.

5. On lock-in set phase to 0° and "monitor/meter" to X1. Check bridge balance again with the bridge temperature control. Then change phase of lock-in to 90°. Make fine adjustment of lock-in phase until slight changes in the bridge temperature control do not change meter reading. Return 4 position phase switch to 0°.

6. With the bridge in balance, set sensitivity of lock-in low and turn on power amplifier with S₂ set to "test" with power on dummy load. Adjust R₁ of Figure 19, the power amplifier bias control, so that a small voltage appears across the load. Increase the bridge temperature control resistance, (i.e., set for lower regulated temperature), so that the bridge is slightly out of balance to the low temperature side, which will drive voltage across dummy load to 0.

7. Change S₂ from dummy load to hot jm heater. Bring bridge slowly back to balance. If sudden departure from balance is observed when voltage starts to appear across bottom heater, change phase of lock-in to 180° and repeat Steps 6 and 7.

8. Further decrease the bridge temperature control. This will slowly increase the heater current, raising the cell temperature. Adjust the power amplifier bias control to bring the lock-in meter back to 0. Increase lock-in sensitivity until oscillation occurs and reduce two steps. Check that no form of overload is occurring.
The steps necessary to assemble and operate the temperature regulator are contained in Table 3, which may be understood by reference to the figures of Chapter II and to the instruction manuals for the PAR 120 lock-in amplifier and the PAR CR 4 amplifier. The following paragraphs contain additional information concerning Table 3.

In brief, the steps in Table 3 first set up the PAR units for the 5 kHz signal generated by the lock-in with a fixed frequency determining board. Then noise and signal quadrature, which does not contain bridge balance information, are minimized. Finally the signal is regulated at each processing stage so it is as large as possible without causing overload, which would result in a loss of information about the balance condition of the bridge.

Specifically, steps 1 and 2 concern signal frequency adjustments. Steps 3 and 4 put the bridge in an approximately balance condition with respect to both the signal and any quadrature that may have been introduced by stray reactances. Step 5 describes the procedure for ascertaining that the phase of the lock-in is set exactly right for the signal and is completely insensitive to any quadrature signal. In actual operation some quadrature signal is tolerable provided overload does not occur. Except for the most critical applications the phase of the lock-in need not be set exactly. Only at the lowest temperatures when the carbon resistance thermometer has its highest values, will the phase of the signal change rapidly. The phase of the signal
is reproducible from run to run for a given set of leads and carbon resistors.

Once the phase of the signal for different cell temperatures has been measured, the phase of the lock-in may be set by reference to a table composed of these measurements of phase angle versus temperature.

Steps 6 and 7 show the proper method of putting the temperature regulator into operation. If power were suddenly put into the bottom heater with the bridge far out of balance, or if the sensitivity of the amplifier were set extremely high, overload conditions would of course occur with resulting signal extremes going into the power amplifier resulting in violent temperature fluctuations in the cell. These temperature fluctuations in themselves do no damage but are not appropriate for making measurements nor will the bridge necessarily settle down and start regulating.

In step 7 the possibility of the regulator failing to regulate is mentioned. The remedy is to change the phase of the lock-in by 180 degrees. The reason for this phenomenon is that the phase of the signal tells the lock-in which way the temperature regulator bridge is out of balance. Since the power amplifier is driven by only one polarity, the phase of the lock-in must be set so that this polarity appears when the temperature regulator bridge is out of balance on the low temperature side. In this case power from the power amplifier fed to the bottom heater will heat up the cell, raising the temperature and bringing the temperature regulator bridge back into balance.
In step 8, a decrease in the bridge temperature control resistance means, of course, an increase in the temperature for which the regulator is set. While the bridge is regulating the temperature in step 8, the sensitivity of the lock-in amplifier is increased. Usually oscillations in the negative feedback system of the temperature regulator will occur because of the time lag in heat pulses going from the bottom heater to the carbon resistance thermometer of the temperature regulator bridge. The exact sensitivity setting at which oscillations appear will depend upon the temperature of the cell.

When superfluid liquid helium is put in the cell the time constant of the cell will be so small that no oscillation will occur due to the excellent thermal conductivity of the superfluid helium. The limit of sensitivity that may be used with the lock-in in this case depends upon the amount of noise present in the signal coming from the temperature regulator bridge. If the signal is being monitored by an oscilloscope the amount of noise will be observed. Also second harmonic generation will be observed due to slight nonlinearity of the field effect transistor in the temperature regulator bridge. This second harmonic component becomes important only when superfluid liquid He is present in the cell and can limit the sensitivity of the lock-in due to overloading the lock-in amplifier. However, before this overload condition occurs the sensitivity of the temperature regulator is usually considerably greater than needed for the experiment.
The signal delivered by the ac amplifier of the lock-in may be monitored while the temperature regulator bridge is actually in operation since the filtered dc output of the phase detector is available at a separate output on the back of the lock-in. The power amplifier is always plugged into the outlet on the back which is not affected by the setting of the monitor/meter switch.

The last part of step 8 involves rechecking overload at different temperatures. It must be emphasized again that it is not always obvious when an overload situation is present, as pointed out earlier in this section. Overload of the preamplifier may be suspected if changing the gain of the preamplifier by a factor of ten does not change the amplitude of the ac signal by a factor of ten. The final test of the correct operation of the temperature regulator bridge is whether it is regulating the temperature to the degree required for the experiment. In the measurements described in this dissertation regulation over a period of several seconds was attained to a few micro-degrees. Long term drift also remained quite small. Since to first order, the measurements were insensitive to this drift, it was not measured.
APPENDIX F

DETAILED STEPS FOR BALANCING HEAT INPUT TO GUARD RING AND ACTIVE CENTER

The steps followed for this procedure are given in Table 4. In step 3 a ΔR is selected with S₂ which will be included in the lower left hand arm of the temperature regulator bridge in step 4. This will cause the temperature regulator bridge suddenly to start regulating at a lower temperature which gives rise to a negative ΔT. However, in step 4 when the top heaters are turned on, the top half of the cell will rise in temperature giving rise to a positive ΔT so that it just equals the negative ΔT caused by the ΔT bypass switch of the temperature regulator bridge. When the adjustment in step 5 has been made correctly the net result of repeating step 4 will be to leave the temperature of the top half of the cell unchanged. This fact is very important since it means that the calibration of $T_1$ and $T_2$ need not be known in order to set the temperature of the guard ring and active center equal when heat is being put into the top heaters.

The reason for this is as follows. First, consider that all steps in Table 4 have been completed successfully. Then when step 4 is repeated, $T_1$ will remain unchanged because of step 8. Therefore, $T_2$ will remain unchanged and thus the only requirement on carbon resistance thermometers
$T_1$ and $T_2$ to balance the heat input to the guard ring and active center, is that each varies in some regular manner with temperature. Provided it is sufficiently fast, it is not important how $T_1$ and $T_2$ vary their resistance with temperature since only an absence of change of resistance between $T_1$ and $T_2$ is necessary in Table 4. Thus are the heaters balanced.

**TABLE 4**

**BALANCING HEAT INPUT TO GUARD RING AND ACTIVE CENTER AT GIVEN TEMPERATURE AND PRESSURE**

1. Select temperature with temperature regulator bridge and have $S_1$ of Figure 17, the $\Delta T$ bypass switch, closed.
2. Look at $T_1$ with ac resistance bridge and chart recorder (channel #2).
3. Select $\Delta R$ with $S_2$ of Figure 17 on temperature regulator bridge.
4. Open the $\Delta T$ bypass switch and turn on top heaters simultaneously.
5. Adjust total heater current with decade box #1, Figure 5 so that $T_1$ remains unchanged during Step 4.
6. Close the $\Delta T$ bypass switch and turn off top heaters. Look at $\Delta(T_1, T_2)$ using switch setting shown for $S_2$ and $S_3$, Figure 5.
7. Open $\Delta T$ bypass switch and turn on top heaters simultaneously.
8. Adjust center heater only, with decade box #2, Figure 5 so that $\Delta(T_1, T_2)$ remains unchanged during Step 7.
9. If adjustment made on #2 decade box in Step 8 was greater than ten percent, repeat Steps 2 through 8.
The reason for including step 9 of Table 4 is that a greater than ten percent change in #2 decade box could increase the amount of power to the top half of the cell so that a change in $T_1$ would no longer remain negligible when step 4 is performed. A few hundredths of a degree rise in temperature of the top half of the cell during an actual measurement is not enough change in temperature to cause a significant imbalance of heat input to the guard ring and active center.
APPENDIX G

SOLUTION FOR FINDING THE CONSTANTS OF THE FIVE CONSTANT FORMULA

The choice of the five constants, $X$, $Y$, $A$, $B$, and $C$ must be found from the 11 primary calibration points of $R_1$ versus $T_1$ for Equation (2).

$$\frac{Y}{T} = \log^X R \ (A + B \log R + C \log^2 R) = \log^X R \cdot P (\log R) \tag{2}$$

Equation (2) is non-linear, so calculations to solve for the constants could become quite involved. A simple method for the evaluation of these constants was found involving the use of a computer. If Equation (2) is put in the following form, the computer can solve for the constants $A$, $B$, and $C$ in a fraction of a second by a standard library subroutine if $X$ and $Y$ are given.

$$A + B \log R + C \log^2 R = \frac{Y}{T} / \log^X R \tag{3}$$

The method was then simple, letting the computer do all the work. The computer solved Equation (3) for the constants $A$, $B$, and $C$ for every reasonable $X$ and $Y$, and computed the percent error of the fit to every data
point for each X and Y. A contour plot, shown in Figure 20 was made by the computer with the maximum percent error for each X and Y as the z axis plotted against X and Y.

Figure 20 like all contour plots, is a projection of a three dimensional surface onto a two dimensional surface. Normally contours of constant height of the z axis are shown. (In Figure 20 only one such contour is shown: the line of constant error of 0.7%. ) In this figure every symbol 0, 1, . . . . 9, A, B, . . . Z, appearing on the plot represents a specific pair of X and Y for which the maximum percentage error was calculated when used in Equation (2), assuming the best choice of the other three constants. The total range of error from 0.17 to 1000% error was divided up systematically between the 35 symbols 0, 1, 2, . . . . Y, Z as shown in the symbol index included in Figure 20. For example the symbol, 4, would be used for an error between 0.4771 and 0.6105%. To find the maximum percent error over the range of temperatures for the primary calibration for a particular X and Y, find the symbol nearest that point on the plot and look up its value in the symbol index included with the plot. For example, the point X = -1, Y = 1 has the symbol, 6, so the maximum error for that choice of X and Y would be between 0.7814 and 1%, (the case for the old three constant formula). Notice the error for the five constant formula is 2 1/2 times less for the best choice of X and Y.
Figure 20

Contour Plot of Percent Error of Five Constant Formula (Equation #2)

\[ Z = \log \left( \frac{T - T_{cal}}{4.2 \times 0.01} \right) \]
Contour lines of constant error may be drawn by connecting together all the occurrences in the plot of a particular symbol like the example shown in the contour plot of the symbol, 6.

A choice of the best X and Y was made visually using a different contour plot for each calibration. In Figure 20 two branches of best fit are evident; in this case preference was given to the broader minimum. Figure 21 shown an atypical case where only one of the branches of best fit is present. Here the best values of X and Y are quite different from those of Figure 20. Tables in Figure 20 and 21 give the values of the symbols used in the contour plots shown in Figures 20 and 21. Once the constants for the best fit of Equation (2) have been found, the temperature corresponding to the measured resistance of that particular carbon resistance thermometer may be found from

\[ T(R) = \left[ \log^X R \cdot P(\log R) \right]^{-1/Y} \]
Figure 21

Carbon Resistance Thermometer Data Where One Branch Of Contour Plot Is Missing
APPENDIX II

INTERPOLATION WITH THE SECONDARY CALIBRATION AS EXAMPLE

Many numbers needed for calculations leading to the KBR had to be interpolated from tables such as the vapor pressure tables for $^4\text{He}$. This section describes the method of interpolation used in every case in this dissertation. The method used has the advantage that a point of inflection may appear between two given points, and that the interpolation at a given point is nearly continuous in slope as well as continuous in value.

Figure 22 shows an example of an interpolation between points that might appear in a table giving values of a dependent variable in terms of an independent variable. In this figure a cubic of the form $Y = A + Bx + Cx^2 + Dx^3$ is found to pass through the four points, $P_i$, $P_{i+1}$, $P_{i+2}$, and $P_{i+3}$. This cubic is used to interpolate between $P_{i+1}$ and $P_{i+2}$ for all points on segment $S_{i+1}$. Another cubic is fitted to points $P_{i+1}$ through $P_{i+4}$ for segment $S_{i+2}$.

Two additional points must be extended beyond either end of the sequence, $P_0, P_1, \ldots, P_i, \ldots, P_n$ to find the cubics for $S_0$ and $S_{n-1}$. For the case of $S_0$, place $P_e$ on the straight line through $P_0$ and $P_1$ such that $P_0$ lies midway between $P_e$ and $P_1$. All this interpolation was done automatically by computer for a particular table by calling the appropriate subroutine in one Fortran statement.
Figure 22

Example of Interpolation Scheme
An example of how this interpolation subroutine was used is the secondary calibration of Channel #1 position in recording paper units (0-1000) versus the resistance, $R_3$, of carbon resistance thermometer $T_3$ over the range of temperature of the experiment. Channel #1 position $Ch_1$ is proportional to temperature (Figure 18, Appendix B). A set of 12 points was used as the input for the interpolation. The closer a set of points fall to a straight line, the more accurate will the interpolation be. For this reason $Ch_1$ and the parameter $1/(\log R_3 - 2)$ were used for the interpolation.

Figure 23 shows that $Ch_1$ and this parameter fall very close to a straight line. Once the set of 12 points from the secondary calibration have been put into the interpolation subroutine, the value of any $\log R_3$ may be found for an arbitrary $Ch_1$ where $\log R_3 = (1/Ch_1) + 2$. 
Figure 23

$(\log R_3 - 2)^{-1}$ vs. Channel #1
\( \left( \log R_3 - 2 \right)^{-1} \) vs. \( \text{Ch}_1 \)


