WATER: THE WAVEGUIDE ASSEMBLY THERMAL ENERGY ROUTINE
THERMAL CONDUCTIVITY

Richard F. Bradley

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# WATER: THE WAVEGUIDE ASSEMBLY THERMAL ENERGY ROUTINE
## THERMAL CONDUCTIVITY

Richard F. Bradley

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1.0 INTRODUCTION

The Waveguide Assembly Thermal Energy Routine (WATER) is a BASIC program used for calculation of thermal resistance and conduction type heat flow through various waveguide and transmission line sections. WATER can handle a wide variety of single material and plated sections of rectangular and circular waveguides. Many forms of coaxial transmission line can also be analyzed with WATER. Both the inner and outer conductors of the coaxial line can be single material or of the plated style. WATER cannot calculate the thermal resistance or heat flow through cascaded sections of dissimilar waveguide or coaxial lines. Thus, the calculations performed by WATER are for a single section of a particular waveguide or transmission line.

By far, the largest input parameter of the program is the thermal conductivity for the material used. A complete section of WATER is devoted to thermal conductivity data input, storage and analysis. This data can be stored on the disk along with the program and used repeatedly in calculations. Aside from alleviating the laborious process of entering this data for each waveguide assembly under analysis, this feature provides the user with a complete library of thermal conductivity data. A list of such data currently stored on the disk can be found in Appendix D.

The other input parameters are entered into the program directly. Other inputs to the program include waveguide cross-sectional dimensions, source and sink temperatures, and the total length of the waveguide. If the section is plated, the depth of the plating is also required. Information found in Appendix C may be helpful in the determination of the plating depth.
The program was designed to be a versatile tool for solving heat transfer problems encountered in receiver system engineering. The formal calculations and user interactions are performed in a smooth and economical way. The output of the program displays the input parameters along with the calculated thermal resistance and heat flow values. All the input parameters can be altered separately and new calculations performed quite easily. WATER is constructed in modular form so that additional computations and special purpose routines can be easily added. WATER is written in Applesoft BASIC and was especially created for use with the APPLE II plus microcomputing system.

2.0 PROGRAM OPERATION

The Waveguide Assembly Thermal Energy Routine, WATER, consists of six sub-level programs, illustrated in Figure 1. The routines listed in Figure 1 can only be accessed when in the monitor level. Although each sub-level is a complete, independent program, routines which are common along the sub-levels are shared. This process decreases the number of programming steps needed and thus conserves memory space. A comprehensive description of each sub-level is now in order.

2.1 Thermal Conductivity Data Analysis

This sub-level program allows the user to enter thermal conductivity data into the program, check the data for errors, and store the data on the disk for use in the heat flow calculation sub-levels. A diagram of this sub-program is shown in Figure 2.

Upon entering this sub-level program, the user is queried about the status of the thermal conductivity data. To answer this question, the user must choose one of the following:
FIGURE 1
Sub-Level Diagram

MONITOR LEVEL

T
THERMAL CONDUCTIVITY ANALYSIS

R
RECTANGULAR WAVEGUIDE HEAT FLOW

C
CIRCULAR WAVEGUIDE HEAT FLOW

X
COAXIAL TRANSMISSION LINE HEAT FLOW

I
CM TO INCH CONVERSION

M
INCH TO CM CONVERSION
FIGURE 2
Flow Diagram of
Thermal Conductivity Subprogram
(P) Previously stored data.

This statement refers to data that has already been stored on the disk. A list of such data can be found in Appendix D. After typing (P), enter the type of material needed. The program will read the data from the disk and then display the (T) level menu.

(N) New data for disk.

This statement refers to a new list of data that the user would like to have stored on the disk. After typing (N), enter the name of the material. The corresponding thermal conductivity data can now be entered into the program by rows. Data can be entered into the program in any order. Start with the first row by entering a temperature followed by its corresponding thermal conductivity. Remember, the temperature is in degrees Kelvin and the thermal conductivity must be in W/cm K. The program displays which row the user is currently entering data. To jump out of the "input data" mode, enter a zero for the temperature or conductivity. The program then disregards that row and displays the (T) level menu.

The (T) level menu is shown below and a brief description of each menu selection follows.

(T) Level menu.

(M) More data. (C) Change data.
(D) Display data. (S) Store data.
(P) Print data. (X) Delete line.
(E) Exit to monitor.

(M) More data.

After this command is typed, the user can then begin entering thermal conductivity data into the existing table. The program will jump to the next row after the last previous entry, and begin placing the incoming data. To drop out of this mode, enter a zero for the temperature or the conductivity. The program will return to the menu.

(D) Display data.

When (D) is typed, the program will begin listing the entire table of data. The data may move off the screen, so to stop the moving process type "esc" or "CTRL-s". To continue, type any key. At the end of the table, the menu will be displayed again.
(P) Print data.

This command is similar to the (D) command except this time the printer is enabled and a hard-copy of the data is thus created. The printer will print the name of the material along with table but will not print the menu. The menu will be displayed on the CRT.

(C) Change data.

This is a useful command if an error is found in a particular entry of the table. After typing (C), the program asks what row the error lies, and then whether the error is in the temperature or the conductivity column. After entering the proper column, the program displays the previous number and asks for the corrected value. Upon entering the corrected value, the menu is displayed once again.

(S) Store data.

When (S) is typed, the program orders the data from lowest to highest temperature. When the ordering procedure is completed, the data is stored on the disk and the program returns to the monitor level.

(X) Delete row.

This command is handy when an entire row needs erased. When in the (X) mode type the number of the row that is to be deleted. The program then places the value 10,000 into the temperature slot for that row. When the (S) mode is activated, the program will not store the rows with 10,000 for a temperature. To exit the (X) mode, type in a zero for the row number and the program will display the (T) level menu.

(E) Exit to monitor.

This command returns the program to the monitor level. The monitor level command list is then displayed.
2.2 Conduction Heat Flow Calculation Programs.

(R) Rectangular Waveguide
(C) Circular Waveguide
(X) Coaxial Transmission Line

The above three sub-level programs form the heart of the Waveguide Assembly Thermal Energy Routine, WATER. All three sub-levels are quite similar in many respects and a flow diagram of each is shown in Figures 3, 4 and 5. After the (R), (C), or (X) routine is executed, all the waveguide parameters must be entered into the program. The program will ask for each parameter individually. The units for each parameter is displayed along with the input request. If any of the above three modes is entered by mistake, or an exit to the monitor level is needed, type in a zero for any numerical input. This will immediately return the program to the monitor level.

Both the waveguides and transmission lines analyzed by WATER are assumed to be in a vacuum environment so that convection processes can be ignored. An important factor that is not considered in this program is radiation. Radiation processes should be minimized before program/measurement correlation is attempted. Additional information about heat flow measurements can be found in section 4.0 of this report.

After an initial set of input parameters, the program will calculate the thermal resistance and heat flow for a given waveguide or transmission line section. At this point, the user can change any of the parameters and the above calculations are performed once again. This process will continue until the user exits from this mode or by entering a zero for any numerical entry.

The following is a detailed catalog of input parameters used with the various heat flow calculation sub-levels.
FIGURE 3
Flow Diagram of Rectangular Waveguide Analysis Subprogram
MONITOR LEVEL

C

SOURCE TEMPERATURE

SINK TEMPERATURE

PRINCIPAL MATERIAL

IS WAVEGUIDE PLATED?

Yes

PLATING MATERIAL

PLATING DEPTH

OUTSIDE DIAMETER

TOTAL WALL THICKNESS

TOTAL LENGTH

DISPLAY RESULTS

MENU

FIGURE 4
Flow Diagram of Circular Waveguide Analysis Subprogram
FIGURE 5
Flow Diagram of Coaxial Analysis Subprogram
2.2.1 Temperature input.

At the beginning of each sub-level program is the request for the source and sink temperatures. These temperatures can be any value between the extreme limits set forth by the thermal conductivity versus temperature table used for the current calculation. The source temperature must be greater than the sink temperature, and the units must be degrees Kelvin.

2.2.2 Material input.

The thermal conductivity data for a particular material must be stored on the disk before the material can be used in the heat flow calculation section. See Appendix D for a list of thermal conductivity data currently stored on the disk. If the data for the material in question does not appear in Appendix D, see Section 2.1 of this report.

If the waveguide or transmission line is plated, the depth of the plating must be entered into the program. Unless the plating depth is supplied with the waveguide, an accurate approximation must suffice. To aid in this estimation, a graph of frequency versus skin depth for various electrical conductivity levels can be found in Appendix C.

WATER assumes that rectangular and circular waveguides are made either of two ways: (1) The only material present is the principal material which forms the structure of the waveguide; and (2) the principal or structure material is plated with an additional substance. If the waveguide under analysis is plated, enter the name of the plating material and then the depth of the plating. The plating depth must have units of cm. A zero input for the plating depth will cause the program to jump to the monitor level.
WATER can handle a wide variety of coaxial transmission lines. Both the inner and outer conductors may be single material or plated. In any event, the name of the outer conductor structural material is entered first — then the name of the inner conductor structural material. In some cases, the structural material is the only material present, and a "no" should be entered for the plating questions. If the outer conductor is plated, answer "yes" to the corresponding plating question and then enter the type of plating material and the plating depth. The same procedure should be followed if the inner conductor is plated. Note that the plating depth must have units of cm.

After the material data is entered, the program will begin to read thermal conductivity information from the disk and integrate the data over the limits set forth by the source and sink temperatures. After a few seconds, the dimension routine will begin its request for data.

2.2.3 Dimension input.

Only the cross-sectional dimensions are placed into the program at this point. Remember, the dimensional parameters are entered one at a time upon request. All dimensions must be in cm.

Rectangular waveguides.

To aid in the process of entering the cross-sectional dimensions, a graphic picture of a typical rectangular waveguide is displayed. For a given waveguide, dimension A is the width of one side, and dimension B is the width of the other side. If a square waveguide is encountered, dimensions A and B may be set equal. Enter the appropriate value for A and B when the corresponding data request is given. Considered next is the total wall thickness. This refers to the principal material wall thickness plus the plating depth, if applicable. Refer to Figure 6a for a detailed sketch of the rectangular cross section.
Circular waveguides.

The circular cross-sectional data is summarized by two inputs. First, the diameter of the waveguide is placed into the program. Next, the total wall thickness is considered. This includes the principal material thickness and the plating thickness if the waveguide is plated. See Figure 6b for a sketch of the circular cross section.

Coaxial transmission lines.

For the coaxial cross section, first enter the outside diameter of the outer conductor, then the outside diameter of the inner conductor. Note the diameter of the inner conductor may include the plating thickness. The program assumes that the inner conductor is solid. If the inner conductor is tabular, the inside diameter of the tube must be given. Finally, the total wall thickness of the outer conductor, structural material thickness plus plating thickness must be given to the program. See Figure 7.

When the dimensional data input routine is complete, the program will jump to the next mode which is "length input".

2.2.4 Length input.

The length input routine is common among all three heat flow calculation sub-levels. The length refers to the distance between the source and the sink. The length of the waveguide or transmission line must have units of cm.

2.2.4 The display.

For each heat-flow sub-level, a unique display of the results follows each calculation routine. All three display the appropriate input parameters and the calculated thermal resistance and heat flow values. For the rectangular and circular waveguides, two CRT screens are used. The results for the coaxial
transmission line is displayed on three CRT screens. To move from one screen to
the next, type any key. The options menu is displayed on a full screen at the
end of the results. Figure 8 shows typical examples of the three displays.

After the results of a calculation are displayed, a menu is displayed which
gives the user certain options:

(T) Temperature change.
(D) Cross-sectional dimension change.
(M) Material change.
(L) Length change.
(P) Print copy of results.
(S) Skin depth change.
(E) Exit to main program.
(R) Retype results.

A detailed list of options should clarify some of the minor points of the
program.

(T) Temperature change.

When the (T) mode is activated, the source and sink temperatures can be
changed. Enter the altered data upon request. The program will recompute the
heat flow for the new parameter set and display the results along with the menu.

(D) Cross-sectional dimension change.

When "D" is typed, the user can enter a new set of cross-sectional dimen-
sions for the waveguide or transmission line. Remember, the units for all
cross-sectional dimensions is cm. Again, the program calculates a new heat
flow and displays the result.

(M) Material change.

This mode is quite useful when structural or plating material needs al-
tered. Also, a plating material can be added or deleted at this time. The
area calculations are altered to correspond to the structural/plating material
change. Again, the heat flow is computed and the results displayed.
HAWEGUIDE PARAMETERS
PRINCIPLE MATERIAL...STAINLESS STEEL
PLATING MATERIAL...COPPER ETP
SOURCE TEMPERATURE 75 (KELVIN)
SINK TEMPERATURE 10 (KELVIN)
LENGTH 15.24 (CH)
DIM A .6220(CH)  DIM B .3353(CH)
TOTAL WALL THICKNESS .0254 (CH)
DEPTH OF PLATING 6E-05 (CH)

CROSS-SECTION AREA
STAINLESS STEEL .0409627906 (50 CH)
COPPER ETP 1.02734397E-04 (50 CH)

THERMAL RESISTANCE (H/K)
STAINLESS STEEL 6621.06415
COPPER ETP 3.562322E+09
TOTAL 4705.05293

HEAT FLOW (WATTS)
STAINLESS STEEL .89155221E-02
COPPER ETP 1.02189448 4.42354271E-03
TOTAL .8138149349

Rectangular

CIRCULAR PARAMETERS
PRINCIPLE MATERIAL...STAINLESS STEEL
PLATING MATERIAL...COPPER ETP
SOURCE TEMPERATURE 75 (KELVIN)
SINK TEMPERATURE 10 (KELVIN)
LENGTH 12 (CH)
OUTSIDE DIAMETER 3(CH)
TOTAL WALL THICKNESS .1016 (CH)
DEPTH OF PLATING 6E-05 (CH)

CROSS-SECTION AREA
STAINLESS STEEL .32460097 (50 CH)
COPPER ETP 5.27191907E-04 (50 CH)

THERMAL RESISTANCE (H/K)
STAINLESS STEEL 276.90786
COPPER ETP +4.2056403E-04 2254.769046
TOTAL 241.850148

HEAT FLOW (WATTS)
STAINLESS STEEL .239553952
COPPER ETP 4.56522886 5.2288275125
TOTAL .268761464

Circular

COAXIAL PARAMETERS
OUTER CONDUCTOR...STAINLESS STEEL
INNER CONDUCTOR...STAINLESS STEEL
OUTER CONDUCTOR PLATING.. COPPER ETP
INNER CONDUCTOR PLATING.. COPPER ETP
SOURCE TEMPERATURE 75 (KELVIN)
SINK TEMPERATURE 10 (KELVIN)
LENGTH 10 (CH)
OUTSIDE DIAM. OF OUTER COND.5 (CH)
OUTSIDE DIAM. OF INNER COND. 3 (CH)
INSIDE DIAM. OF TUBE 1 (CH)
OUTER COND. WALL THICKNESS .1016 (CH)
OUTER COND. PLAT. DEPTH 6E-05 (CH)
INNER COND. PLAT. DEPTH 6E-05 (CH)

CROSS-SECTIONAL AREA
OUTER CONDUCTOR 1.56229656 (50 CH)
INNER CONDUCTOR 6.28261803 (50 CH)
OUTER COND. PLAT 5.4195011E-04 (50 CH)
INNER COND. PLAT 5.6547671E-04 (50 CH)
THERMAL RESISTANCE (KELVIN/WATT)

OUTER CONDUCTOR 133.592065
OUTER CONDUCTOR PLATING 1895.5484
SOURCE TEMPERATURE 75
INNER CONDUCTOR 33.2241569
INNER CONDUCTOR PLATING 1751.77752
HEAT FLOW (WATTS)

OUTER CONDUCTOR .4865227
OUTER CONDUCTOR PLATING .953310161
INNER CONDUCTOR 1.95640762
INNER CONDUCTOR PLATING .3371051684
TOTAL HEAT FLOW 2.53943627

Coaxial

FIGURE 8
Typical Display of Results
(L) Length change.

The length change routine is straightforward. After entering this mode, type in the new length value. Remember to keep the units in cm. The new results are displayed.

(P) Print results.

This mode allows the user to obtain a hard-copy of the result. When "P" is typed, the program will print the input parameters along with the results. The printer will stop after each screen is printed and, to continue, type any key. The options menu will not be printed but will be displayed on the CRT.

(S) Skin depth change.

If the waveguide is plated, the plating depth can be changed by entering this mode. After typing "S", type in the revised plating depth. The plating depth must be in cm. Note that if nothing is plated, the user cannot enter this mode. The new results are displayed.

(E) Exit to monitor.

This option is self-explanatory. When "E" is typed, the program will jump to the monitor level but will not erase any data from its memory.

(R) Retype results.

If the results and input parameters need to be analyzed again, type "R". This will display the results exactly as before.

2.3 Additional monitor level commands.

Other commands are available to the user at the Monitor level. A description of these follow:

(I) Cm to inch conversion.
(M) Inch to cm conversion.

This set of sub-levels is independent of all other sub-levels within the Waveguide Assembly Thermal Energy Routine. All dimensional quantities in WATER are expressed in cm. Any other dimensional unit must be converted to cm before placement into the program. This conversion routine will help with this chore.
(D) Display calculation results.

This simple command allows the user to display the current calculation results again. The command also places control back to the heat flow sub-level. This feature is only possible when a calculation has already been performed.

(E) Exit program.

Type "E" to exit from program and return the BASIC monitor.

3.0 SUMMARY OF ALGORITHMS

3.1 Thermal Resistance Calculation

The central theme of WATER is the thermal resistance calculation. The thermal resistance for a section of waveguide containing two materials is:

\[
R = \frac{d(SO - SI)}{A_2 \int K_1(T) \, dT + A_2 \int K_2(T) \, dT}
\]

where
- \(d\) = length of the waveguide.
- \(SO\) = Source of temperature.
- \(SI\) = Sink temperature.
- \(A_1\) = Cross-sectional area of material 1.
- \(A_2\) = Cross-sectional area of material 2.
- \(K_1(T)\) = Thermal conductivity of material 1.
- \(K_2(T)\) = Thermal conductivity of material 2.

The length and the source and sink temperatures are directly supplied by the user. The thermal conductivity data is read off the disk and a unique temperature ranging process incorporated with a standard integration routine is used to solve the integrals. The user supplies the cross-sectional dimensions and the program computes the corresponding area. The thermal
resistance is then calculated and displayed along with the heat flow through each material.

3.2 **Ranging and Integration Routine.**

After the source and sink temperatures and the type of material is entered into the program, the ranging and integration process begins. The thermal conductivity data for the particular material is loaded from the disk into an array. The data on the disk and hence in the array was previously ordered from lowest to highest temperature by the thermal conductivity analysis routine. The program then finds the values in the array that are greater than the sink but less than the source. If the source and sink temperatures do not exactly match any of the temperatures in the array, a thermal conductivity value is found for the source and sink by straight line interpolation. The original data in the array is replaced by this newly formed sub-set. At this point, a straight line integration process takes place and the result is stored in the integration results array. This routine is performed for each material used in the waveguide.

3.3 **Additional Procedures.**

From the ranging and integration routine, the program moves to the cross-sectional dimension input mode. To keep the inputs simple and straightforward, the program only asks for one-dimensional values. The cross-sectional area for each type of material is calculated. Finally, the length of the waveguide is placed into the program.

The thermal resistance is computed for each material used in the waveguide. A total thermal resistance for the waveguide is also computed. The heat flow through each material is found from the relation:

\[ Q = \frac{S_0 - S_I}{R_m} \]
where \( S_0 \) = Source temperature.
\( S_I \) = Sink temperature.
\( R_m \) = Thermal resistance of the material.

The results of the calculations are displayed along with the related input parameters.

4.0 SUPPORTING MEASUREMENTS

4.1 Introduction.

To achieve some level of confidence in the calculations performed by WATER, an attempt was made to correlate measured values of heat flow with that computed by the program. A special apparatus was constructed to mount a section of waveguide and provide a source and sink for heat transfer. The power supplied to the source was considered to be the heat flow through the waveguide. The results of the measurements are then compared to the calculated values. Possible sources of error are mentioned and a brief discussion of improvements to the testing apparatus are given at the end of the report.

4.2 Assumptions.

1. A perfect thermal connection exists between the waveguide end flange and the 20° Kelvin station and between the opposite end flange and the copper block.
2. All the energy generated by the heater is transferred to the copper block.
3. Since the vacuum in the dewar is quite good, convection processes can be ignored.
4.3 Material Specifications.

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<th>Waveguide #1</th>
<th>Material .......... Copper (TE)</th>
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<tr>
<td>Dimensions: A ....</td>
<td>1.27 cm</td>
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<tr>
<td>B ....</td>
<td>0.635 cm</td>
</tr>
<tr>
<td>T ....</td>
<td>0.1016 cm</td>
</tr>
<tr>
<td>Length ............</td>
<td>11.43 cm</td>
</tr>
<tr>
<td>Description ......</td>
<td>WR-42 waveguide with brass end flanges. Inside polished; outside is oxide coated.</td>
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<table>
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<tr>
<th>Waveguide #2</th>
<th>Material .......... Copper (OFHC)</th>
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<tr>
<td>Dimensions: A ....</td>
<td>1.27 cm</td>
</tr>
<tr>
<td>B ....</td>
<td>0.635 cm</td>
</tr>
<tr>
<td>T ....</td>
<td>0.1016 cm</td>
</tr>
<tr>
<td>Length ............</td>
<td>8.73125 cm</td>
</tr>
<tr>
<td>Description ......</td>
<td>WR-42 waveguide with brass end flanges. Inside polished; outside is oxide coated.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Waveguide #3</th>
<th>Material .......... Stainless steel -- Copper (ETP) plating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions: A ....</td>
<td>0.6223 cm</td>
</tr>
<tr>
<td>B ....</td>
<td>0.3353 cm</td>
</tr>
<tr>
<td>T ....</td>
<td>0.0254 cm</td>
</tr>
<tr>
<td>Length ............</td>
<td>7.62 cm</td>
</tr>
<tr>
<td>*Plating depth .....</td>
<td>$6 \times 10^{-5}$ cm</td>
</tr>
<tr>
<td>Description ......</td>
<td>WR-22 waveguide with brass end flanges. Inside polished; outside clean but not polished.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Waveguide #4</th>
<th>Material .......... Stainless steel -- Copper (ETP) plating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions: A ....</td>
<td>0.6223 cm</td>
</tr>
<tr>
<td>B ....</td>
<td>0.3353 cm</td>
</tr>
<tr>
<td>T ....</td>
<td>0.0254 cm</td>
</tr>
<tr>
<td>Length ............</td>
<td>15.24 cm</td>
</tr>
<tr>
<td>*Plating depth .....</td>
<td>$6 \times 10^{-5}$ cm</td>
</tr>
<tr>
<td>Description ......</td>
<td>WR-22 waveguide with brass end flanges. Inside polished; outside clean but not polished.</td>
</tr>
</tbody>
</table>

* Approximation of plating thickness.

4.4 Laboratory Set-Up.

The apparatus used in the heat flow measurement experiment consists of a test dewar housing a two stage CTI refrigerator unit. One end of the waveguide under test was mounted directly to the 20 K station of the refrigerator. This formed the heat sink end of the waveguide. The source end of the waveguide was
terminated with a copper block used to position the heater and temperature sensitive diode. A second diode was secured to the 20 K station to monitor the sink. The sensors are connected to a special readout unit that is calibrated to the specific diode used. Indium is used at all thermal connections to assure proper heat transfer. Two #36 gauge copper wires deliver the power to the heater. A pair of #38 gauge copper wire connects the diode to the outside world. All four wires originate from the copper block and are a source of loading at the heat source. To minimize this effect, all four wires are wrapped around the 20 K station to decrease the $\Delta T$, hence decreasing the unwanted heat flow.

Thermal radiation effects are minimized by use of a copper heat shield encapsulating the waveguide. The shield is tied to the 77 K station of the refrigeration unit. The entire experiment is done in a vacuum environment where the pressure ranges from 4 to 10 $\mu$Hg. The same apparatus was used with all four sections of waveguide.

4.5 Test Procedure.

Once the section of waveguide is mounted in the testing apparatus, a vacuum is drawn on the dewar. When the pressure drops below 150 $\mu$Hg, the refrigeration unit is activated. The system is cooled down and allowed to remain at the low temperature level until the source and sink stabilize. The pressure decreases to about 10 $\mu$Hg where equilibrium exists. At this point, the source and sink temperatures should be equal since only a very small load exists. The source and sink are within 2° of each other before the measurements begin.

The power is supplied to the heater. This is done by setting the power supply voltage to a specific level and allowing the current to stabilize. The source will first increase sharply and then slowly approach its equilibrium value. At equilibrium, the source and sink temperatures are recorded along with the corresponding heater voltage and current. The power supplied to the heater and hence the source, is then equal to the heat flow through the waveguide.
FIGURE 9
Waveguide Dimensions

FIGURE 10
Diagram of Test Apparatus
4.6 Results

Waveguide #1: The copper (TE) waveguide gave the best computation-measurement correlation. The maximum deviation from the calculated values is about 200 mW.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.8</td>
<td>10.5</td>
<td>47.41</td>
<td>30.02</td>
<td>1.423</td>
<td>1.268</td>
</tr>
<tr>
<td>2</td>
<td>23.5</td>
<td>11.0</td>
<td>60.00</td>
<td>38.20</td>
<td>2.29</td>
<td>2.175</td>
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<tr>
<td>3</td>
<td>31.0</td>
<td>12.0</td>
<td>77.81</td>
<td>50.00</td>
<td>3.89</td>
<td>3.789</td>
</tr>
<tr>
<td>4</td>
<td>41.0</td>
<td>13.5</td>
<td>93.04</td>
<td>60.32</td>
<td>5.61</td>
<td>5.950</td>
</tr>
<tr>
<td>5</td>
<td>56.0</td>
<td>16.7</td>
<td>114.00</td>
<td>74.70</td>
<td>8.52</td>
<td>8.472</td>
</tr>
<tr>
<td>6</td>
<td>56.0</td>
<td>17.3</td>
<td>114.00</td>
<td>75.00</td>
<td>8.60</td>
<td>8.367</td>
</tr>
<tr>
<td>7</td>
<td>130.0</td>
<td>33.0</td>
<td>148.00</td>
<td>100.10</td>
<td>14.80</td>
<td>14.973</td>
</tr>
</tbody>
</table>
WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL: COPPER TE
SOURCE TEMPERATURE 31.6 (KEVIN)
SINK TEMPERATURE 12 (KEVIN)
LENGTH 11.43 (CM)
DIM A 1.27 (CM)  DIM B .035 (CM)
TOTAL WALL THICKNESS .1016 (CM)
CROSS-SECTION AREA
COPPER TE .34588576 (SQ CM)
THERMAL RESISTANCE (H/K)
COPPER TE 5.81350542
TOTAL 5.81350542
HEAT FLOW (WATTS)
COPPER TE 3.76850498
TOTAL 3.76850498

WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL: COPPER TE
SOURCE TEMPERATURE 25.5 (KEVIN)
SINK TEMPERATURE 11 (KEVIN)
LENGTH 11.43 (CM)
DIM A 1.27 (CM)  DIM B .035 (CM)
TOTAL WALL THICKNESS .1016 (CM)
CROSS-SECTION AREA
COPPER TE .34588576 (SQ CM)
THERMAL RESISTANCE (H/K)
COPPER TE 5.88458699
TOTAL 5.88458699
HEAT FLOW (WATTS)
COPPER TE 2.17508649
TOTAL 2.17508649

WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL: COPPER TE
SOURCE TEMPERATURE 41 (KEVIN)
SINK TEMPERATURE 13.5 (KEVIN)
LENGTH 11.43 (CM)
DIM A 1.27 (CM)  DIM B .035 (CM)
TOTAL WALL THICKNESS .1016 (CM)
CROSS-SECTION AREA
COPPER TE .34588576 (SQ CM)
THERMAL RESISTANCE (H/K)
COPPER TE 4.62269506
TOTAL 4.62269506
HEAT FLOW (WATTS)
COPPER TE 5.94968189
TOTAL 5.94968189

WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL: COPPER TE
SOURCE TEMPERATURE 56 (KEVIN)
SINK TEMPERATURE 12.5 (KEVIN)
LENGTH 11.43 (CM)
DIM A 1.27 (CM)  DIM B .035 (CM)
TOTAL WALL THICKNESS .1016 (CM)
CROSS-SECTION AREA
COPPER TE .34588576 (SQ CM)
THERMAL RESISTANCE (H/K)
COPPER TE 4.62269506
TOTAL 4.62269506
HEAT FLOW (WATTS)
COPPER TE 8.47265293
TOTAL 8.47265293

WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL: COPPER TE
SOURCE TEMPERATURE 60 (KEVIN)
SINK TEMPERATURE 17.5 (KEVIN)
LENGTH 11.43 (CM)
DIM A 1.27 (CM)  DIM B .035 (CM)
TOTAL WALL THICKNESS .1016 (CM)
CROSS-SECTION AREA
COPPER TE .34588576 (SQ CM)
THERMAL RESISTANCE (H/K)
COPPER TE 4.62269506
TOTAL 4.62269506
HEAT FLOW (WATTS)
COPPER TE 8.47265293
TOTAL 8.47265293

FIGURE 11
Calculation Results: Waveguide 1
4.6 Continued:

Waveguide #2

The copper (OFHC) waveguide test produced interesting results. When \( \Delta T \) is small, the measured value was extremely close to the calculated value. As \( \Delta T \) increases, the measured values oscillate about the computed result. Maximum deviation was approximately 1 watt.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Source Temperature ( \text{K} )</th>
<th>Sink Temperature ( \text{K} )</th>
<th>Heater Current mA</th>
<th>Heater Voltage V</th>
<th>Measured Heat Flow W</th>
<th>Calculated Heat Flow W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.7</td>
<td>12.4</td>
<td>76.87</td>
<td>50.0</td>
<td>3.843</td>
<td>3.839</td>
</tr>
<tr>
<td>2</td>
<td>24.1</td>
<td>13.2</td>
<td>76.82</td>
<td>50.0</td>
<td>3.841</td>
<td>3.807</td>
</tr>
<tr>
<td>3</td>
<td>25.9</td>
<td>14.0</td>
<td>91.47</td>
<td>60.0</td>
<td>5.488</td>
<td>4.376</td>
</tr>
<tr>
<td>4</td>
<td>38.0</td>
<td>17.1</td>
<td>105.85</td>
<td>70.0</td>
<td>7.409</td>
<td>8.695</td>
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<tr>
<td>5</td>
<td>53.0</td>
<td>23.1</td>
<td>126.94</td>
<td>84.99</td>
<td>10.788</td>
<td>11.538</td>
</tr>
</tbody>
</table>

Waveguide #3

An interesting problem developed when the stainless steel waveguide structure was cooling down. The source end of the structure could not be cooled below 57\( ^\circ \text{K} \) for the initial equalization. This waveguide was not used for normal heat flow measurements. WATER computed the leakage to be approximately 15 mW.

Waveguide #4

This piece of waveguide is longer than waveguide #3 but all other parameters are equal. Again, the problem developed during cooling and the source would not drop below 73\( ^\circ \text{K} \). WATER computed the unwanted heat flow to be about 15 mW.
Figure 12

Calculation Results: Waveguide 2

Waveguide #3

**Waveguide Parameters**
- **Principle Material**: Copper OFHC
- **Source Temperature**: 25.1 (K)
- **Sink Temperature**: 14.5 (K)
- **Length**: 8.3125 (CM)
- **Diameter A**: 1.27 (CM)
- **Diameter B**: 0.635 (CM)
- **Total Wall Thickness**: 0.1016 (CM)
- **Cross-Section Area**: Copper OFHC .34560576 (SQ CM)
- **Thermal Resistance (W/K)**: Copper OFHC 2.84339637
- **Heat Flow (Watts)**: Copper OFHC 5.38910238
  - **Total**: 3.8970928

Waveguide #4

**Waveguide Parameters**
- **Principle Material**: Copper OFHC
- **Source Temperature**: 25.1 (K)
- **Sink Temperature**: 14.5 (K)
- **Length**: 8.3125 (CM)
- **Diameter A**: 1.27 (CM)
- **Diameter B**: 0.635 (CM)
- **Total Wall Thickness**: 0.1016 (CM)
- **Cross-Section Area**: Copper OFHC .34560576 (SQ CM)
- **Thermal Resistance (W/K)**: Copper OFHC 2.84339637
- **Heat Flow (Watts)**: Copper OFHC 5.38910238
  - **Total**: 3.8970928

Figure 13

Computation Results: Waveguides 3 and 4
4.7 Apparatus Component Description

4.7.1 Diode temperature sensors.

Lake Shore Cryotronics series DT-500-CU-36 temperature sensing diodes were used in the measurements experiment. The pair of diodes was checked at 300, 77 and 10 degrees Kelvin against room temperature, LN, and hydrogen vapor pressure, respectively. The two diodes have very similar response characteristics and are within 2° of each other at the 10° Kelvin level.

The temperature readout unit was properly calibrated to the DT-500 series diodes. The diodes are connected to the readout unit via phosphor bronze wire. The wire was wrapped around the 20 K refrigeration station to reduce unwanted heat transfer.

Indium foil was used between the diode sensors and the copper source and sink stations so that good heat transfer is assured.

4.7.2 Miniature heater.

The source heater used in the apparatus is the MINCO products H4A series button heater. The unit is able to deliver 20 W at 115 V. Indium was used between the heater and the copper block to assure proper heat transfer. Number 36 gauge copper wire connects the heater to a variable power supply.

4.8 Sources of Error.

1. The small wires connecting the source heater and temperature diode to the outside world cause a slight loading to occur at the source end of the waveguide.

2. The waveguide may be radiating significant energy to the 77 K heat shield. This energy leakage will produce a slight thermal load on the entire waveguide structure.

3. The temperature diodes do not correlate exactly with actual temperature. For copper (TE), a 1 degree change may correspond to 400 mW of heat transfer as shown below.
4. When the heater current is large, power may be lost in the small wires feeding the heater.

Resistance of #36 copper wire: 0.415 Ω/ft.

A total of about 4 ft of #36 wire is used to connect the heater to the power supply. This wire creates a 1.66 Ω load on the power supply.

If the current is 100 mA, then the power lost in the wires is 166 mW.

5. Thickness of the plating material is at best a close approximation and may not be uniform over the length of the waveguide.

4.9 Possible Improvements.

1. Use a 20 K and a 77 K heat shield around the waveguide. Radiation effects should be greatly attenuated by use of the additional shield.

2. The outside of the waveguide and the inside of the heat shield should be highly polished. This action should reduce radiation loading.

3. Use more accurate temperature sensing elements.

<table>
<thead>
<tr>
<th>WAVEGUIDE PARAMETERS</th>
<th>WAVEGUIDE PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRINCIPLE MATERIAL...COPPER TE</td>
<td>PRINCIPLE MATERIAL...COPPER TE</td>
</tr>
<tr>
<td>SOURCE TEMPERATURE 55 (KELVIN)</td>
<td>SOURCE TEMPERATURE 56 (KELVIN)</td>
</tr>
<tr>
<td>SINK TEMPERATURE 16.7 (KELVIN)</td>
<td>SINK TEMPERATURE 16.7 (KELVIN)</td>
</tr>
<tr>
<td>LENGTH 11.43 (CM)</td>
<td>LENGTH 11.43 (CM)</td>
</tr>
<tr>
<td>DIM A 1.27(CM)</td>
<td>DIM A 1.27(CM)</td>
</tr>
<tr>
<td>DIM B .635(CM)</td>
<td>DIM B .635(CM)</td>
</tr>
<tr>
<td>TOTAL WALL THICKNESS .1016 (CM)</td>
<td>TOTAL WALL THICKNESS .1016 (CM)</td>
</tr>
<tr>
<td>CROSS-SECTION AREA</td>
<td>CROSS-SECTION AREA</td>
</tr>
<tr>
<td>COPPER TE .34580576 (SQ CM)</td>
<td>COPPER TE .34580576 (SQ CM)</td>
</tr>
<tr>
<td>THERMAL RESISTANCE (W/K)</td>
<td>THERMAL RESISTANCE (W/K)</td>
</tr>
<tr>
<td>COPPER TE 4.6190016</td>
<td>COPPER TE 4.63856223</td>
</tr>
<tr>
<td>TOTAL 4.6190016</td>
<td>TOTAL 4.63856223</td>
</tr>
<tr>
<td>HEAT FLOW (WATTS)</td>
<td>HEAT FLOW (WATTS)</td>
</tr>
<tr>
<td>COPPER TE 8.29183519</td>
<td>COPPER TE 8.4724529</td>
</tr>
<tr>
<td>TOTAL 8.29183519</td>
<td>TOTAL 8.4724529</td>
</tr>
</tbody>
</table>
5.0 CONCLUSION

WATER, the Waveguide Assembly Thermal Energy Routine, is an effort to compute the heat transfer through any general waveguide configuration. The program is structured to enable the user to calculate the needed information easily and efficiently. The calculations performed by WATER are considered to be reasonably accurate, the method used to test the program's validity is somewhat crude and many improvements must be made on the testing apparatus before close correlation will be witnessed. At present, the engineer may use the program as a tool to solve waveguide thermal loading problems encountered in the cryogenic world.

6.0 ACKNOWLEDGEMENTS

I wish to express my sincere thanks to Roger Norrod who mentioned the treasures that may exist under WATER and to Carl Chestnut for helping me prove the treasures are there.
APPENDIX A

List of Important Variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>AA (75, 2)</td>
<td>Thermal conductivity versus temperature table.</td>
</tr>
<tr>
<td>MS (6)</td>
<td>Material name list.</td>
</tr>
<tr>
<td>PA (6)</td>
<td>Integration results.</td>
</tr>
<tr>
<td>CC (75, 2)</td>
<td>Conductivity analysis array.</td>
</tr>
<tr>
<td>A</td>
<td>Dimension A (R).</td>
</tr>
<tr>
<td>B</td>
<td>Dimension B (R).</td>
</tr>
<tr>
<td>T</td>
<td>Total wall thickness.</td>
</tr>
<tr>
<td>OD</td>
<td>Outside diameter (C).</td>
</tr>
<tr>
<td>D1</td>
<td>Outside diameter of outer conductor (X).</td>
</tr>
<tr>
<td>D2</td>
<td>Outside diameter of inner conductor (X).</td>
</tr>
<tr>
<td>D3</td>
<td>Inside diameter of tube (X).</td>
</tr>
<tr>
<td>SD</td>
<td>Skin depth of plating (R), (C), (X, outer conductor).</td>
</tr>
<tr>
<td>SC</td>
<td>Skin depth of plating (R), (C), (X, inner conductor).</td>
</tr>
<tr>
<td>TCS</td>
<td>Total cross-sectional area (R), (C).</td>
</tr>
<tr>
<td>MCS</td>
<td>Principal material cross-sectional area (R), (C).</td>
</tr>
<tr>
<td>PCS</td>
<td>Plating cross-sectional area (C), (R).</td>
</tr>
<tr>
<td>L</td>
<td>Length.</td>
</tr>
<tr>
<td>M1</td>
<td>Outer conductor structural area (X).</td>
</tr>
<tr>
<td>P1</td>
<td>Outer conductor plating area (X).</td>
</tr>
<tr>
<td>M2</td>
<td>Inner conductor structural area (X).</td>
</tr>
<tr>
<td>P2</td>
<td>Inner conductor plating area (X).</td>
</tr>
<tr>
<td>R</td>
<td>Total thermal resistance.</td>
</tr>
<tr>
<td>R1</td>
<td>Resistance of outer conductor structural material (X).</td>
</tr>
<tr>
<td>R2</td>
<td>Resistance of outer conductor plating material (X).</td>
</tr>
<tr>
<td>R3</td>
<td>Resistance to inner conductor structural material (X).</td>
</tr>
<tr>
<td>R4</td>
<td>Resistance to inner conductor plating material (X).</td>
</tr>
<tr>
<td>RM</td>
<td>Main material thermal resistance (R), (C).</td>
</tr>
<tr>
<td>RP</td>
<td>Plating material thermal resistance (R), (C).</td>
</tr>
<tr>
<td>Q1</td>
<td>Heat flow through outer conductor structural material (X).</td>
</tr>
<tr>
<td>Q2</td>
<td>Heat flow through outer conductor plating material (X).</td>
</tr>
<tr>
<td>Q3</td>
<td>Heat flow through inner conductor structural material (X).</td>
</tr>
<tr>
<td>Q4</td>
<td>Heat flow through inner conductor plating material (X).</td>
</tr>
<tr>
<td>Q</td>
<td>Total heat flow.</td>
</tr>
<tr>
<td>QM</td>
<td>Heat flow through main material (R), (C).</td>
</tr>
<tr>
<td>QP</td>
<td>Heat flow through principal material (R), (L).</td>
</tr>
</tbody>
</table>

*****
PROGRAM LENGTH= 15204 BYTES       VARIABLES= 2517 BYTES
FREE MEMORY= 2758 BYTES
START=16385 LOMEM=31589 FREE=34097 STRING=36855 HIMEM=36864

10 REM *** WAVEGUIDE ASSEMBLY THERMAL ENERGY ROUTINE ***
20 REM      W.A.T.E.R
30 REM CREATED BY RICHARD F. BRADLEY
40 REM
50 REM
60 REM
70 HOME : PRINT "        W.A.T.E.R"
80 PRINT : PRINT : PRINT : PRINT
90 PRINT "        WAVEGUIDE ASSEMBLY"
100 PRINT "           THERMAL ENERGY ROUTINE"
110 FOR WW = 1 TO 1000
120 NEXT WW
130 REM <>><><><><><><><><><><><><><><><><><><><><><><><><><><>
140 REM <>    MONITOR PROGRAM <>
150 REM <>><><><><><><><><><><><><><><><><><><><><><><><><><><>
160 REM ** MEMORY LOCATION SHIFT **
170 PRINT CHR$(4);"BRUN LOMEM:" & LOMEM: 16384
180 HIMEH: 36864
190 POKE 1013,76: POKE 1014,12
200 POKE 1015,151: POKE 1016,76
210 POKE 1017,0: POKE 1018,151
220 REM ** INITIALIZE ARRAYS **
230 DIM AA(75,2): REM THERMAL CONDUCTIVITY ARRAY
240 DIM M$(6): REM MATERIAL LIST
250 DIM P$(6): REM INTEGRATION RESULTS
260 DIM CC(75,2): REM CONDUCTIVITY ANALYSIS
270 PI = 3.141592653589793
280 D$ = "": REM CTRL-D
290 Q = 0
300 REM ** DISPLAY OPTIONS **
310 TEXT : HOME
320 PRINT "          W.A.T.E.R": PRINT
330 PRINT "        MONITOR LEVEL"
340 PRINT : PRINT "(T) THERMAL CONDUCTIVITY ANALYSIS"
350 PRINT "(R) RECTANGULAR WAVEGUIDE HEAT FLOW"
360 PRINT "(C) CIRCULAR WAVEGUIDE HEAT FLOW"
370 PRINT "(X) COAXIAL TRANSMISSION LINE HEAT FLOW"
380 PRINT "(D) DISPLAY CALCULATION RESULTS"
390 PRINT "(I) CM TO INCHES"
400 PRINT "(H) INCHES TO CM"
410 PRINT "(E) EXIT PROGRAM"
420 GET O$
430 IF O$ = "I" THEN GOTO 4540
440 IF O$ = "C" THEN MM$ = "C": GOTO 560
450 IF O$ = "H" THEN GOTO 4600
460 IF O$ = "T" THEN GOTO 4680
470 IF O$ = "R" THEN MM$ = "R": GOTO 560
480 IF O$ = "D" AND Q > 0 THEN GOTO 3110
490 IF O$ = "E" THEN GOTO 5920
500 IF O$ = "X" THEN MM$ = "X": GOTO 560
510 GOTO 420
520 REM <>><><><><><><><><><><><><><><><><><><><><><><><><><><>
530 REM <> CALCULATION SECTION <>
540 REM <>><><><><><><><><><><><><><><><><><><><><><><><><><><>
550 REM ** INITIAL RUN THRU ROUTINES **
560 60SUB 690
570 60SUB 830
580 IF HH$ = "R" THEN 60SUB 1860: 60SUB 2330
590 IF HH$ = "C" THEN 60SUB 2000: 60SUB 2420
600 IF HH$ = "X" THEN 60SUB 2090: 60SUB 2560
610 60SUB 2740
620 60SUB 2810
630 IF HH$ = "C" OR HH$ = "R" THEN 60TO 3110
640 IF HH$ = "X" THEN 60TO 3410
650 60TO 310
660 REM +++++++++++++++++
670 REM + TEMPERATURE INPUT +
680 REM +++++++++++++++++
690 HOME : PV = 0
700 FOR I = 1 TO 6; PA(I) = 0
710 NEXT I
720 60UTPUT "ENTER SOURCE TEMPERATURE (KELVIN) "; SO
730 IF SO = 0 THEN 60TO 310
740 60UTPUT "ENTER SINK TEMPERATURE (KELVIN) "; SI
750 IF SI = 0 THEN 60TO 310
760 60TURN
770 REM ++++++++++++++++++++
780 REM + INTEGRATION SECTION +
790 REM ++++++++++++++++++++
800 REM + MATERIAL INPUT +
810 REM + MATERIAL INPUT +
820 REM ++++++++++++++++++++
830 HOME : SC = 0; SD = 0
840 FOR I = 1 TO 6; HH(I) = " "; NEXT I
850 IF HH$ = "X" THEN 60TO 970
860 60UTPUT "ENTER PRINCIPLE MATERIAL "; HH(1)
870 IF HH(1) = " " THEN 60TO 310
880 HOME
890 60UTPUT "IS WAVEGUIDE PLATED? "; Z$
900 IF Z$ = "NO" THEN 60TO 970
910 IF Z$ = "YES" THEN 60TO 930
920 60TO 880
930 60UTPUT "ENTER PLATING MATERIAL "; HH(2)
940 IF HH(2) = " " THEN 60TO 310
950 60UTPUT "DEPTH OF PLATING (CH) "; SD
960 IF SD = 0 THEN 60TO 310
970 IF HH$ < > "X" THEN 60TO 1200
980 HOME
990 60UTPUT "OUTER CONDUCTOR STRUCTURAL MATERIAL "; HH(1)
1000 HOME
1010 60UTPUT "INNER CONDUCTOR STRUCTURAL MATERIAL "; HH(2)
1020 HOME
1030 60UTPUT "IS OUTER CONDUCTOR PLATED "; Z$
1040 IF Z$ = "NO" THEN 60TO 1110
1050 IF Z$ = "YES" THEN 60TO 1070
1060 60TO 1020
1070 60UTPUT "OUTER CONDUCTOR PLATING "; HH(3)
1080 60UTPUT "DEPTH OF PLATING (CH) "; SD
1090 IF SD = 0 THEN 60TO 310
1100 HOME
1110 60UTPUT "IS INNER CONDUCTOR PLATED "; Z$
1120 IF Z$ = "NO" THEN 60TO 1200
1130 IF Z$ = "YES" THEN 60TO 1150
1140 60TO 1100
1150 60UTPUT "INNER CONDUCTOR PLATING "; HH(4)
1160 60UTPUT "DEPTH OF PLATING (CH) "; SC
1170 REM ****************************
1180 REM % RANGE SET %
1190 REM ****************************
1200 PV = 0: FOR I = 1 TO 6: PA(I) = 0: NEXT I
1210 PV = PV + 1
1220 IF M$(PV) = "" THEN GOTO 1720
1230 ROW = 0
1240 PRINT D$;"OPEN";H$(PV)
1250 ONERR GOTO 310
1260 PRINT D$;"READ";H$(PV)
1270 ROW = ROW + 1
1280 INPUT A(A(ROW,1))
1290 INPUT A(A(ROW,2))
1300 IF A(ROW,1) = 0 THEN GOTO 1330
1310 GOTO 1270
1320 REM ** RANGE SET **
1330 U1 = 0: K = 0
1340 FOR I = 1 TO ROW
1350 IF A(I,1) > = SI AND A(I,1) < = SO THEN GOTO 1380
1360 IF U1 = 1 THEN GOTO 1530
1370 GOTO 1610
1380 K = K + 1
1390 IF K = 1 AND SI < > A(I,1) THEN GOTO 1430
1400 U1 = 1
1410 A(A(I,1)) = A(A(I,1):A(A(I,2)) = A(A(I,2))
1420 GOTO 1610
1430 X1 = A(A(I,1)) - A(A(I - 1,1))
1440 X2 = A(A(I,2)) - A(A(I - 1,2))
1450 X3 = X2 / X1
1460 X4 = (SI - A(I,1)) * X3
1470 A(A(I,1)) = SI * A(I,2) = X4 + A(I - 1,2)
1480 K = K + 1
1490 A(A(I,1)) = A(I,1):A(A(I,2)) = A(I,2)
1500 X4 = (SI - A(I - 1,1)) * X3
1510 U1 = 1
1520 GOTO 1610
1530 IF SO = A(I - 1,1) THEN U1 = 0: GOTO 1610
1540 K = K + 1
1550 Y1 = A(I,1) - A(I - 1,1)
1560 Y2 = A(I,2) - A(I - 1,2)
1570 Y3 = Y2 / Y1
1580 Y4 = (SO - A(I - 1,1)) * Y3
1590 A(A(I,1)) = SO * A(I,2) = Y4 + A(I - 1,2)
1600 U1 = 0
1610 NEXT I
1620 REM ****************************
1630 REM % INTEGRATION %
1640 REM ****************************
1650 FOR J = 1 TO K - 1
1660 C = A(A(J + 1,1)) - A(A(J,1))
1670 D = (A(A(J + 1,2)) + A(A(J,2))) / 2
1680 PA(PV) = (C * D) + PA(PV)
1690 NEXT J
1700 PRINT D$;"CLOSE";H$(PV)
1710 GOTO 1210
1720 RETURN
1730 REM+++++++++++++++++++++++++
1740 REM +PLATING DEPTH REV.+
1750 REM+++++++++++++++++++++++++
1760 HOME
1770 IF M$ = "X" THEN GOTO 1800
1780 INPUT "NEW PLATING DEPTH" ; SD
1790 GOTO 1820
1800 IF SD < > 0 THEN INPUT "NEW OUTER COND PLATING DEPTH (CH)" ; SD
1810 IF SC < > 0 THEN INPUT "NEW INNER COND PLATING DEPTH (CH)" ; SC
1820 RETURN
1830 REM ++++++++++++++++++++++++++++++++++++++++++++++++++++
1840 REM + RECTANGULAR WAVEGUIDE DIMENSIONS +
1850 REM ++++++++++++++++++++++++++++++++++++++++++++++++++++
1860 HOME : HGR ; TEXT
1870 GOSUB 4110 : REM WAVEGUIDE GRAPHICS
1880 INPUT "DIMENSION A (CH) " ; A
1890 IF A$ = "X" THEN MM$ = "X" ; GOTO 560
1900 IF A = 0 THEN GOTO 310
1910 INPUT "DIMENSION B (CH) " ; B
1920 IF B = 0 THEN GOTO 310
1930 INPUT "TOTAL WALL THICKNESS (CH) " ; T
1940 IF T = 0 THEN GOTO 310
1950 TEXT
1960 RETURN
1970 REM ++++++++++++++++++++++++++++++++++++++++++++++++++++
1980 REM + CIRCULAR WAVEGUIDE DIMENSIONS +
1990 REM ++++++++++++++++++++++++++++++++++++++++++++++++++++
2000 TEXT ; HOME
2010 INPUT "OUTSIDE DIAMETER (CH) " ; OD
2020 IF OD = 0 THEN GOTO 310
2030 PRINT ; INPUT "TOTAL WALL THICKNESS (CH) " ; T
2040 IF T = 0 THEN GOTO 310
2050 RETURN
2060 REM ++++++++++++++++++++++++++++++++++++++++++++++++++++
2070 REM + COAX DIMENSION +
2080 REM ++++++++++++++++++++++++++++++++++++++++++++++++++++
2090 HOME
2100 PRINT "OUTSIDE DIA OF OUTER CONDUCTOR"
2110 PRINT ; INPUT "(CH) " ; D1
2120 IF D1 = 0 THEN GOTO 310
2130 HOME
2140 PRINT "OUTSIDE DIA OF INNER CONDUCTOR"
2150 PRINT " (CONDUCTOR + PLATING)"
2160 PRINT ; INPUT "CH) " ; D2
2170 IF D2 = 0 THEN GOTO 310
2180 HOME
2190 INPUT "IS INNER CONDUCTOR TUBULAR? " ; Z$
2200 IF Z$ = "NO" THEN GOTO 2250
2210 IF Z$ = "YES" THEN GOTO 2230
2220 GOTO 2180
2230 INPUT "INSIDE DIA OF TUBE (CM) " ; D3
2240 IF D3 = 0 THEN GOTO 310
2250 HOME
2260 PRINT "TOTAL WALL THICKNESS OF OUTER CONDUCTOR"
2270 PRINT ; INPUT "(CH) " ; T
2280 IF T = 0 THEN GOTO 310
2290 RETURN
2300 REM ++++++++++++++++++++++++++++++++++++++++++++++++++++
2310 REM + RECTANGULAR AREA ROUTINE +
2320 REM ++++++++++++++++++++++++++++++++++++++++++++++++++++
2330 TCS = 0 ; MCS = 0 ; PCS = 0
2340 TCS = (A * B) - (A - 2 * T) * (B - 2 * T)
2350 MCS = (A * B) - (A - 2 * (T - SD)) * (B - 2 * (T - SD))
2360 PCS = TCS - MCS
2370 RETURN
2380 REM ++++++++++++++++++++++++++++++++++++++++++++++++++++
2390 REM + CIRCULAR AREA CALCULATION +
2400 REM ++++++++++++++++++++++++++++++++++++++++
2410 TCS = 0;MCS = 0;PCS = 0
2420 A1 = 0;A2 = 0;A3 = 0
2430 A2 = PI * (OD / 2 - T) * (OD / 2 - T)
2440 A1 = PI * (OD / 2) * (OD / 2)
2450 TCS = A1 - A2
2460 A3 = PI * (OD / 2 - T + SD) * (OD / 2 - T + SD)
2470 MCS = A1 - A3
2480 PCS = TCS - MCS
2490 RETURN
2500 REM ++++++++++++++++++++++++++++++++++++++++
2510 REM + COAXIAL AREA ROUTINE +
2520 REM ++++++++++++++++++++++++++++++++++++++++
2530 H1 = 0;M2 = 0;P1 = 0;P2 = 0
2540 REM ** OUTER CONDUCTOR **
2550 REM PRINCIPLE
2560 A1 = PI * (D1 / 2) * (D1 / 2)
2570 A2 = PI * (D1 / 2 - T + SD) * (D1 / 2 - T + SD)
2580 H1 = A1 - A2
2590 REM PLATING
2600 A3 = PI * (D1 / 2 - T) * (D1 / 2 - T)
2610 P1 = A2 - A3
2620 REM ** INNER CONDUCTOR **
2630 REM PRINCIPLE
2640 A4 = (D2 / 2 - SC) * (D2 / 2 - SC) * PI
2650 A5 = (D3 / 2) * (D3 / 2) * PI
2660 H2 = A4 - A5
2670 REM PLATING
2680 A6 = (D2 / 2) * (D2 / 2) * PI
2690 P2 = A6 - A4
2700 RETURN
2710 REM ++++++++++++++++++++++++++++++++++++++++
2720 REM + LENGTH INPUT ROUTINE +
2730 REM ++++++++++++++++++++++++++++++++++++++++
2740 HOME
2750 INPUT "TOTAL LENGTH OF WAVEGUIDE (CH) ";L
2760 IF L = 0 THEN GOTO 310
2770 RETURN
2780 REM ++++++++++++++++++++++++++++++++++++++++
2790 REM + RESISTANCE CALCULATION +
2800 REM ++++++++++++++++++++++++++++++++++++++++
2810 R1 = 0;R2 = 0;R3 = 0;R4 = 0;R = 0
2820 IF MM# = "x" THEN GOTO 2870
2830 R = (L * (SO - SI)) / (MCS * PA(1) + PCS * PA(2))
2840 RM = (L * (SO - SI)) / (MCS * PA(1))
2850 IF PA(2) = 0 THEN GOTO 2870
2860 RP = (L * (SO - SI)) / (PCS * PA(2))
2870 IF MM# < > "x" THEN GOTO 2960
2880 R1 = (L * (SO - SI)) / (M1 * PA(1))
2890 IF PA(3) < > 0 THEN R2 = (L * (SO - SI)) / (P1 * PA(3))
2900 R3 = (L * (SO - SI)) / (M2 * PA(2))
2910 IF PA(4) < > 0 THEN R4 = (L * (SO - SI)) / (P2 * PA(4))
2920 R = L * (SO - SI) / (M1 * PA(1) + P1 * PA(3) + M2 * PA(2) + P2 * PA(4))
2930 REM ++++++++++++++++++++++++++++++++++++++++
2940 REM + HEAT FLOW CALCULATION +
2950 REM ++++++++++++++++++++++++++++++++++++++++
2960 IF MM# = "x" THEN GOTO 3010
2970 Q = (SO - SI) / R
2980 QM = (SO - SI) / RM
2990 IF PA(2) = 0 THEN GOTO 3010
3000 QP = (SO - SI) / RP
3010 IF MM$ < > "X" THEN GOTO 3070
3020 Q1 = (SO - SI) / R1
3030 IF R2 < > 0 THEN Q2 = (SO - SI) / R2
3040 Q3 = (SO - SI) / R3
3050 IF R4 < > 0 THEN Q4 = (SO - SI) / R4
3060 Q = (SO - SI) / R
3070 RETURN
3080 REM ++++++++++++++++++++++++++++++++++++++
3090 REM + DISPLAY OF PARAMETERS +
3100 REM ++++++++++++++++++++++++++++++++++++++
3110 IF MM$ = "X" THEN GOTO 3410
3120 HOME : PRINT " WAVEGUIDE PARAMETERS"
3130 PRINT "PRINCIPLE MATERIAL..."; M$(1)
3140 IF M$(2) = "" THEN GOTO 3160
3150 PRINT "PLATING MATERIAL..."; M$(2)
3160 PRINT "SOURCE TEMPERATURE "; SO$ ; "(KELVIN)"
3170 PRINT "SINK TEMPERATURE " ; SI$ ; "(KELVIN)"
3180 PRINT "LENGTH " ; jL$ ; "(CM)"
3190 IF MM$ = "R" THEN PRINT "DIM A " ; jA$ ; "(CH)" ; "j" ; DIM B "jB$" ; "(CM)"
3200 IF MM$ = "C" THEN PRINT "OUTSIDE DIAMETER=" ; OD$ ; "(CH)"
3210 PRINT "TOTAL WALL THICKNESS " ; jT$ ; "(CH)"
3220 IF M$(2) = "" THEN GOTO 3240
3230 PRINT "DEPTH OF PLATING " ; SO$ ; "(CM)"
3240 PRINT "CROSS-SECTION AREA"
3250 PRINT M$(1) ; "" ; jHCS$ ; "(SQ CH)"
3260 IF M$(2) = "" THEN GOTO 3280
3270 PRINT M$(2) ; "" ; jPCS$ ; "(SQ CH)"
3280 GET K$ #: IF DD$ = "P" THEN PR# 1
3290 HOME
3300 PRINT " THERMAL RESISTANCE (W/K)"
3310 PRINT M$(1) ; "" ; jRM
3320 IF M$(2) = "" THEN GOTO 3340
3330 PRINT M$(2) ; "" ; jRP
3340 PRINT "HEAT FLOW (WATTS)"
3350 PRINT M$(1) ; "" ; jQH
3360 IF M$(2) = "" THEN GOTO 3380
3370 PRINT M$(2) ; "" ; jQP
3380 PRINT "TOTAL " ; jQ
3390 GOTO 3750
3400 GOTO 3750
3410 HOME : PRINT " TRANSMISSION LINE PARAMETERS"
3420 PRINT "OUTER CONDUCTOR.. " ; M$(1)
3430 PRINT "INNER CONDUCTOR.. " ; M$(2)
3440 IF M$(3) < > "" THEN PRINT "OUTER CONDUCTOR PLATING.. " ; M$(3)
3450 IF M$(4) < > "" THEN PRINT "INNER CONDUCTOR PLATING.. " ; M$(4)
3460 PRINT "SOURCE TEMPERATURE " ; SO$ ; "(KELVIN)"
3470 PRINT "SINK TEMPERATURE " ; SI$ ; "(KELVIN)"
3480 PRINT "LENGTH " ; jL$ ; "(CH)"
3490 PRINT "OUTSIDE DIA. OF OUTER COND." ; DO$ ; "(CH)"
3500 PRINT "OUTSIDE DIA. OF INNER COND." ; D2$ ; "(CH)"
3510 IF D3 < > 0 THEN PRINT "INSIDE DIA. OF TUBE " ; D3$ ; "(CH)"
3520 PRINT "OUTER COND. WALL THICKNESS " ; jT$ ; "(CH)"
3530 IF M$(3) < > "" THEN PRINT "OUTER COND. PLAT. DEPTH " ; SD$ ; "(CH)"
3540 IF M$(4) < > "" THEN PRINT "INNER COND. PLAT. DEPTH " ; SC$ ; "(CH)"
3550 PRINT " CROSS-SECTIONAL AREA"
3560 PRINT "OUTER CONDUCTOR " ; jH1$ ; "(SQ CH)"
3570 PRINT "INNER CONDUCTOR ":H2:" (SQ CM)"
3580 IF M$(3) < > "" THEN PRINT "OUTER COND. PLAT ":P1:" (SQ CM)"
3590 IF M$(4) < > "" THEN PRINT "INNER COND. PLAT ":P2:" (SQ CM)"
3600 GET KK$: IF DD$ = "P" THEN PR# 1
3610 HOME
3620 PRINT "THERMAL RESISTANCE (KELVIN/WATT)"
3630 PRINT : PRINT "OUTER CONDUCTOR ":R1
3640 IF R2 < > 0 THEN PRINT "OUTER CONDUCT PLATING ":R2
3650 PRINT : PRINT "INNER CONDUCTOR ":R3
3660 IF R4 < > 0 THEN PRINT "INNER CONDUCTOR PLATING ":R4
3670 GET KK$: IF DD$ = "P" THEN PR# 1
3680 HOME
3690 PRINT "HEAT FLOW (WATTS)"
3700 PRINT : PRINT "OUTER CONDUCTOR ":Q1
3710 IF R2 < > 0 THEN PRINT "OUTER CONDUCT PLATING ":Q2
3720 PRINT "INNER CONDUCTOR ":Q3
3730 IF R4 < > 0 THEN PRINT "INNER CONDUCTOR PLATING ":Q4
3740 PRINT : PRINT "TOTAL HEAT FLOW ":Q
3750 PR# 0
3760 PRINT : PRINT "<RETURN> FOR OPTIONS": GET KK$
3770 REM ____________________________________________
3780 REM % DISPLAY OPTIONS %
3790 REM ____________________________________________
3800 HOME : PRINT "OPTIONS"
3810 PRINT : PRINT "(T) TEMPERATURE CHANGE"
3820 PRINT "(D) CROSS-SECTION DIMENSION CHANGE"
3830 PRINT "(M) MATERIAL CHANGE"
3840 PRINT "(L) LENGTH CHANGE"
3850 PRINT "(P) PRINT COPY OF RESULT"
3860 PRINT "(S) SKIN DEPTH CHANGE"
3870 PRINT "(E) EXIT TO MAIN PROGRAM"
3880 PRINT "(R) RETYPE RESULTS"
3890 GET DD$
3900 IF DD$ = "T" AND MM$ < "X" THEN GOSUB 690: PV = 0: GOSUB 1210:
60 SUB 2810: GOTO 3110
3910 IF DD$ = "T" AND MM$ = "X" THEN GOSUB 690: PV = 0: GOSUB 1210:
60 SUB 2810: GOTO 3410
3920 IF DD$ = "D" AND MM$ = "R" THEN GOSUB 1860: GOSUB 2330: GOSUB
2810: GOTO 3110
3930 IF DD$ = "D" AND MM$ = "C" THEN GOSUB 2000: GOSUB 2410: GOSUB
2810: GOTO 3110
3940 IF DD$ = "D" AND MM$ = "X" THEN GOSUB 2690: GOSUB 2530: GOSUB
2810: GOTO 3410
3950 IF DD$ = "L" AND MM$ < "X" THEN GOSUB 2740: GOSUB 2810: GOTO
3110
3960 IF DD$ = "L" AND MM$ = "X" THEN GOSUB 2740: GOSUB 2810: GOTO
3410
3970 IF DD$ = "P" AND MM$ < "X" THEN PR# 1: GOTO 3110
3980 IF DD$ = "P" AND MM$ = "X" THEN PR# 1: GOTO 3410
3990 IF DD$ = "R" AND MM$ < "X" THEN GOTO 3110
4000 IF DD$ = "R" AND MM$ = "X" THEN GOTO 3410
4010 IF DD$ = "H" AND MM$ < "X" THEN GOSUB 830: GOSUB 2810: GOTO
3110
4020 IF DD$ = "H" AND MM$ = "X" THEN GOSUB 830: GOSUB 2530: GOSUB
2810: GOTO 3410
4030 IF DD$ = "S" AND SD < 0 AND MM$ = "R" THEN GOSUB 1760: GOSUB
2330: GOSUB 2810: GOTO 3110
4040 IF DD$ = "S" AND SD > 0 AND MM$ = "C" THEN GOSUB 1760: GOSUB
2410: GOSUB 2810: GOTO 3110
4050 IF DD$ = "S" AND MM$ = "X" AND SD > 0 THEN GOSUB 1760: GOSUB
2530: GOSUB 2810: GOTO 3410
4060 IF DD$ = "E" THEN GOTO 310
4070 GOTO 3800
4090 REM +++++++++++++++++++++++++++++++++++++++
4090 REM + WAVEGUIDE GRAPHICS  +
4100 REM +++++++++++++++++++++++++++++++++++++++
4110 HGR
4120 HPLIT 41.91 TO 99.91
4130 HPLIT 99.91 TO 99.129
4140 HPLIT 41.129 TO 99.129
4150 HPLIT 41.91 TO 41.129
4160 HPLIT 46.96 TO 94.96
4170 HPLIT 46.96 TO 46.124
4180 HPLIT 46.124 TO 94.124
4190 HPLIT 94.96 TO 94.124
4200 HPLIT 181.21 TO 239.21
4210 HPLIT 239.21 TO 239.59
4220 HPLIT 41.91 TO 181.21
4230 HPLIT 99.91 TO 239.21
4240 HPLIT 99.129 TO 239.59
4250 HPLIT 46.124 TO 94.101
4260 HPLIT 67.141 TO 67.145
4270 HPLIT 71.141 TO 71.145
4280 HPLIT 68.142 TO 70.142
4290 HPLIT 69.139
4300 HPLIT 68.140
4310 HPLIT 70.140
4320 HPLIT 99.140 TO 99.144
4330 HPLIT 41.140 TO 41.144
4340 HPLIT 25.109 TO 25.115
4350 HPLIT 25.109 TO 27.109
4360 HPLIT 25.112 TO 27.112
4370 HPLIT 25.115 TO 27.115
4380 HPLIT 28.110 TO 28.111
4390 HPLIT 28.113 TO 28.114
4400 HPLIT 25.91 TO 29.91
4410 HPLIT 25.129 TO 29.129
4420 HPLIT 175.106 TO 175.112
4430 HPLIT 175.112 TO 179.112
4440 HPLIT 239.70 TO 239.74
4450 HPLIT 89.110 TO 92.110
4460 HPLIT 101.110 TO 104.110
4470 HPLIT 106.106 TO 110.106
4480 HPLIT 108.107 TO 108.113
4490 RETURN
4500 REM <><><><><><><><><><><><><><><><><><><>
4510 REM <- DATA CONVERSION CH-IN <-
4520 REM <><><><><><><><><><><><><><><><><><><>
4530 REM ** INCH TO CH **
4540 HOME
4550 INPUT "INPUT CH ";CH
4560 PRINT CH;" (CH)= ";CH / 2.54;" (INCHES)
4570 IF CH = 0 THEN GOTO 310
4580 GOTO 4550
4590 REM ** INCHES TO CH **
4600 HOME
4610 INPUT "INPUT INCHES ";IN
4620 PRINT IN;" (INCHES)= ";IN * 2.54;" (CM)
4630 IF IN = 0 THEN GOTO 310
4640 GOTO 4610
4650 REM <><><><><><><><><><><><><><><><><><><>
4660 REM <- DATA ANALYSIS SECTION <-
4670 REM <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<>
4680 REM THERMAL CONDUCTIVITY DATA
4690 D$ = "": REM CTRL-D
4700 HOME
4710 PRINT "THERMAL CONDUCTIVITY"
4720 PRINT "": PRINT
4730 PRINT "(P) PREVIOUSLY STORED DATA"
4740 PRINT "(N) NEW DATA FOR DISK"
4750 GET F$
4760 HOME
4770 INPUT "ENTER TYPE OF MATERIAL ": A$
4780 IF F$ = "P" THEN GOTO 4810
4790 IF F$ = "O" THEN GOTO 5800
4800 GOTO 310
4810 ROW = 0
4820 REM ** NEW DATA INPUT **
4830 HOME
4840 ROW = ROW + 1
4850 PRINT "ROW ": ROW$: PRINT
4860 INPUT "ENTER TEMPERATURE (KELVIN) ": TEMP
4870 IF TEMP = 0 THEN ROW = ROW - 1: GOTO 5100
4880 INPUT "ENTER CONDUCTIVITY (W/CM-K) ": C
4890 IF C = 0 THEN ROW = ROW - 1: GOTO 5100
4900 CC(ROW,1) = TEMP
4910 CC(ROW,2) = C
4920 GOTO 4830
4930 REM ** ERROR..TEMP OR CONDUCT **
4940 HOME
4950 INPUT "ENTER ROW OF ERROR ": ER
4960 INPUT "TEMP OR CONDUCT ": Z$
4970 IF Z$ = "TEMP" THEN GOTO 5020
4980 IF Z$ = "CONDUCT" THEN GOTO 5070
4990 PRINT "BAD ENTRY, TRY AGAIN"
5000 GOTO 4960
5010 REM ** TEMP CHANGE **
5020 HOME
5030 PRINT "OLD ENTRY ": CC(ER,1)
5040 INPUT "ENTER NEW TEMPERATURE ": CC(ER,1)
5050 GOTO 5100
5060 REM ** CONDUCTIVITY CHANGE **
5070 HOME
5080 PRINT "OLD ENTRY ": CC(ER,2)
5090 INPUT "ENTER NEW CONDUCTIVITY ": CC(ER,2)
5100 HOME
5110 REM ** OPTIONS DISPLAY **
5120 HOME
5130 PRINT "(H) MORE DATA (C) CHANGE DATA"
5140 PRINT "(D) DISPLAY DATA (S) STORE DATA"
5150 PRINT "(P) PRINT DATA (X) DELETE ROW"
5160 PRINT "(E) EXIT TO MONITOR"
5170 GET Q$
5180 IF Q$ = "E" THEN GOTO 5780
5190 IF Q$ = "H" THEN GOTO 4830
5200 IF Q$ = "C" THEN GOTO 4940
5210 IF Q$ = "D" THEN GOTO 5250
5220 IF Q$ = "S" THEN GOTO 5460
5230 IF Q$ = "P" THEN PR$: GOTO 5350
5240 IF Q$ = "X" THEN GOTO 5270
5250 GOTO 5120
5260 REM ** DELETE LINE ROUTINE **
5270 Q$ = 1
5280 HOME
5290 INPUT "DELETE ROW # ";LL
5300 IF LL = 0 THEN GOTO 5100
5310 CC(LL,1) = 10000
5320 QQ = QQ + 1
5330 GOTO 5290
5340 REM ** DISPLAY OF DATA **
5350 HOME
5360 PRINT ";A$
5370 PRINT
5380 PRINT "TEMPERATURE","CONDUCTIVITY"
5390 PRINT " KELVIN"," W/CH-K"
5400 PRINT
5410 FOR K = 1 TO ROW
5420 PRINT K;" ";CC(K,1);" ";CC(K,2)
5430 NEXT K
5440 PRINT
5450 PR# 0; GOTO 5130
5460 REM ** ORDERING ROUTINE **
5470 REM ** LOWEST TO HIGHEST TEMP **
5480 HOME; PRINT " ORDERING DATA"
5490 CH = 0
5500 FOR J = 1 TO ROW - 1
5510 IF CC(J,1) < = CC(J + 1,1) THEN GOTO 5590
5520 TEM(1,1) = CC(J,1)
5530 TEM(1,2) = CC(J,2)
5540 CC(J,1) = CC(J + 1,1)
5550 CC(J,2) = CC(J + 1,2)
5560 CC(J + 1,1) = TEM(1,1)
5570 CC(J + 1,2) = TEM(1,2)
5580 CH = 1
5590 NEXT J
5600 IF CH = 0 THEN GOTO 5620
5610 GOTO 5490
5620 FOR I = 1 TO ROW
5630 IF CC(I,1) = 10000 THEN CC(I,1) = 0;CC(I,2) = 0
5640 NEXT I
5650 REM ** STORE DATA ON DISK **
5660 PRINT D$;"OPEN";A$
5670 PRINT D$;"DELETE";A$
5680 PRINT D$;"OPEN";A$
5690 PRINT D$;"WRITE";A$
5700 FOR I = 1 TO ROW
5710 PRINT CC(I,1)
5720 PRINT CC(I,2)
5730 NEXT I
5740 CC(ROW + 1,1) = 0;CC(ROW + 1,2) = 0
5750 PRINT CC(ROW + 1,1)
5760 PRINT CC(ROW + 1,2)
5770 PRINT D$;"CLOSE";A$
5780 GOTO 310: REM ..TO MONITOR LEVEL
5790 REM ** READ DATA FROM DISK **
5800 HOME
5810 REM RETRIEVE THERMAL DATA
5820 ROW = 0
5830 PRINT D$;"OPEN";A$
5840 PRINT D$;"READ";A$
5850 ROW = ROW + 1
5860 INPUT CC(Row,1)
5870 INPUT CC(Row,2)
5880 IF CC(Row,1) = 0 THEN ROW = ROW - 1: GOTO 5900
5890 GOTO 5850
5900 PRINT D$;"CLOSE";A$
5910 GOTO 5100
5920 END : REM ..OF PROGRAM
5930 REM <> PRINTER SET-UP ROUTINE <>
5950 REM <> PRINTER SET-UP ROUTINE <>
5960 REM FORMATTED LIST
5970 POKE 33,33
5980 GOSUB 6090: REM TURN ON PRINTER
5990 DEF FN CT(AD) = PEEK(AD) + 256 * PEEK(AD + 1)
6000 SR = FN CT(103)
6010 LM = FN CT(105);FR = FN CT(108)
6020 HH = FN CT(115);ST = FN CT(111)
6030 PRINT "PROGRAM LENGTH= ";LM - SR;" BYTES VARIABLES= ";HH
- ST + FR - LM;" BYTES"
6040 PRINT "FREE MEMORY= ";ST - FR;" BYTES"
6050 PRINT "START=";SR;" LOMEM=";LM;" FREE=";FR;" STRING=";ST;" HIMEH=";HM
6060 PRINT
6070 LIST
6080 CALL 1013: END
6090 REM GOTO 60038 : REM FOR APPLE PRINTER
6100 REM FOLLOWING FOR TRENDCOM 200 PRINTER
6110 PR# 1: PRINT CHR$(0): REM FIRST CHARACTER NOT PRINTED
6120 POKE 1913,6: POKE 1785,72: REM MARGINS
6130 POKE 1657,80: REM LINE LENGTH
6140 RETURN
6150 REM FOR APPLE PRINTER
6160 PRINT CHR$(4);"PR#1"
6170 O$ = CHR$(17): REM PRINT O$ TO PRINT GRAPHICS
6180 POKE - 12524,0: REM BLACK ON WHITE
6190 POKE - 12528,7: REM DARK PRINT
6200 POKE - 12527,8: REM LEFT MARGIN
6210 RETURN
APPENDIX C

SKIN DEPTH VS. FREQUENCY GRAPH
FOR NON-MAGNETIC MATERIALS, THE VALUE OF SKIN DEPTH AS A FUNCTION OF FREQUENCY IS READ DIRECTLY FROM THE CHART.

FOR MAGNETIC MATERIALS THE VALUE OF $\delta$ FROM THE CHART MUST BE DIVIDED BY $\sqrt{\mu}$, WHERE $\mu$ IS THE PERMEABILITY AT THE FREQUENCY SPECIFIED.

THE CONDUCTIVITY OF SOME COMMON METALS:

- SILVER $61 \times 10^4$ MHOS/M
- COPPER 58
- GOLD 41
- ALUMINUM 35
- MAGNESIUM 22
- BRASS 15
- PLATINUM 9

10 $\times 10^4$ MHOS/METER (CONDUCTIVITY)
APPENDIX D

THERMAL CONDUCTIVITY DATA
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NBS MONOGRAPH 121 p. 257

THERMAL CONDUCTIVITY W/M·K

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<td>20</td>
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<td>1.91E-03</td>
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<td>1.96E-03</td>
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APPENDIX E

APPARATUS COMPONENT DATA
<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Available Configuration (See Pages 8 and 9)</th>
<th>Sensing Element Material</th>
<th>Heat Dissipation (at 0.2K and recommended operating current)</th>
<th>Usable Temperature Range</th>
<th>Operating Voltage Nominal Value</th>
<th>Sensitivity</th>
<th>Interchangeability</th>
<th>Thermal Response (at 0.2K)</th>
<th>Repeatability</th>
<th>Input Field Effect (at 0.2K)</th>
<th>Reliability</th>
<th>Ageing Temperature Stability</th>
<th>Temp. Readout Accuracy</th>
<th>Remarks</th>
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<tr>
<td>Diode Thermometry</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Gallium Arsenide</td>
<td>15 µW</td>
<td>1 Ω to 300 K</td>
<td>0.6 mV/K</td>
<td>42 K at 77 K</td>
<td>77 K at 2.75 mV/K</td>
<td>See Fig. 2, 4</td>
<td>N.A.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Silicon</td>
<td>250 µW</td>
<td>1 Ω to 300 K</td>
<td>0.4 V</td>
<td>10 K at 50 K</td>
<td>50 mV/K</td>
<td>See Fig. 1, 4</td>
<td>10 K at 50 K</td>
<td>N.A.</td>
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<td></td>
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<tr>
<td>Capacitance Thermometry</td>
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<td></td>
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<td></td>
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<tr>
<td>Strontium Titanate</td>
<td>200 mW</td>
<td>1 Ω to 300 K</td>
<td>250 pF/K</td>
<td>42 K</td>
<td>See Fig. 3</td>
<td>See Fig. 3</td>
<td>N.A.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Resistance Thermometry</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Glass</td>
<td>CGR-1 (2000)</td>
<td>0.3 µW</td>
<td>1 Ω to 2000 ohm</td>
<td>1000 ohm</td>
<td>See Figs. 4, 5, 7</td>
<td>Consult Factory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Germanium</td>
<td>GR-200A-1000 or GR-2000-1000</td>
<td>0.3 µW</td>
<td>300 ohm</td>
<td>300 ohm</td>
<td>See Figs. 4, 5, 7</td>
<td>Limited with Bridge Techniques</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Rhodium with 0.5 atomic % iron</td>
<td></td>
<td></td>
<td>20.47 ohm</td>
<td>20.47 ohm</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Platinum</td>
<td>22 K</td>
<td>100 ohms</td>
<td>0.00035°C</td>
<td>273.2 K</td>
<td>N.A.</td>
<td>N.A.</td>
<td>-9 K at 20 K</td>
<td>Excellent</td>
<td>100 µV</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**LAKE SHORE CRYOTRONICS**

**ASK FOR BULLETIN "CRYOGENIC INSTRUMENTATION" FROM LAKE SHORE CRYOTRONICS, INC.**
Figure 1: Detailed Response of DT-500 Silicon Diode Temperature Sensor

Figure 2: Comparison of typical forward voltage versus temperature characteristics for the gallium arsenide (GaAs) and silicon (Si) diode thermometers.

Figure 3: Typical capacitance temperature characteristics for SrTiO₃ capacitance thermometers.

Figure 4: Temperature sensitivity of voltage (dV/dT) as a function of temperature for silicon (Si) and gallium arsenide (GaAs) diodes (solid and dotted line) thermometers and carbon glass (CG) (solid line), germanium (Ge) (dotted line), and platinum (Pt) (R₀ = 470 ohms) resistors. Numbers for resistors indicate current in microamperes. Diode thermometer data is at 10 microamperes.

Temperature Sensitivity of Voltage (dV/dT) vs Temperature

<table>
<thead>
<tr>
<th>Material</th>
<th>2.5</th>
<th>5</th>
<th>10</th>
<th>15</th>
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<tr>
<td>Magnetic Field-Tesla</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>TG-100</td>
<td>-13</td>
<td>-8</td>
<td>-2.25</td>
<td>N.R.*</td>
</tr>
<tr>
<td>GaAs</td>
<td>-3.15</td>
<td></td>
<td>N.R.*</td>
<td></td>
</tr>
<tr>
<td>DT-500 Silicon</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>CS-400 SrTiO₃</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>CGR Carbon Glass</td>
<td>-0.02</td>
<td>-0.06</td>
<td>-0.17</td>
<td>-0.28</td>
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<tr>
<td>GR-200 Germanium</td>
<td>-0.8</td>
<td>-1.6</td>
<td>-2.5</td>
<td>-3.0</td>
</tr>
</tbody>
</table>

*N.R.* = Not Recommended

Figure 5: Relative sensitivity data (d(lnR)/dT) versus temperature for carbon glass (CG) and germanium (Ge) resistors.

Figure 6: Typical Magnetic Field Induced Temperature Errors at Selected Field Levels at 4.2 K.

Figure 7: Resistance-temperature characteristics of the germanium (Ge), platinum (Pt) (R₀ = 1380 ohms), and carbon glass (CG) resistors.
<table>
<thead>
<tr>
<th>SENSOR SERIES DESIGNATION</th>
<th>REF. NO.</th>
<th>LEAD IDENT. AND ISOLATION</th>
<th>CONFIGURATION</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>LEAD</th>
<th>WEIGHT</th>
<th>ENDURATION MATERIALS</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TG-100K DT-500K</td>
<td>1</td>
<td>Cathode is at case potential</td>
<td>Tab index is anode</td>
<td>.25</td>
<td>.6</td>
<td>.8</td>
<td>1.5</td>
<td>.10</td>
<td>2</td>
<td>Gold Plated Kovar TO-46 Package</td>
<td>.019</td>
<td>.32 gr</td>
</tr>
<tr>
<td>DT-500K-L</td>
<td>2</td>
<td>Both leads isolated</td>
<td>Tab index is anode</td>
<td>.25</td>
<td>.6</td>
<td>.8</td>
<td>1.5</td>
<td>.10</td>
<td>2</td>
<td>Gold Plated Kovar TO-46 Package</td>
<td>.019</td>
<td>.3 gr</td>
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<tr>
<td>TG-100K-L</td>
<td>3</td>
<td>Both leads isolated</td>
<td>Tab index is anode</td>
<td>.25</td>
<td>.6</td>
<td>.8</td>
<td>1.5</td>
<td>.10</td>
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<td>TG-100P DT-500P</td>
<td>4</td>
<td>Cathode is at case potential</td>
<td>Anode is shorter lead</td>
<td>.15</td>
<td>3.6</td>
<td>1.65</td>
<td>1.0</td>
<td>.06</td>
<td>2</td>
<td>Gold Plated Kovar TO-46 Package</td>
<td>.019</td>
<td>.16 gr</td>
</tr>
<tr>
<td>TG-100K-T95 DT-500K-T95</td>
<td>5</td>
<td>Cathode is at case potential</td>
<td>Tab index is anode</td>
<td>.137</td>
<td>3.6</td>
<td>1.0</td>
<td>.10</td>
<td>2</td>
<td>Gold Plated Kovar TO-46 Package</td>
<td>.019</td>
<td>.137 gr</td>
<td>Gold Plated Kovar TO-46 Parkase in 0.32 x 0.32 x 0.32 inch thick aluminum head cover screw</td>
</tr>
<tr>
<td>TG-100K-L-T95 DT-500K-L-T95</td>
<td>6</td>
<td>Both leads isolated</td>
<td>Tab index is anode</td>
<td>.137</td>
<td>3.6</td>
<td>1.0</td>
<td>.10</td>
<td>2</td>
<td>Gold Plated Kovar TO-46 Package</td>
<td>.019</td>
<td>.14 gr</td>
<td>Gold Plated Kovar TO-46 Parkase in 0.32 x 0.32 x 0.32 inch thick aluminum head cover screw</td>
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<tr>
<td>DT-500P IGR-MIN/1 DT-500 DRC</td>
<td>7</td>
<td>Standard version</td>
<td>Same as Ref #4</td>
<td>.06</td>
<td>1.5</td>
<td>4.1</td>
<td>1.0</td>
<td>.294</td>
<td>2</td>
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<td>.005</td>
<td>.045 gr</td>
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<tr>
<td>TG-100P IGR DT-500P-GR</td>
<td>8</td>
<td>Standard version</td>
<td>Same as Ref #4</td>
<td>.12</td>
<td>3.5</td>
<td>8.9</td>
<td>1.0</td>
<td>.06</td>
<td>2</td>
<td>Gold Plated Kovar TO-46 Package</td>
<td>.019</td>
<td>.19 gr</td>
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<tr>
<td>TG-100PF DT-500PF</td>
<td>9</td>
<td>Gold lead—anode</td>
<td>Flat lead—cathode</td>
<td>.06</td>
<td>1.5</td>
<td>—</td>
<td>1.0</td>
<td>.25</td>
<td>1</td>
<td>Gold Plated Kovar TO-46 Package</td>
<td>.005</td>
<td>25 mg</td>
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<td>DRD-10, GR-200A</td>
<td>10</td>
<td>See Installation &amp; Application Notes</td>
<td>For Cryogenic Sensors</td>
<td>.120</td>
<td>3.05</td>
<td>8.5</td>
<td>6</td>
<td>0.025</td>
<td>0-6</td>
<td>4</td>
<td>Porcelain Insulation</td>
<td>32 AWG</td>
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<tr>
<td>GR-200B</td>
<td>11</td>
<td>See Installation &amp; Application Notes</td>
<td>For Cryogenic Sensors</td>
<td>.063</td>
<td>2.36</td>
<td>6.1</td>
<td>6</td>
<td>0.025</td>
<td>0-6</td>
<td>4</td>
<td>Porcelain Insulation</td>
<td>32 AWG</td>
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<td>CS-400 GR</td>
<td>12</td>
<td>Interchangeable—</td>
<td>Leads have no polarity</td>
<td>.125</td>
<td>3.18</td>
<td>8.5</td>
<td>6</td>
<td>0.025</td>
<td>0-6</td>
<td>4</td>
<td>Copper</td>
<td>32 AWG</td>
</tr>
<tr>
<td>CS-400FP</td>
<td>13</td>
<td>Interchangeable—</td>
<td>Leads have no polarity</td>
<td>A = 0.107</td>
<td>2.7</td>
<td>0.044</td>
<td>1.1</td>
<td>.06</td>
<td>2</td>
<td>Copper</td>
<td>32 AWG</td>
<td>0.13 gr</td>
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<tr>
<td>DT-500-CU-58 DT-500-CU-DRC-95</td>
<td>14</td>
<td>Leads are Heat Sensed for Cryogenic medium</td>
<td>No ferromagnetic materials are utilized in the construction of these sensors</td>
<td>.313</td>
<td>8</td>
<td>1.30</td>
<td>3.3</td>
<td>.10</td>
<td>2</td>
<td>Copper and Phosphor Bronze</td>
<td>32 AWG</td>
<td>1.45 gr</td>
</tr>
</tbody>
</table>

OTHER CONFIGURATIONS ENGINEERED ON REQUEST
MINIATURE HEATER-BUTTONS

1. **Provide Localized, Concentrated Heat** . . . give you localized heat in minimum space . . . just .750" diameter and only .180" or .165" thick.

2. **Application Versatility** . . . ideal heat source for small mechanical, electrical or electronic assemblies and components such as gyro's, valves, relays, crystal ovens, instruments, circuits, thermal time delays, for laboratory and medical use, cryogenics temperature control, etc.

3. **Installation Simplicity** . . . lets you put heat where you need it . . . simple to install on flat surface with #2 machine screw or high temperature cement.

4. **“Off-Shelf” Availability** . . . 2, 5, 10, 15 and 20 watt units at 28 and 115 volts available from stock for immediate shipment.

5. **Correct Wattage Easily Determined** . . . a special combination Heater-Sensor is available, from stock, for prototype work . . . lets you experimentally select the right wattage for your use . . . saves time, prevents errors.

6. **Custom Units Available** . . . you can specify non-standard voltage, wattage for your critical or special applications.

Minco's Miniature Heater-Buttons are a widely accepted means for providing concentrated, localized heat in minimum space, and give you a reliable method of warming to operating temperature such mechanical, electrical or electronic devices as valves, gyro's, relays, crystal ovens, instruments, circuit modules, thermal time delay devices, etc. They are easily mounted by means of small (#2) machine screw or high temperature cement, or the Model H7A units can be clamped between surfaces.

In conjunction with temperature controls, the Heater-Buttons can be used to maintain devices at precise temperature levels for critical applications. Minco's Heater-Buttons are widely used as heat sources for aero-space, laboratory and commercial applications.

Three standard models, each available for immediate delivery in 5 power ratings and in both 28 and 115 volt versions, offer the user a choice of regular, low silhouette, and environmentally sealed units. Other wattages and voltages are available on special order. To help you select the proper Heater-Button, and for other experimental or temperature sensing purposes, a special combination Heater-Sensor Button, the HS4A100, is available from stock for your prototype work. You can experimentally select the right value of wattage for your application. Brief instructions for use are on the reverse side of this bulletin; complete instructions are included with each Heater-Sensor.

**H4A SERIES**

**H6A SERIES**

**H7A SERIES**

**H8A SERIES**

**SMALL, LIGHTWEIGHT**

- 0.750 diameter
- 0.180 or 0.165 thick
- 4 to 6 grams

**SIMPLE INSTALLATION**

Use #2 machine screw, high temperature cement, or clamp between surfaces.

**4 STANDARD STYLES**

1. Regular or
2. Solder-sealed with axial leads
3. Low-profile with radial leads
4. Low-profile immersible

**WIDE SELECTION**

40 standard models, plus special Heater-Sensor available from stock, 115 or 28 volts, 2, 5, 10, 15, 20 watts.

**EASY SELECTION**

Use Heater-Sensor model to determine wattage requirements.

**CUSTOM UNITS AVAILABLE**

Non-Standard voltage, wattage, lead lengths available on special order.

**THERMAL EFFICIENCY**

Solid internal structure, flat mounting surface give good thermal coupling, shock and vibration resistance.

**HIGH TEMPERATURE USE**

Usable to 500° F. (260° C.) element temperature.

**H8A SERIES**

Will meet moisture resistance and immersion per MIL-H-22577A.

**MINCO PRODUCTS, INC.**

7300 Commerce Lane / Minneapolis, Minnesota 55432 / TWX: 910-576-2848 / Telephone: (612) 571-3121
MINIATURE HEATER-BUTTONS

SPECIFICATIONS

<table>
<thead>
<tr>
<th>WATTAGE</th>
<th>MODEL NO. 115 Volts AC or DC</th>
<th>MODEL NO. 28 Volts AC or DC</th>
</tr>
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<tr>
<td></td>
<td>STANDARD (ENV. SEALED) LOW PROFILE</td>
<td>STANDARD (ENV. SEALED) LOW PROFILE</td>
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<tr>
<td></td>
<td>H4A2W115</td>
<td>H6A2W115</td>
</tr>
<tr>
<td>2</td>
<td>H4A5W115</td>
<td>H6A5W115</td>
</tr>
<tr>
<td>5</td>
<td>H4A10W115</td>
<td>H6A10W115</td>
</tr>
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<td>10</td>
<td>H4A15W115</td>
<td>H6A15W115</td>
</tr>
<tr>
<td>15</td>
<td>H4A20W115</td>
<td>H6A20W115</td>
</tr>
</tbody>
</table>

**HS4A100 HEATER-SENSOR**

HS4A100 Heater-Sensor has same dimensions as H4A Series. Element resistance is 100 ± 1 ohms at 0°C (32°F) and varies approximately .7 ohms per degree C. (approximately .39 ohms per degree F.) from 0°C to 200°C. A table of resistance versus temperature and instructions for use (Application Aid #5) are included with each unit.

**MAXIMUM POWER ALLOWABLE RELATIVE TO ELEMENT TEMPERATURE RISE ABOVE MOUNTING SURFACE TEMPERATURE**

The maximum power at which the Heater-Buttons can be used is determined by the temperature of the surface to which they are attached. To assist in evaluation of this factor, the above derating curve is used. Internal element temperature of all models is limited to 260°C (500°F) and therefore the sum of the temperature rise of the element, added to the temperature of the heated surface cannot exceed this figure. Please ask for Minco Application Aid #4 for detailed information.

The HS4A100 Heater-Sensor Button is used for prototype and empirical determination of the power required in an application. By operating the HS4A100 from an adjustable power source, the temperature of the element and the power required for an application can easily be determined by simple voltage and current measurement. Please ask for Minco Application Aid #5 for detailed instructions.

**POWER RATING DETERMINATION**

**PHYSICAL SPECIFICATIONS**

SIZE: 0.75" diameter, .165 or .180 thick maximum not including terminals. See dimensional sketch above.


LEADS: AWG#28, stranded, Teflon insulated, nominally 6" long.


MOUNTING: Clearance hole for #2 machine screw. Mounting surface must be flat and burr free for good thermal contact. A thermal transfer compound (Dow Corning Heat Sink Compound #340 or equivalent) should be used on mounting surface. Tighten to screw manufacturer's recommended torque.

IMMERSION: Immersion in non-conductive liquids is permissible. H6A and H8A Models are solder sealed to protect the element under adverse environment. Since the terminals are exposed on all models other than the H8A, precaution should be taken not to immerse terminals in conductive fluids. H8A Models meet moisture resistance and immersion per MIL-H-22577A.

WEIGHT: Standard and low profile models 4 grams max. Environmentally sealed models 6 grams max.
REFERENCES

