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R: THE WAVEGUIDE ASSEMBLY THERMAL ENERGY ROUTINE THERMAL CONDUCTIVITY

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WATER: THE WAVEGUIDE ASSEMBLY THERMAL ENERGY ROUTINE THERMAL CONDUCTIVITY

Richard F. Bradley

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Richard F. Bradley

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:

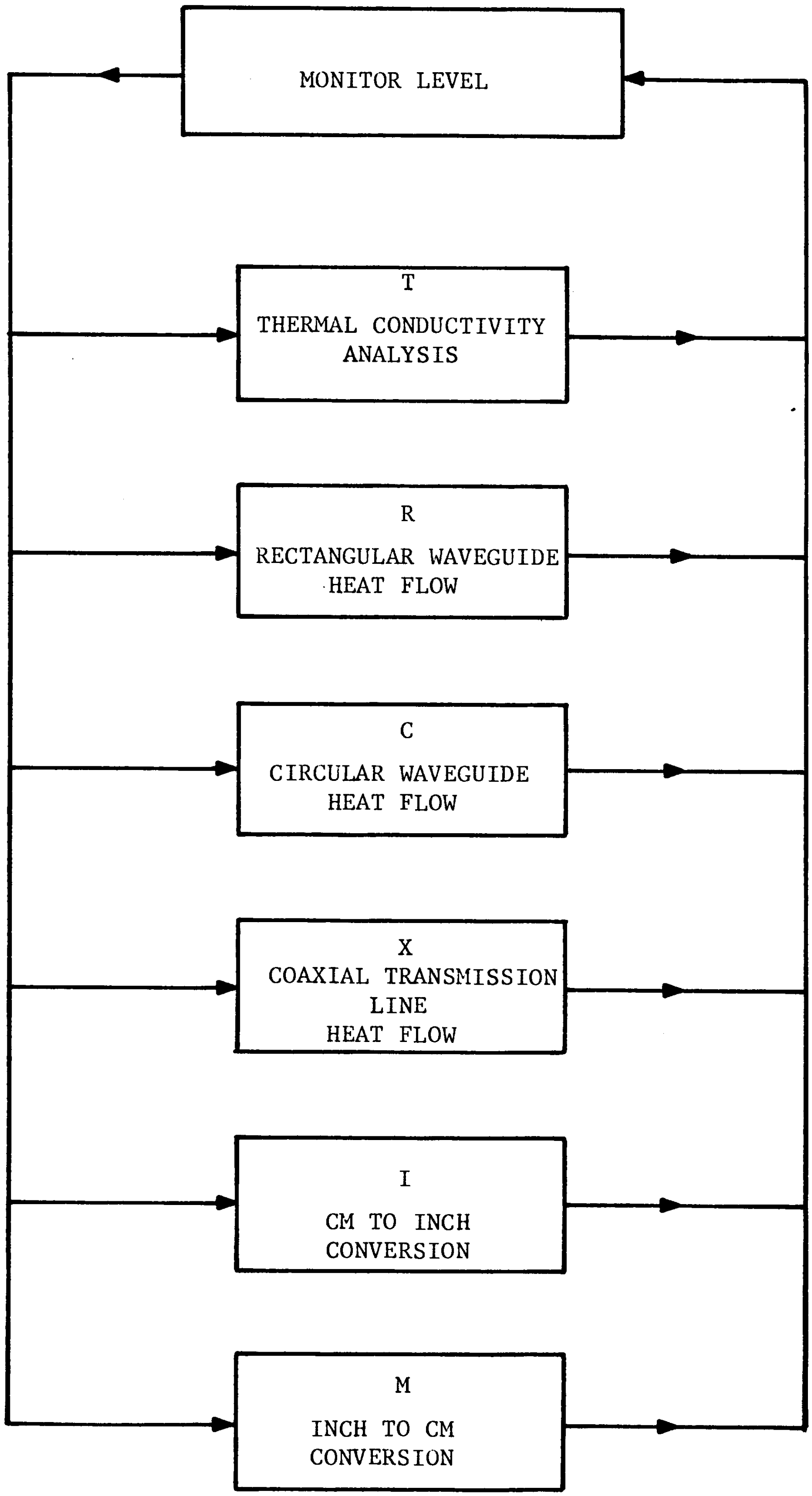


FIGURE 1

Sub-Level Diagram

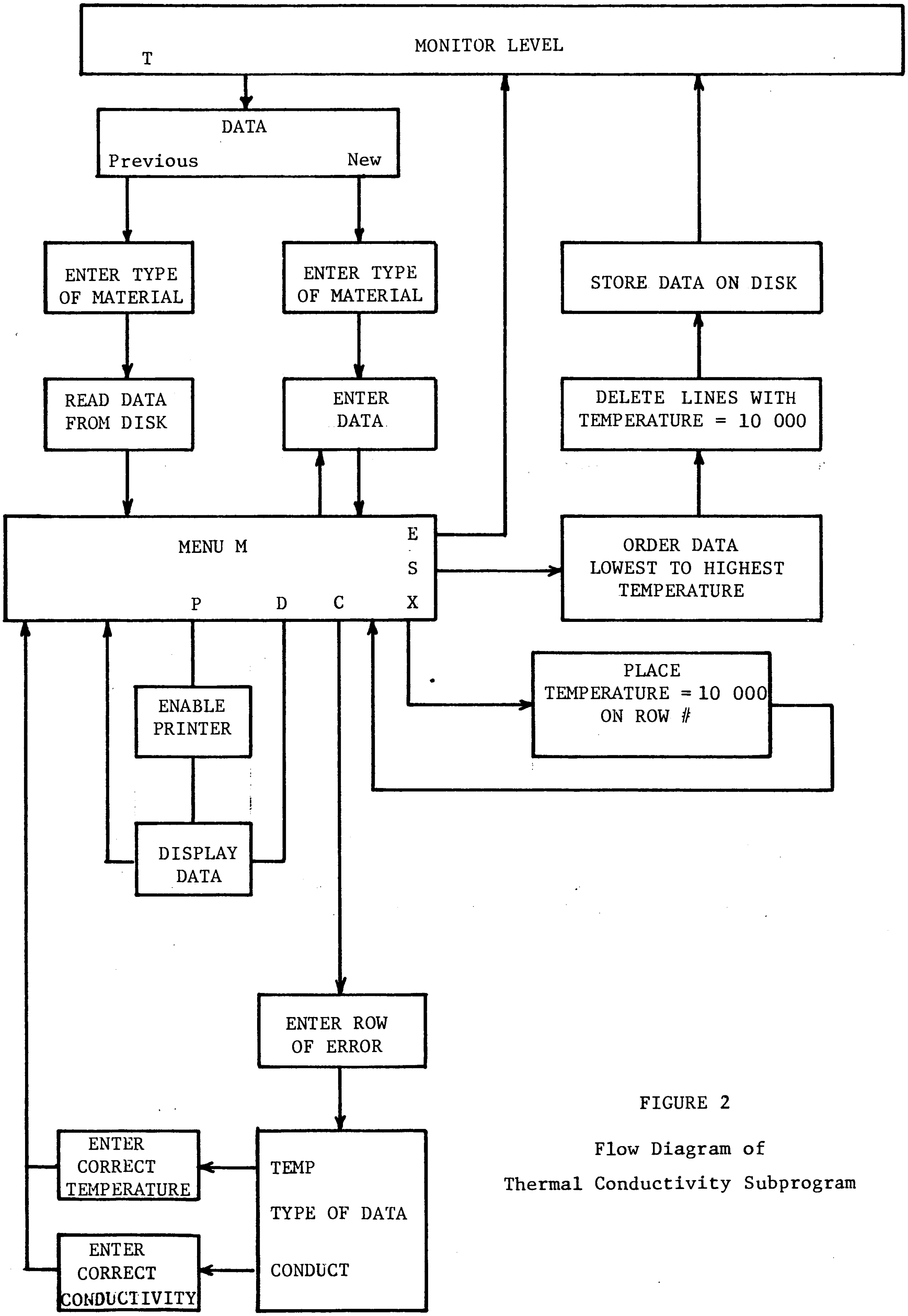


FIGURE 2

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.

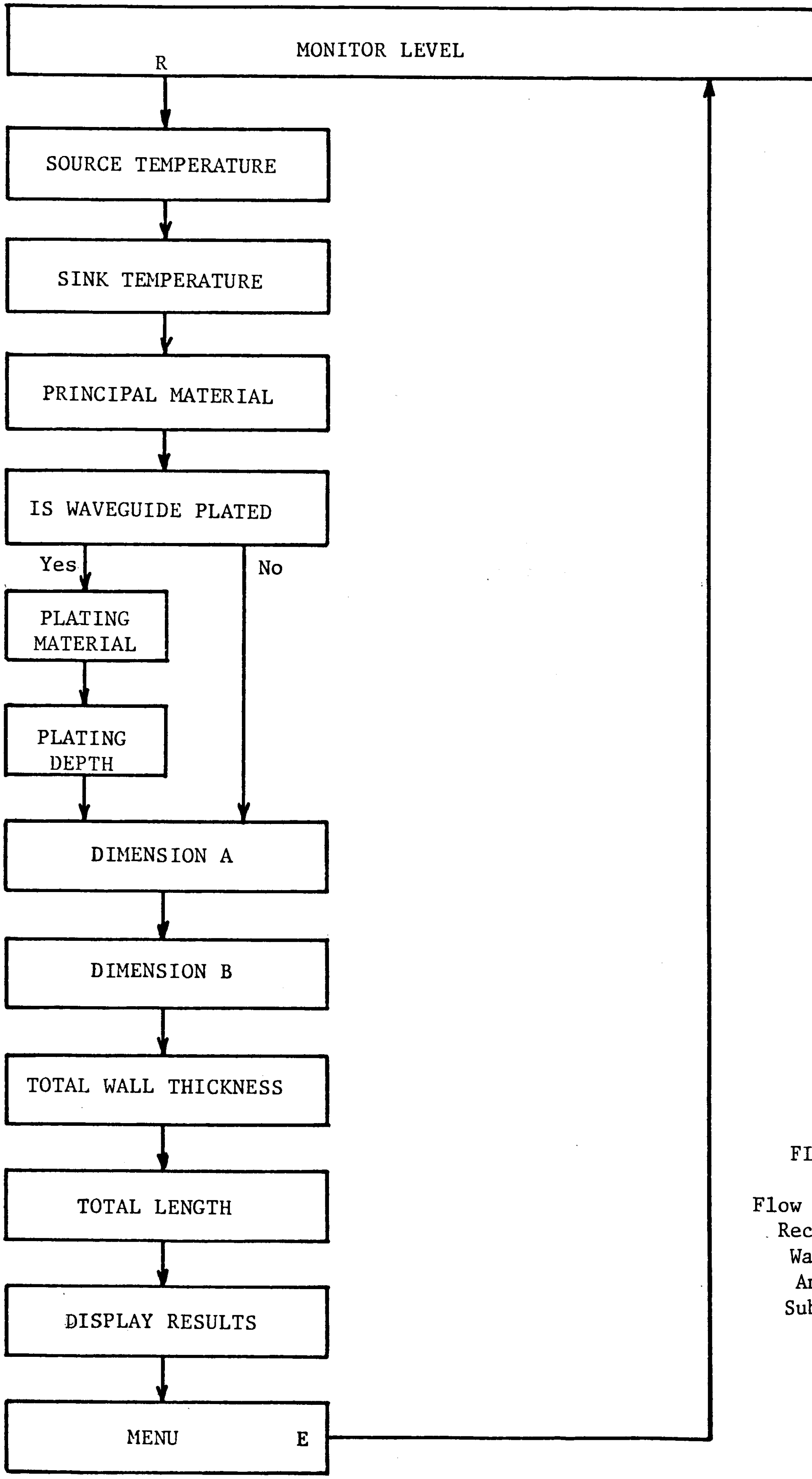


FIGURE 3

Flow Diagram of Rectangular Waveguide Analysis Subprogram

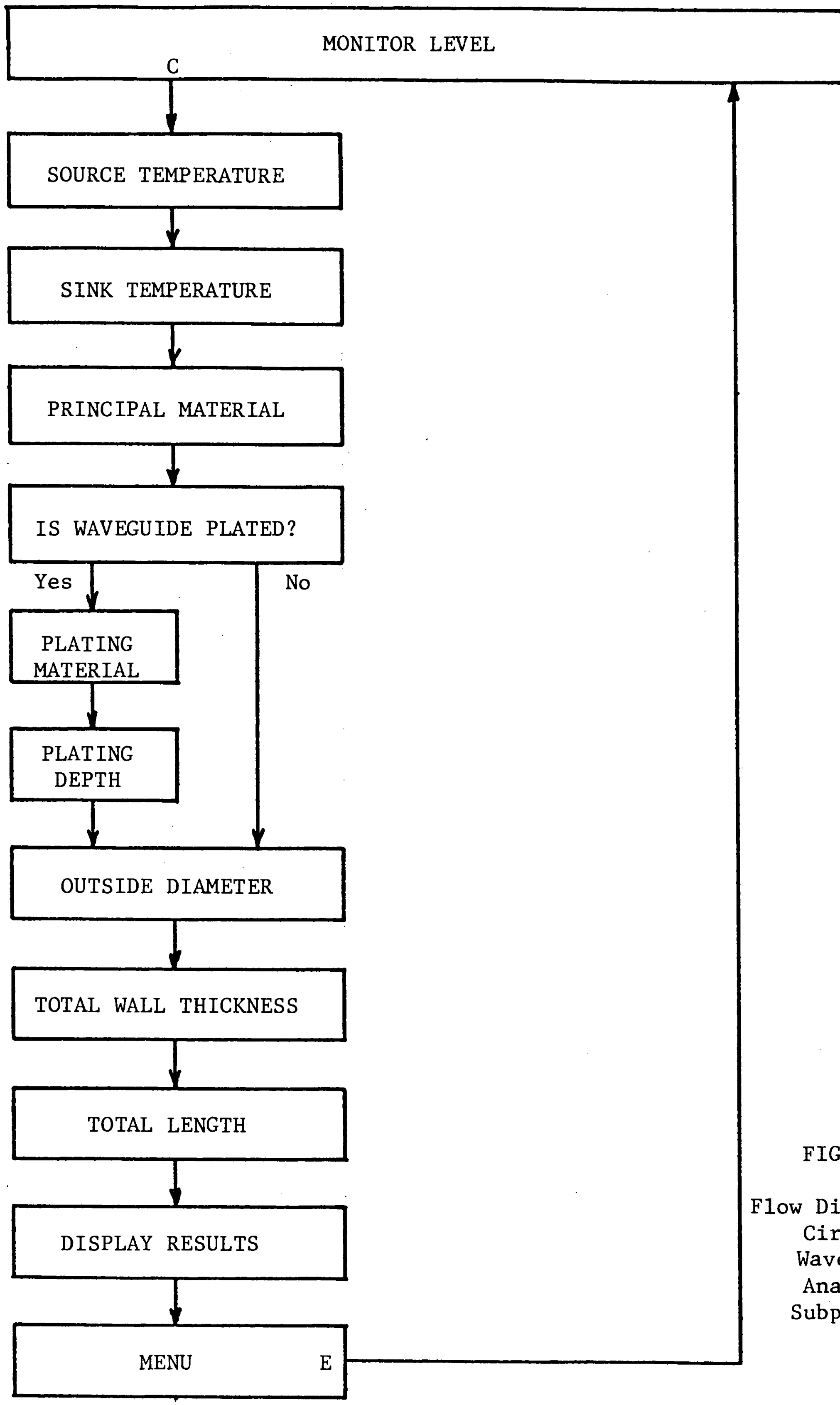


FIGURE 4

Flow Diagram Circular Waveguide Analysis Subprogram

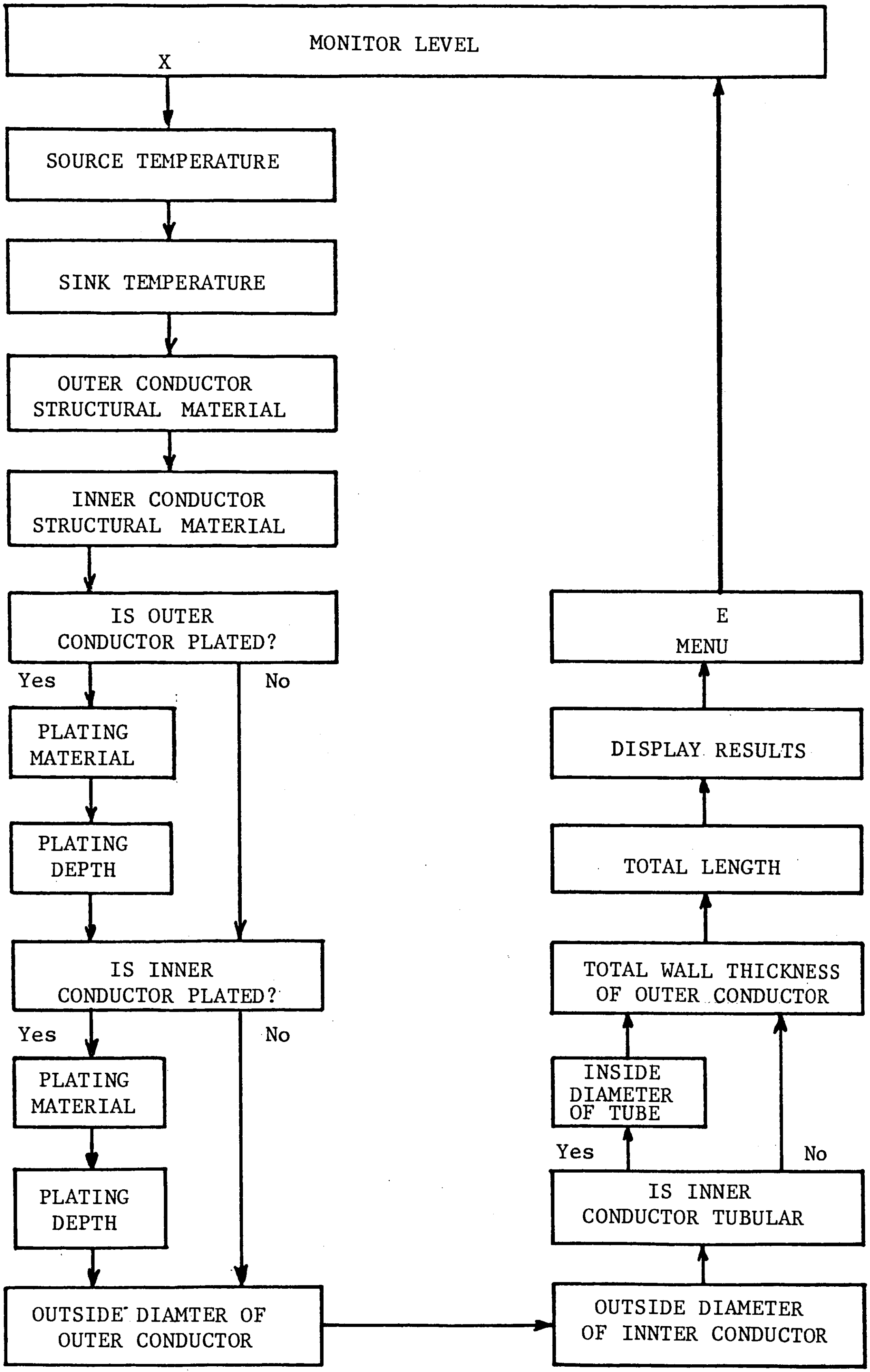


FIGURE 5

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".

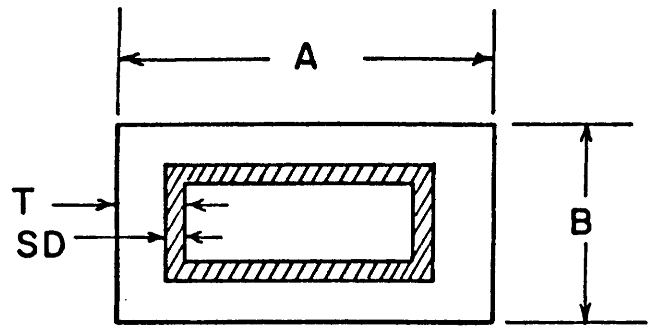
2.2.4 Length input.

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.

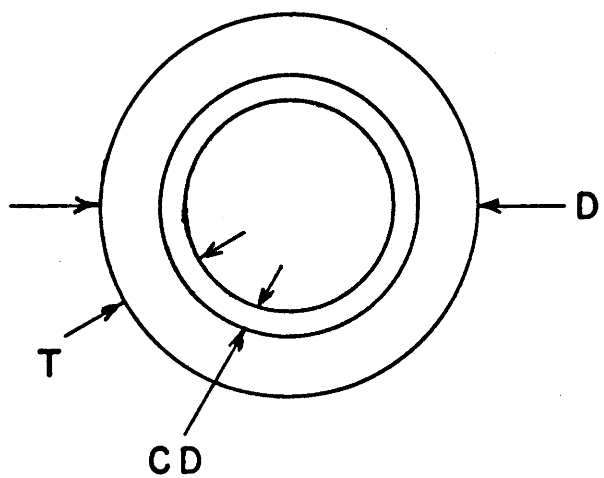
For each heat-flow sub-level, a unique display of the results follows each calculation routine. All three display the appropriate input parameters and the calculated thermal resistance and heat flow values. For the rectangular and circular waveguides, two CRT screens are used. The results for the coaxial

(a)



Detailed sketch of rectangular cross-section.

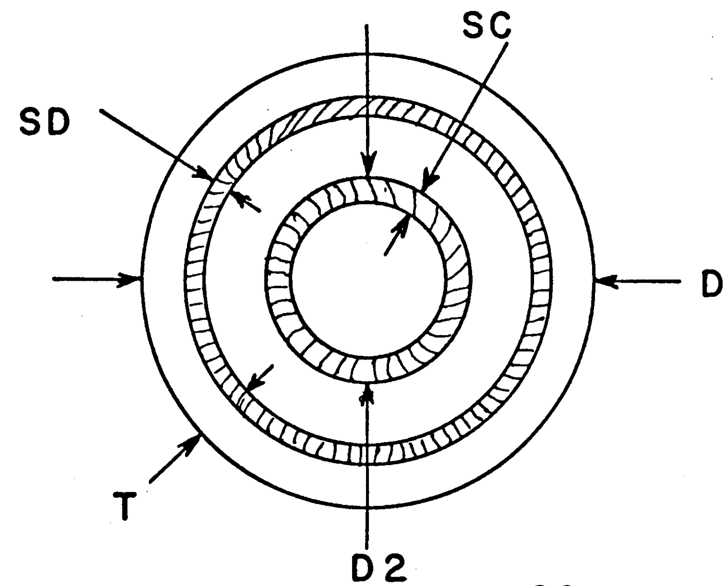
(b)



Detailed sketch of circular cross-section.

FIGURE 6

Sketch of Coaxial Transmission Line (Solid Center Conductor)



Sketch of Coaxial Transmission Line (Tubular Inner Conductor)

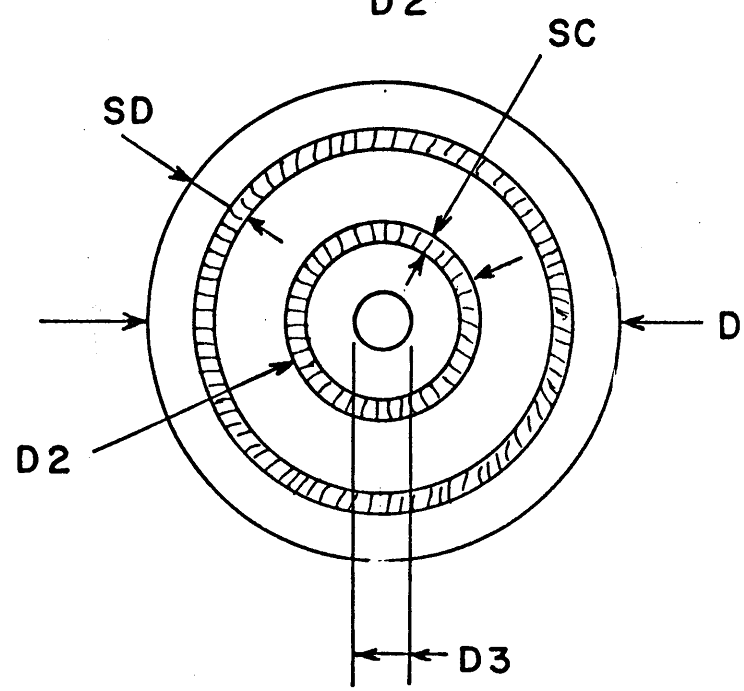


FIGURE 7

transmission line is displayed on three CRT screens. To move from one screen tc 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) Exist 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 dimensions 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 altered. 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.

Rectangul

WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...STAINLESS STEEL
PLATING MATERIAL...COPPER ETP
SOURCE TEMPERATURE 75 (KELVIN)
SINK TEMPERATURE 10 (KELVIN)
LENGTH 15.24 (CM)
DIM A .6223(CM)   DIM B .3353(CM)
TOTAL WALL THICKNESS .0254 (CM)
DEPTH OF PLATING 6E-05 (CM)

CROSS-SECTION AREA
STAINLESS STEEL .0459627056 (SQ CM)
COPPER ETP 1.02734397E-04 (SQ CM)

THERMAL RESISTANCE (W/K)
STAINLESS STEEL 6921.08415
COPPER ETP ~~32.8452868~~ 14694.7692
TOTAL 4705.05293

HEAT FLOW (WATTS)
STAINLESS STEEL 9.39159221E-03
COPPER ETP ~~1.87887496~~ 4.42334271E-03
TOTAL .0138149349

Circular

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

CROSS-SECTION AREA
STAINLESS STEEL .92460097 (SQ CM)
COPPER ETP 5.27191907E-04 (SQ CM)

THERMAL RESISTANCE (W/K)
STAINLESS STEEL 270.907888
COPPER ETP ~~1.28564356~~ 2254.79046
TOTAL 241.850148

HEAT FLOW (WATTS)
STAINLESS STEEL .239933952
COPPER ETP ~~50.5523368~~ .0288275125
TOTAL .268761464

Coaxial

TRANSMISSION LINE 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 (CM)
OUTSIDE DIA. OF OUTER COND.5 (CM)
OUTSIDE DIA. OF INNER COND. 3 (CM)
INSIDE DIA. OF TUBE 1 (CM)
OUTER COND. WALL THICKNESS .1016 (CM)
OUTER COND. PLAT. DEPTH 6E-05 (CM)
INNER COND. PLAT. DEPTH 6E-05 (CM)

CROSS-SECTIONAL AREA
OUTER CONDUCTOR 1.5625956 (SQ CM)
INNER CONDUCTOR 6.28261983 (SQ CM)
OUTER COND. PLAT 9.04195011E-04 (SQ CM)
INNER COND. PLAT 5.65476716E-04 (SQ CM)
THERMAL RESISTANCE (KELVIN/WATT)

OUTER CONDUCTOR 133.582065
OUTER CONDUCTOR PLATING 1095.5484

INNER CONDUCTOR 33.2241568
INNER CONDUCTOR PLATING 1751.77752
HEAT FLOW (WATTS)

OUTER CONDUCTOR .48659227
OUTER CONDUCTOR PLATING .0593310161
INNER CONDUCTOR 1.95640782
INNER CONDUCTOR PLATING .0371051684

TOTAL HEAT FLOW 2.53943627

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:

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

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:

$$Q = \frac{SO - SI}{R_m}$$

where SO = Source temperature.

SI = 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.

Waveguide #1

Material	Copper (TE)
Dimensions: A	1.27 cm
B	0.635 cm
T	0.1016 cm
Length	11.43 cm
Description	WR-42 waveguide with brass end flanges. Inside polished; outside is oxide coated.

Waveguide #2

Material	Copper (OFHC)
Dimensions: A	1.27 cm
B	0.635 cm
T	0.1016 cm
Length	8.73125 cm
Description	WR-42 waveguide with brass end flanges. Inside polished; outside is oxide coated.

Waveguide #3

Material	Stainless steel -- Copper (ETP) plating
Dimensions: A	0.6223 cm
B	0.3353 cm
T	0.0254 cm
Length	7.62 cm
*Plating depth	6×10^{-5} cm
Description	WR-22 waveguide with brass end flanges. Inside polished; outside clean but not polished.

Waveguide #4

Material	Stainless steel -- Copper (ETP) plating
Dimensions: A	0.6223 cm
B	03353 cm
T	0.0254 cm
Length	15.24 cm
*Plating depth	6×10^{-5} cm
Description	WR-22 waveguide with brass end flanges. Inside polished; outside clean but not polished.

* 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 ΔT, 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 μHg. 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 μHg, 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 μHg 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.

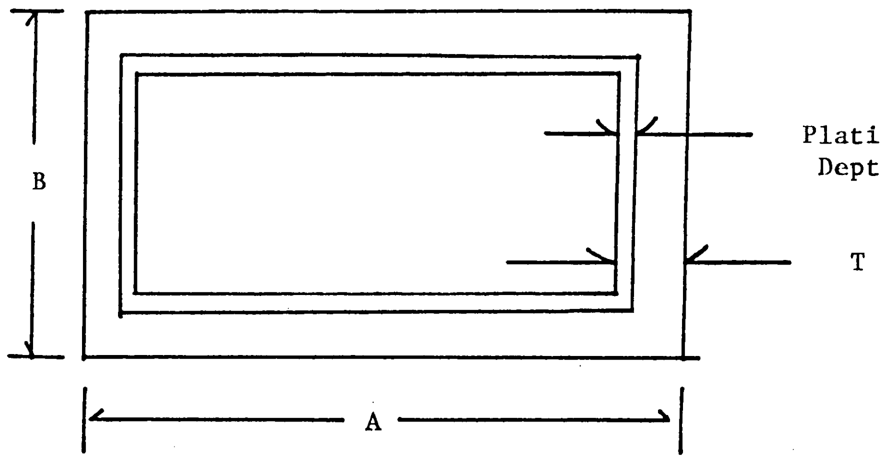


FIGURE 9

Waveguide Dimensions

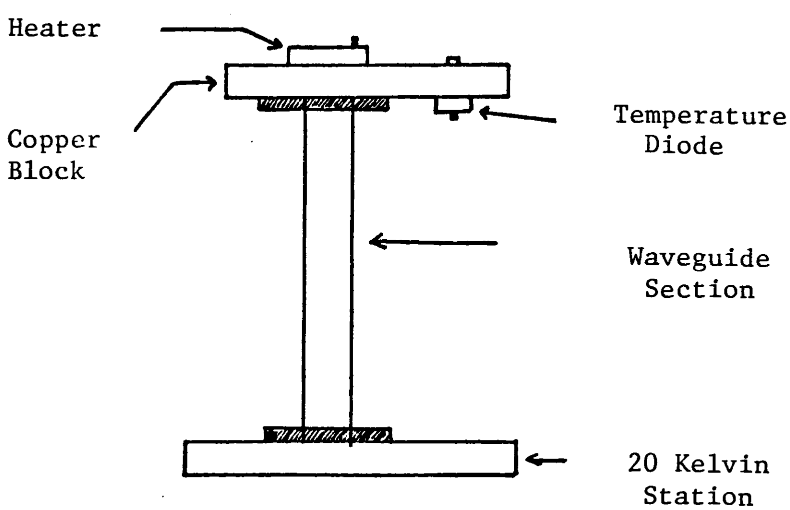


FIGURE 10

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 1

Waveguide 1 Heat Flow

Test No.	Source Temperature K	Sink Temperature K	Heater Current mA	Heater Voltage V	Measured Heat Flow W	Calculated Heat Flow W
1	18.8	10.5	47.41	30.02	1.423	1.268
2	23.5	11.0	60.00	38.20	2.29	2.175
3	31.0	12.0	77.81	50.00	3.89	3.789
4	41.0	13.5	93.04	60.32	5.61	5.950
5	56.0	16.7	114.00	74.70	8.52	8.472
6	56.0	17.3	114.00	75.00	8.60	8.367
7	130.0	33.0	148.00	100.10	14.80	14.973

1

```
WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...COPPER TE
SOURCE TEMPERATURE 18.8 (KELVIN)
SINK TEMPERATURE 10.5 (KELVIN)
LENGTH 11.43 (CM)
DIM A 1.27(CM)      DIM B .635(CM)
TOTAL WALL THICKNESS .1016 (CM)

CROSS-SECTION AREA
COPPER TE .34580576 (SQ CM)

THERMAL RESISTANCE (W/K )
COPPER TE  6.54531271
TOTAL   6.54531271

HEAT FLOW  (WATTS)
COPPER TE   1.26808303
TOTAL   1.26808303
```

2

```
WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...COPPER TE
SOURCE TEMPERATURE 23.5 (KELVIN)
SINK TEMPERATURE 11 (KELVIN)
LENGTH 11.43 (CM)
DIM A 1.27(CM)      DIM B .635(CM)
TOTAL WALL THICKNESS .1016 (CM)

CROSS-SECTION AREA
COPPER TE .34580576 (SQ CM)

THERMAL RESISTANCE (W/K )
COPPER TE  5.74688999
TOTAL   5.74688999

HEAT FLOW  (WATTS)
COPPER TE   2.17508949
TOTAL   2.17508949
```

3

```
WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...COPPER TE
SOURCE TEMPERATURE 31 (KELVIN)
SINK TEMPERATURE 12 (KELVIN)
LENGTH 11.43 (CM)
DIM A 1.27(CM)      DIM B .635(C
TOTAL WALL THICKNESS .1016 (CM)

CROSS-SECTION AREA
COPPER TE .34580576 (SQ CM)

THERMAL RESISTANCE (W/K
COPPER TE  5.01506502
TOTAL   5.01506502

HEAT FLOW  (WATTS)
COPPER TE   3.78858498
TOTAL   3.78858498
```

4

```
WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...COPPER TE
SOURCE TEMPERATURE 41 (KELVIN)
SINK TEMPERATURE 13.5 (KELVIN)
LENGTH 11.43 (CM)
DIM A 1.27(CM)      DIM B .635(CM)
TOTAL WALL THICKNESS .1016 (CM)

CROSS-SECTION AREA
COPPER TE .34580576 (SQ CM)

THERMAL RESISTANCE (W/K )
COPPER TE  4.62209586
TOTAL   4.62209586

HEAT FLOW  (WATTS)
COPPER TE   5.94968189
TOTAL   5.94968189
```

5

```
WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...COPPER TE
SOURCE TEMPERATURE 56 (KELVIN)
SINK TEMPERATURE 16.7 (KELVIN)
LENGTH 11.43 (CM)
DIM A 1.27(CM)      DIM B .635(CM)
TOTAL WALL THICKNESS .1016 (CM)

CROSS-SECTION AREA
COPPER TE .34580576 (SQ CM)

THERMAL RESISTANCE (W/K )
COPPER TE  4.63856223
TOTAL   4.63856223

HEAT FLOW  (WATTS)
COPPER TE   8.4724529
TOTAL   8.4724529
```

6

```
WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...COPPER TE
SOURCE TEMPERATURE 56 (KELVIN)
SINK TEMPERATURE 17.3 (KELVIN)
LENGTH 11.43 (CM)
DIM A 1.27(CM)      DIM B .635(CM)
TOTAL WALL THICKNESS .1016 (CM)

CROSS-SECTION AREA
COPPER TE .34580576 (SQ CM)

THERMAL RESISTANCE (W/K )
COPPER TE  4.62522075
TOTAL   4.62522075

HEAT FLOW  (WATTS)
COPPER TE   8.3671682
TOTAL   8.3671682
```

7

```
WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...COPPER TE
SOURCE TEMPERATURE 130 (KELVIN)
SINK TEMPERATURE 33 (KELVIN)
LENGTH 11.43 (CM)
DIM A 1.27(CM)      DIM B .635(CM)
TOTAL WALL THICKNESS .1016 (CM)

CROSS-SECTION AREA
COPPER TE .34580576 (SQ CM)

THERMAL RESISTANCE (W/K )
COPPER TE  6.47840788
TOTAL   6.47840788

HEAT FLOW  (WATTS)
COPPER TE   14.9728146
TOTAL   14.9728146
```

FIGURE 11

Calculation Results: Waveguide 1

4.6 Continued:

Waveguide #2

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

TABLE 2

Waveguide 2 Heat Flow

Test No.	Source Temperature K	Sink Temperature K	Heater Current mA	Heater Voltage V	Measured Heat Flow W	Calculated Heat Flow W
1	23.7	12.4	76.87	50.0	3.843	3.839
2	24.1	13.2	76.82	50.0	3.841	3.807
3	25.9	14.0	91.47	60.0	5.488	4.376
4	38.0	17.1	105.85	70.0	7.409	8.695
5	53.0	23.1	126.94	84.99	10.788	11.538

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°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°K. WATER computed the unwanted heat flow to be about 15 mW.

1

WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...COPPER OFHC
SOURCE TEMPERATURE 23.7 (KELVIN)
SINK TEMPERATURE 12.4 (KELVIN)
LENGTH 8.73125 (CM)
DIM A 1.27(CM)   DIM B .635(CM)
TOTAL WALL THICKNESS .1016 (CM)

CROSS-SECTION AREA
COPPER OFHC .34580576 (SQ CM)

THERMAL RESISTANCE (W/K)
COPPER OFHC 2.94339637
TOTAL   2.94339637

HEAT FLOW (WATTS)
COPPER OFHC   3.83910238
TOTAL   3.83910238

2

WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...COPPER OFHC
SOURCE TEMPERATURE 24.1 (KELVIN)
SINK TEMPERATURE 13.2 (KELVIN)
LENGTH 8.73125 (CM)
DIM A 1.27(CM)   DIM B .635(CM)
TOTAL WALL THICKNESS .1016 (CM)

CROSS-SECTION AREA
COPPER OFHC .34580576 (SQ CM)

THERMAL RESISTANCE (W/K)
COPPER OFHC 2.86314526
TOTAL   2.86314526

HEAT FLOW (WATTS)
COPPER OFHC   3.8070021
TOTAL   3.8070021

3

WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...COPPER OFHC
SOURCE TEMPERATURE 25.9 (KELVIN)
SINK TEMPERATURE 14 (KELVIN)
LENGTH 8.73125 (CM)
DIM A 1.27(CM)   DIM B .635(CM
TOTAL WALL THICKNESS .1016 (CM)

CROSS-SECTION AREA
COPPER OFHC .34580576 (SQ CM)

THERMAL RESISTANCE (W/K)
COPPER OFHC 2.71935698
TOTAL   2.71935698

HEAT FLOW (WATTS)
COPPER OFHC   4.37603451
TOTAL   4.37603451

4

WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...COPPER OFHC
SOURCE TEMPERATURE 38 (KELVIN)
SINK TEMPERATURE 17.1 (KELVIN)
LENGTH 8.73125 (CM)
DIM A 1.27(CM)   DIM B .635(CM)
TOTAL WALL THICKNESS .1016 (CM)

CROSS-SECTION AREA
COPPER OFHC .34580576 (SQ CM)

THERMAL RESISTANCE (W/K)
COPPER OFHC 2.40381237
TOTAL   2.40381237

HEAT FLOW (WATTS)
COPPER OFHC   8.69452219
TOTAL   8.69452219

5

WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...COPPER OFHC
SOURCE TEMPERATURE 52 (KELVIN)
SINK TEMPERATURE 23.1 (KELVIN)
LENGTH 8.73125 (CM)
DIM A 1.27(CM)   DIM B .635(CM)
TOTAL WALL THICKNESS .1016 (CM)

CROSS-SECTION AREA
COPPER OFHC .34580576 (SQ CM)

THERMAL RESISTANCE (W/K)
COPPER OFHC 2.50471935
TOTAL   2.50471935

HEAT FLOW (WATTS)
COPPER OFHC   11.5382189
TOTAL   11.5382189

FIGURE 12

Calculation Results: Waveguide 2

Waveguide #3

WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...STAINLESS STEEL
PLATING MATERIAL...COPPER ETP
SOURCE TEMPERATURE 57 (KELVIN)
SINK TEMPERATURE 10 (KELVIN)
LENGTH 7.62 (CM)
DIM A .6223(CM)   DIM B .3353(CM)
TOTAL WALL THICKNESS .0254 (CM)
DEPTH OF PLATING 6E-05 (CM)

CROSS-SECTION AREA
STAINLESS STEEL .0459627056 (SQ CM)
COPPER ETP 1.02734397E-04 (SQ CM)

THERMAL RESISTANCE (W/K)
STAINLESS STEEL 4452.29958
COPPER ETP ~~14.3842893~~ 6435.43811
TOTAL   2631.63012

HEAT FLOW (WATTS)
STAINLESS STEEL   .0105563427
COPPER ETP   ~~3.26745376~~ 7.3033100BE-03
TOTAL   .0178596528

Waveguide #4

WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...STAINLESS STEEL
PLATING MATERIAL...COPPER ETP
SOURCE TEMPERATURE 75 (KELVIN)
SINK TEMPERATURE 10 (KELVIN)
LENGTH 15.24 (CM)
DIM A .6223(CM)   DIM B .3353(CM
TOTAL WALL THICKNESS .0254 (CM)
DEPTH OF PLATING 6E-05 (CM)

CROSS-SECTION AREA
STAINLESS STEEL .0459627056 (SQ CM)
COPPER ETP 1.02734397E-04 (SQ CM)

THERMAL RESISTANCE (W/K)
STAINLESS STEEL 6921.08415
COPPER ETP ~~32.8452868~~ 14694.7692
TOTAL   4705.05293

HEAT FLOW (WATTS)
STAINLESS STEEL   9.39159221E-03
COPPER ETP   ~~1.97897436~~ 4.42334271E-4
TOTAL   .0138149349

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.

.9 <u>Possible Improvements.</u>

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.

```
          WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...COPPER TE
SOURCE TEMPERATURE 55 (KELVIN)
SINK TEMPERATURE 16.7 (KELVIN)
LENGTH 11.43 (CM)
DIM A 1.27(CM)        DIM B .635(CM)
TOTAL WALL THICKNESS .1016 (CM)

         CROSS-SECTION AREA
COPPER TE .34580576 (SQ CM)

       THERMAL RESISTANCE (W/K )
COPPER TE  4.6190016
TOTAL   4.6190016

       HEAT FLOW  (WATTS)
COPPER TE   8.29183519
TOTAL   8.29183519
```

```
          WAVEGUIDE PARAMETERS
PRINCIPLE MATERIAL...COPPER TE
SOURCE TEMPERATURE 56 (KELVIN)
SINK TEMPERATURE 16.7 (KELVIN)
LENGTH 11.43 (CM)
DIM A 1.27(CM)        DIM B .635(C
TOTAL WALL THICKNESS .1016 (CM)

         CROSS-SECTION AREA
COPPER TE .34580576 (SQ CM)

       THERMAL RESISTANCE (W/K
COPPER TE  4.63856223
TOTAL   4.63856223

       HEAT FLOW  (WATTS)
COPPER TE   8.4724529
TOTAL   8.4724529
```

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

AA (75, 2) .... Thermal conductivity versus temperature table.

M$ (6) .... Material name list.

PA (6) .... Integration results.

CC (75, 2) .... Conductivity analysis array.

A .... Dimension A (R).

B .... Dimension B (R).

T .... Total wall thickness.

OD .... Outside diameter (C).

D1 .... Outside diameter of outer conductor (X).

D2 .... Outside diameter of inner conductor (X).

D3 .... Inside diameter of tube (X).

SD .... Skin depth of plating (R), (C), (X, outer conductor).

SC .... Skin depth of plating (R), (C), (X, inner conductor).

TCS .... Total cross-sectional area (R), (C).

MCS .... Principal material cross-sectional area (R), (C).

PCS .... Plating cross-sectional area (C), (R).

L .... Length.

M1 .... Outer conductor structural area (X).

P1 .... Outer conductor plating area (X).

M2 .... Inner conductor structural area (X).

P2 .... Inner conductor plating area (X).

R .... Total thermal resistance.

R1 .... Resistance of outer conductor structural material (X).

R2 .... Resistance of outer conductor plating material (X).

R3 .... Resistance to inner conductor structural material (X).

R4 .... Reistance to inner conductor plating material (X).

RM .... Main material thermal resistance (R), (C).

RP .... Plating material thermal resistance (R), (C).

Q1 .... Heat flow through outer conductor structural material (X)

Q2 .... Heat flow through outer conductor plating material (X).

Q3 .... Heat flow through inner conductor structural material (X)

Q4 .... Heat flow through inner conductor plating material (X).

Q .... Total heat flow.

QM .... Heat flow through main material (R), (C).

QP .... Heat flow through principal material (R), (L).

******

APPENDIX B

PROGRAM LISTING

```
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  HIMEM: 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$(6): REM  MATERIAL LIST
250  DIM PA(6): REM  INTEGRATION RESULTS
260  DIM CC(75,2): REM  CONDUCTIVITY ANALYSIS
270 PI = 3.141592653589793
280 D$ = "": 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 "(M) INCHES TO CM"
410  PRINT "(E) EXIT PROGRAM"
420  GET Q$
430  IF Q$ = "I" THEN  GOTO 4540
440  IF Q$ = "C" THEN MM$ = "C": GOTO 560
450  IF Q$ = "M" THEN  GOTO 4600
460  IF Q$ = "T" THEN  GOTO 4680
470  IF Q$ = "R" THEN MM$ = "R": GOTO 560
480  IF Q$ = "D" AND Q <  > 0 THEN  GOTO 3110
490  IF Q$ = "E" THEN  GOTO 5920
500  IF Q$ = "X" THEN MM$ = "X": GOTO 560
510  GOTO 420
520  REM  <><><><><><><><><><><><><><>
530  REM  <> CALCULATION SECTION    <>
540  REM  <><><><><><><><><><><><><><>
550  REM   ** INITIAL RUN THRU ROUTINES **
```

```
560  GOSUB 690
570  GOSUB 830
580  IF MM$ = "R" THEN  GOSUB 1860: GOSUB 2330
590  IF MM$ = "C" THEN  GOSUB 2000: GOSUB 2420
600  IF MM$ = "X" THEN  GOSUB 2090: GOSUB 2560
610  GOSUB 2740
620  GOSUB 2810
630  IF MM$ = "C" OR MM$ = "R" THEN  GOTO 3110
640  IF MM$ = "X" THEN  GOTO 3410
650  GOTO 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  INPUT "ENTER SOURCE TEMPERATURE (KELVIN) ";SO
730  IF SO = 0 THEN  GOTO 310
740  INPUT "ENTER SINK TEMPERATURE (KELVIN) ";SI
750  IF SI = 0 THEN  GOTO 310
760  RETURN
770  REM  ++++++++++++++++++++++++
780  REM  + INTEGRATION SECTION +
790  REM  ++++++++++++++++++++++++
800  REM  %%%%%%%%%%%%%%%%%%
810  REM  % MATERIAL INPUT %
820  REM  %%%%%%%%%%%%%%%%%%
830  HOME :SC = 0:SD = 0
840  FOR I = 1 TO 6:M$(I) = "": NEXT I
850  IF MM$ = "X" THEN  GOTO 970
860  INPUT "ENTER PRINCIPLE MATERIAL ";M$(1)
870  IF M$(1) = "" THEN  GOTO 310
880  HOME
890  INPUT "IS WAVEGUIDE PLATED? ";Z$
900  IF Z$ = "NO" THEN  GOTO 970
910  IF Z$ = "YES" THEN  GOTO 930
920  GOTO 880
930  INPUT "ENTER PLATING MATERIAL ";M$(2)
940  IF M$(2) = "" THEN  GOTO 310
950  INPUT "DEPTH OF PLATING (CM) ";SD
960  IF SD = 0 THEN  GOTO 310
970  IF MM$ <  > "X" THEN  GOTO 1200
980  HOME
990  INPUT "OUTER CONDUCTOR STRUCTURAL MATERIAL ";M$(1)
1000  HOME
1010  INPUT "INNER CONDUCTOR STRUCTURAL MATERIAL ";M$(2)
1020  HOME
1030  INPUT "IS OUTER CONDUCTOR PLATED ";Z$
1040  IF Z$ = "NO" THEN  GOTO 1110
1050  IF Z$ = "YES" THEN  GOTO 1070
1060  GOTO 1020
1070  INPUT "OUTER CONDUCTOR PLATING ";M$(3)
1080  INPUT "DEPTH OF PLATING (CM) ";SD
1090  IF SD = 0 THEN  GOTO 310
1100  HOME
1110  INPUT "IS INNER CONDUCTOR PLATED ";Z$
1120  IF Z$ = "NO" THEN  GOTO 1200
1130  IF Z$ = "YES" THEN  GOTO 1150
1140  GOTO 1100
1150  INPUT "INNER CONDUCTOR PLATING ";M$(4)
1160  INPUT "DEPTH OF PLATING (CM) ";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";M$(PV)
1250  ONERR  GOTO 310
1260  PRINT D$;"READ";M$(PV)
1270 ROW = ROW + 1
1280  INPUT AA(ROW,1)
1290  INPUT AA(ROW,2)
1300  IF AA(ROW,1) = 0 THEN  GOTO 1330
1310  GOTO 1270
1320  REM   ** RANGE SET **
1330 V1 = 0:K = 0
1340  FOR I = 1 TO ROW
1350  IF AA(I,1) >  = SI AND AA(I,1) <  = SO THEN
1360  IF V1 = 1 THEN  GOTO 1530
1370  GOTO 1610
1380 K = K + 1
1390  IF K = 1 AND SI <  > AA(I,1) THEN  GOTO 1430
1400 V1 = 1
1410 AA(K,1) = AA(I,1):AA(K,2) = AA(I,2)
1420  GOTO 1610
1430 X1 = AA(I,1) - AA(I - 1,1)
1440 X2 = AA(I,2) - AA(I - 1,2)
1450 X3 = X2 / X1
1460 X4 = (SI - AA(I - 1,1)) * X3
1470 AA(K,1) = SI:AA(K,2) = X4 + AA(I - 1,2)
1480 K = K + 1
1490 AA(K,1) = AA(I,1):AA(K,2) = AA(I,2)
1500 X4 = (SI - AA(I - 1,1)) * X3
1510 V1 = 1
1520  GOTO 1610
1530  IF SO = AA(I - 1,1) THEN V1 = 0: GOTO 1610
1540 K = K + 1
1550 Y1 = AA(I,1) - AA(I - 1,1)
1560 Y2 = AA(I,2) - AA(I - 1,2)
1570 Y3 = Y2 / Y1
1580 Y4 = (SO - AA(I - 1,1)) * Y3
1590 AA(K,1) = SO:AA(K,2) = Y4 + AA(I - 1,2)
1600 V1 = 0
1610  NEXT I
1620  REM  %%%%%%%%%%%%%%%
1630  REM  % INTEGRATION %
1640  REM  %%%%%%%%%%%%%%%
1650  FOR J = 1 TO K - 1
1660 C = AA(J + 1,1) - AA(J,1)
1670 D = (AA(J + 1,2) + AA(J,2)) / 2
1680 PA(PV) = (C * D) + PA(PV)
1690  NEXT J
1700  PRINT D$;"CLOSE";M$(PV)
1710  GOTO 1210
1720  RETURN
1730  REM  +++++++++++++++++++++
1740  REM  +PLATING DEPTH REV.+
1750  REM  +++++++++++++++++++++
1760  HOME
1770  IF MM$ = "X" THEN  GOTO 1800
```

```
1780  INPUT "NEW PLATING DEPTH ";SD
1790  GOTO 1820
1800  IF SD <  > 0 THEN  INPUT "NEW OUTER COND PLATING DEPTH (CM)";SD
1810  IF SC <  > 0 THEN  INPUT "NEW INNER COND PLATING DEPTH (CM) ";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 (CM) ";A
1890  IF Q$ = "X" THEN MM$ = "X": GOTO 560
1900  IF A = 0 THEN  GOTO 310
1910  INPUT "DIMENSION B (CM) ";B
1920  IF B = 0 THEN  GOTO 310
1930  INPUT "TOTAL WALL THICKNESS (CM) ";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 (CM) ";OD
2020  IF OD = 0 THEN  GOTO 310
2030  PRINT : INPUT "TOTAL WALL THICKNESS (CM) ";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 "(CM) ";D1
2120  IF D1 = 0 THEN  GOTO 310
2130  HOME
2140  PRINT "OUTSIDE DIA OF INNER CONDUCTOR"
2150  PRINT "       (CONDUCTOR + PLATING)"
2160  PRINT : INPUT "CM) ";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 "(CM) ";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 M1 = 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 M1 = 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 M2 = 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 (CM) ";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$(2)
3160  PRINT "SOURCE TEMPERATURE ";SO;" (KELVIN)"
3170  PRINT "SINK TEMPERATURE ";SI;" (KELVIN)"
3180  PRINT "LENGTH ";L;" (CM)"
3190  IF MM$ = "R" THEN  PRINT "DIM A ";A;"(CM)";"      ";"DIM B ";B;"(
"
3200  IF MM$ = "C" THEN  PRINT "OUTSIDE DIAMETER= ";OD;"(CM)"
3210  PRINT "TOTAL WALL THICKNESS ";T;" (CM)"
3220  IF M$(2) = "" THEN  GOTO 3240
3230  PRINT "DEPTH OF PLATING ";SD;" (CM)"
3240  PRINT : PRINT "          CROSS-SECTION AREA"
3250  PRINT M$(1);" ";MCS;" (SQ CM)"
3260  IF M$(2) = "" THEN  GOTO 3280
3270  PRINT M$(2);" ";PCS;" (SQ CM)"
3280  GET KK$: IF DD$ = "P" THEN  PR# 1
3290  HOME
3300  PRINT : PRINT "        THERMAL RESISTANCE (W/K )"
3310  PRINT M$(1);"   ";RM
3320  IF M$(2) = "" THEN  GOTO 3340
3330  PRINT M$(2);"   ";RP
3340  PRINT "TOTAL   ";R
3350  PRINT : PRINT "        HEAT FLOW  (WATTS)"
3360  PRINT M$(1);"   ";QM
3370  IF M$(2) = "" THEN  GOTO 3390
3380  PRINT M$(2);"   ";QP
3390  PRINT "TOTAL   ";Q
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 ";L;" (CM)"
3490  PRINT "OUTSIDE DIA. OF OUTER COND.";D1;" (CM)"
3500  PRINT "OUTSIDE DIA. OF INNER COND. ";D2;" (CM)"
3510  IF D3 <  > 0 THEN  PRINT "INSIDE DIA. OF TUBE ";D3;"  (CM)"
3520  PRINT "OUTER COND. WALL THICKNESS ";T;" (CM)"
3530  IF M$(3) <  > "" THEN  PRINT "OUTER COND. PLAT. DEPTH ";SD;"
 (CM)"
3540  IF M$(4) <  > "" THEN  PRINT "INNER COND. PLAT. DEPTH ";SC;"
 (CM)"
3550  PRINT : PRINT "       CROSS-SECTIONAL AREA"
3560  PRINT "OUTER CONDUCTOR ";M1;" (SQ CM)"
```

```
3570  PRINT "INNER CONDUCTOR ";M2;" (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 CONDUCTOR 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 CONDUCTOR 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:
 GOSUB 2810: GOTO 3110
3910  IF DD$ = "T" AND MM$ = "X" THEN  GOSUB 690:PV = 0: GOSUB 1210:
 GOSUB 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 2090: 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$ = "M" AND MM$ <  > "X" THEN  GOSUB 830: GOSUB 2810: GOTO
 3110
4020  IF DD$ = "M" 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
4080  REM  ++++++++++++++++++++++++++++
4090  REM  + WAVEGUIDE GRAPHICS        +
4100  REM  ++++++++++++++++++++++++++++
4110  HGR
4120  HPLOT 41,91 TO 99,91
4130  HPLOT 99,91 TO 99,129
4140  HPLOT 41,129 TO 99,129
4150  HPLOT 41,91 TO 41,129
4160  HPLOT 46,96 TO 94,96
4170  HPLOT 46,96 TO 46,124
4180  HPLOT 46,124 TO 94,124
4190  HPLOT 94,96 TO 94,124
4200  HPLOT 181,21 TO 239,21
4210  HPLOT 239,21 TO 239,59
4220  HPLOT 41,91 TO 181,21
4230  HPLOT 99,91 TO 239,21
4240  HPLOT 99,129 TO 239,59
4250  HPLOT 46,124 TO 94,101
4260  HPLOT 67,141 TO 67,145
4270  HPLOT 71,141 TO 71,145
4280  HPLOT 68,142 TO 70,142
4290  HPLOT 69,139
4300  HPLOT 68,140
4310  HPLOT 70,140
4320  HPLOT 99,140 TO 99,144
4330  HPLOT 41,140 TO 41,144
4340  HPLOT 25,109 TO 25,115
4350  HPLOT 25,109 TO 27,109
4360  HPLOT 25,112 TO 27,112
4370  HPLOT 25,115 TO 27,115
4380  HPLOT 28,110 TO 28,111
4390  HPLOT 28,113 TO 28,114
4400  HPLOT 25,91 TO 29,91
4410  HPLOT 25,129 TO 29,129
4420  HPLOT 175,106 TO 175,112
4430  HPLOT 175,112 TO 179,112
4440  HPLOT 239,70 TO 239,74
4450  HPLOT 89,110 TO 92,110
4460  HPLOT 101,110 TO 104,110
4470  HPLOT 106,106 TO 110,106
4480  HPLOT 108,107 TO 108,113
4490  RETURN
4500  REM  <><><><><><><><><><><><>
4510  REM  <> DATA CONVERSION CM-IN  <>
4520  REM  <><><><><><><><><><><><>
4530  REM  ** INCH TO CM **
4540  HOME
4550  INPUT "INPUT CM ";CM
4560  PRINT CM;" (CM)= ";CM / 2.54;" (INCHES)
4570  IF CM = 0 THEN  GOTO 310
4580  GOTO 4550
4590  REM  ** INCHES TO CM **
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 "(M) 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$ = "M" THEN  GOTO 4830
5200  IF Q$ = "C" THEN  GOTO 4940
5210  IF Q$ = "D" THEN  GOTO 5350
5220  IF Q$ = "S" THEN  GOTO 5460
5230  IF Q$ = "P" THEN  PR# 1: GOTO 5350
5240  IF Q$ = "X" THEN  GOTO 5270
5250  GOTO 5120
5260  REM  ** DELETE LINE ROUTINE **
5270 QQ = 1
```

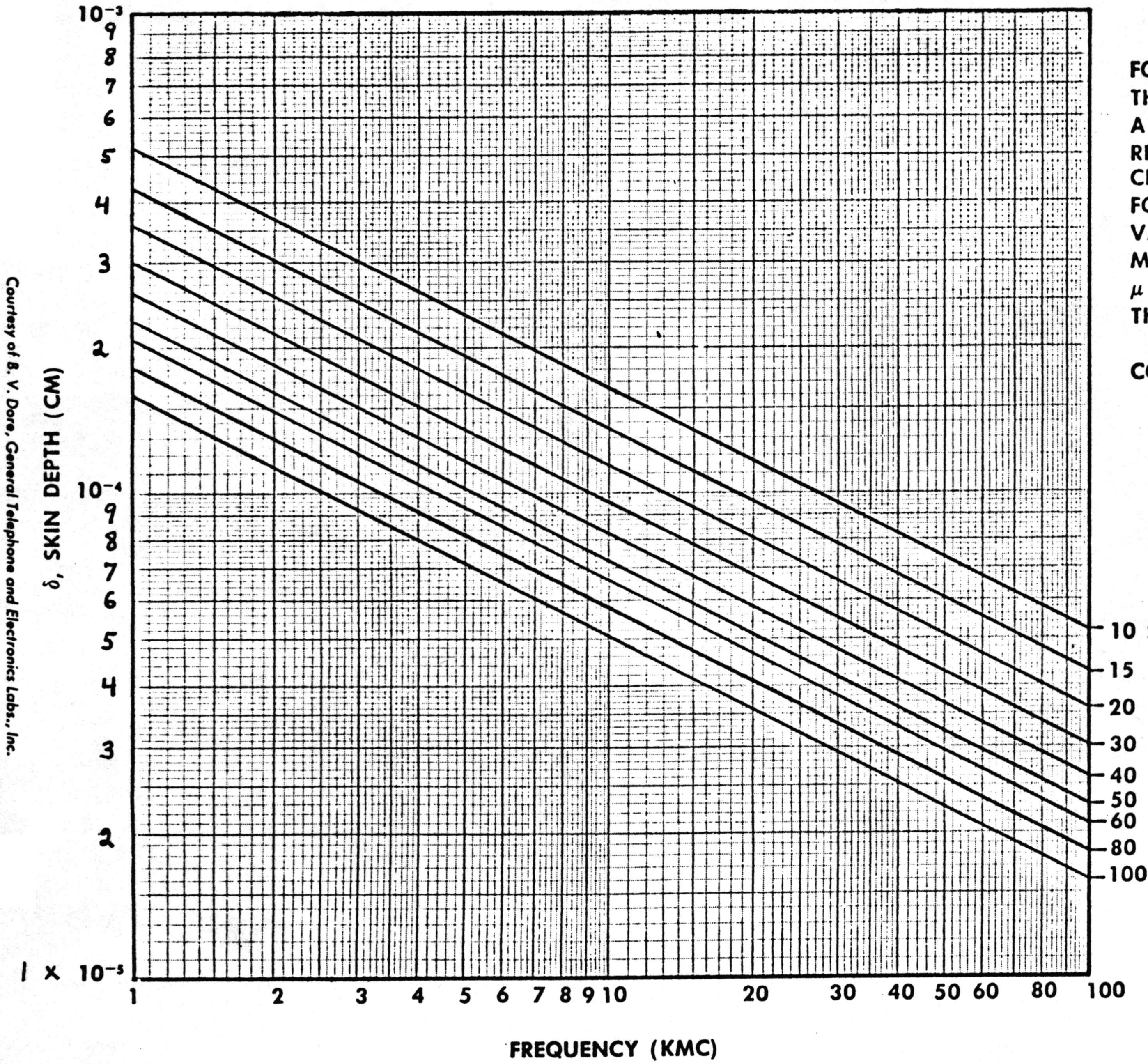
```
5280  HOME
5290  INPUT "DELETE ROW # ";LL
5300  IF LL = 0 THEN  GOTO 5100
5310 CC(LL,1) = 10000
5320 QQ = QQ + 1
5330  GOTO 5290
5340  REM   ** DISPLAY OF DATA **
5350  HOME
5360  PRINT "          ";A$
5370  PRINT
5380  PRINT "TEMPERATURE","CONDUCTIVITY"
5390  PRINT "  KELVIN","   W/CM-K"
5400  PRINT
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  <><><><><><><><><><><><><><><><>
5940  REM  <> PRINTER SET-UP ROUTINE <>
5950  REM  <><><><><><><><><><><><><><><><>
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(109)
6020 HM =  FN CT(115):ST =  FN CT(111)
6030  PRINT "PROGRAM LENGTH= ";LM - SR;" BYTES          VARIABLES= ";HM
 - ST + FR - LM;" BYTES"
6040  PRINT "FREE MEMORY= ";ST - FR;" BYTES"
6050  PRINT "START=";SR;" LOMEM=";LM;" FREE=";FR;" STRING=";ST;" HIMEM=
M
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 Q$ =  CHR$ (17): REM     PRINT Q$ 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

SKIN DEPTH



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 δ FROM THE CHART MUST BE DIVIDED BY $\sqrt{\mu}$, WHERE μ IS THE PERMEABILITY AT THE FREQUENCY SPECIFIED.

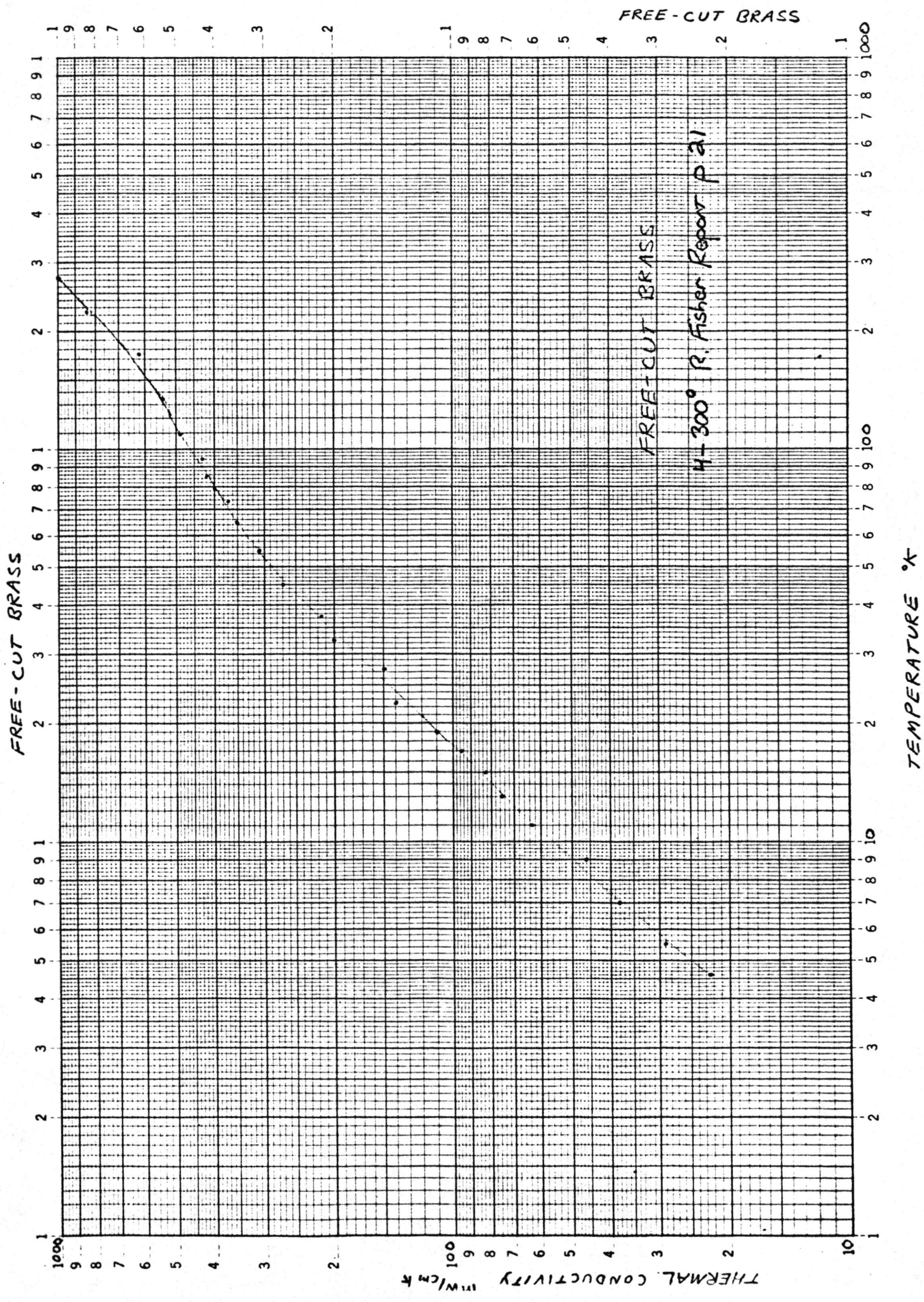
THE CONDUCTIVITY OF SOME COMMON METALS:

SILVER	61×10^6 MHOS/M
COPPER	58
GOLD	41
ALUMINUM	35
MAGNESIUM	22
BRASS	15
PLATINUM	9

Courtesy of B. V. Dore, General Telephone and Electronics Labs., Inc.

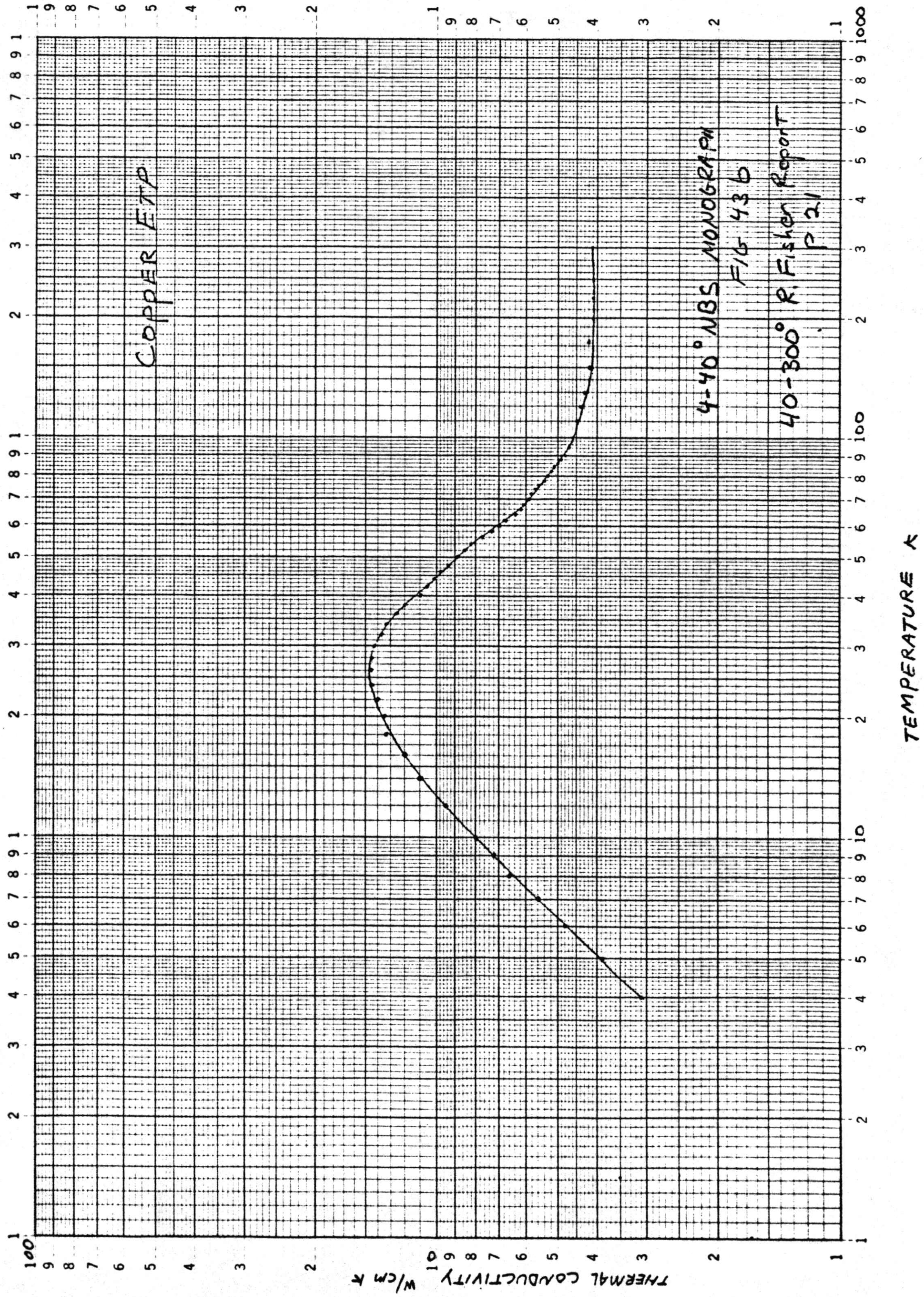
APPENDIX D

THERMAL CONDUCTIVITY DATA


FREE-CUT BRASS
FREE-CUT BRASS
4–300° R. Fisher Report P 21
FREE-CUT BRASS
TEMPERATURE °K
THERMAL CONDUCTIVITY mW/cm K

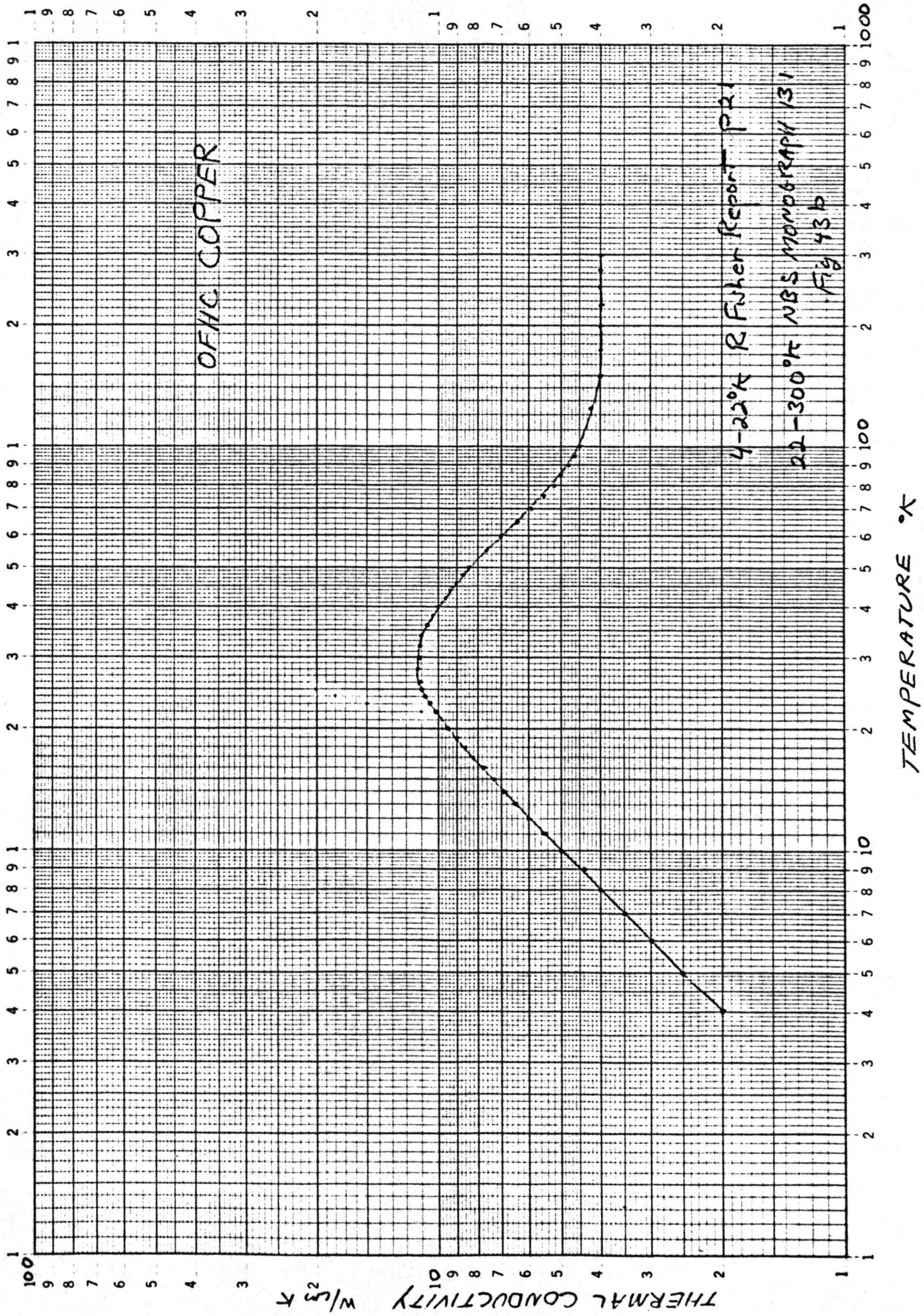
FREE CUT BRASS

	TEMPERATURE KELVIN	CONDUCTIVI W/CM-K
1	4	.02
2	5	.025
3	6	.031
4	7	.038
5	8	.044
6	9	.05
7	10	.056
8	12	.068
9	14	.08
10	16	.09
11	18	.104
12	20	.115
13	22	.127
14	24	.14
15	26	.15
16	28	.165
17	30	.175
18	32	.188
19	34	.2
20	36	.212
21	38	.222
22	40	.234
23	42	.245
24	44	.255
25	46	.27
26	48	.28
27	50	.29
28	55	.31
29	60	.33
30	65	.35
31	70	.37
32	75	.38
33	80	.4
34	85	.415
35	90	.43
36	95	.445
37	100	.46
38	125	.52
39	150	.59
40	175	.66
41	200	.74
42	225	.83
43	250	.9
44	275	1
45	300	1.1


COPPER ETP
4-40° NBS MONOGRAPH
FIG 43b
40-300° R. Fisher Report
P 21
TEMPERATURE K
THERMAL CONDUCTIVITY W/cm K

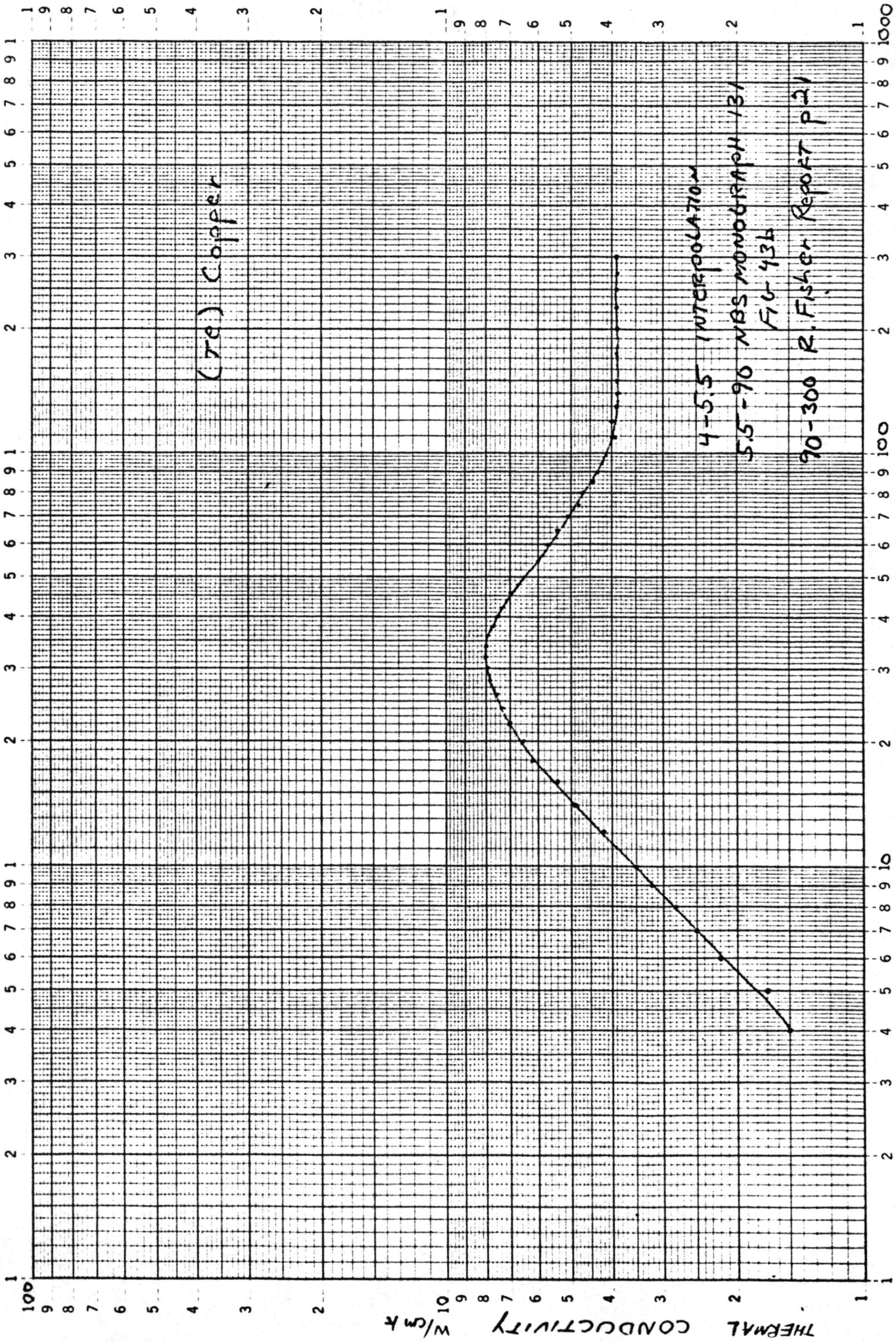
COPPER ETP

	TEMPERATURE KELVIN	CONDUCTIVITY W/CM-K
1	4	3.1
2	5	3.9
3	6	4.8
4	7	5.6
5	8	6.6
6	9	7.2
7	10	8
8	12	9.5
9	14	11
10	16	12
11	18	13.2
12	20	13.5
13	22	14
14	24	14.5
15	26	14.5
16	28	14.5
17	30	14.2
18	32	13.8
19	34	13.3
20	36	12.7
21	38	12
22	40	11
23	42	10.6
24	44	10.1
25	46	9.8
26	48	9.4
27	50	8.9
28	52	8.5
29	54	8.2
30	56	7.7
31	58	7.3
32	60	7
33	62	6.8
34	64	6.4
35	66	6.2
36	68	6.1
37	70	5.9
38	72	5.8
39	74	5.7
40	76	5.6
41	78	5.4
42	80	5.3
43	82	5.2
44	84	5.1
45	86	5
46	88	4.9
47	90	4.8
48	95	4.7
49	100	4.6
50	110	4.5
51	120	4.4
52	130	4.3
53	150	4.2
54	175	4.2
55	200	4.1
56	225	4.1
57	250	4.1
58	275	4.1
59	300	4.1


OF/HC COPPER
4-22°K R Fisher Report P21
22-300°K NBS MONOGRAPH 131 Fig 43 b
TEMPERATURE °K
THERMAL CONDUCTIVITY W/cm K

COPPER OFHC

	TEMPERATURE KELVIN	CONDUCTIVI W/CM-K
1	4	2
2	5	2.5
3	6	3
4	7	3.5
5	8	4
6	9	4.4
7	10	5
8	11	5.5
9	12	6
10	13	6.5
11	14	6.9
12	15	7.3
13	16	7.8
14	17	8.2
15	18	8.6
16	19	9
17	20	9.5
18	22	10.1
19	23	10.5
20	24	10.8
21	25	11
22	26	11.1
23	28	11.2
24	30	11.1
25	32	11.1
26	34	11
27	36	10.6
28	38	10.3
29	40	10
30	42	9.6
31	44	9.3
32	46	9
33	48	8.7
34	50	8.4
35	55	7.6
36	60	7
37	65	6.4
38	70	5.9
39	75	5.5
40	80	5.2
41	85	5
42	90	4.8
43	95	4.6
44	100	4.5
45	125	4.2
46	150	4
47	175	4
48	200	4
49	225	4
50	250	4
51	275	4
52	300	4

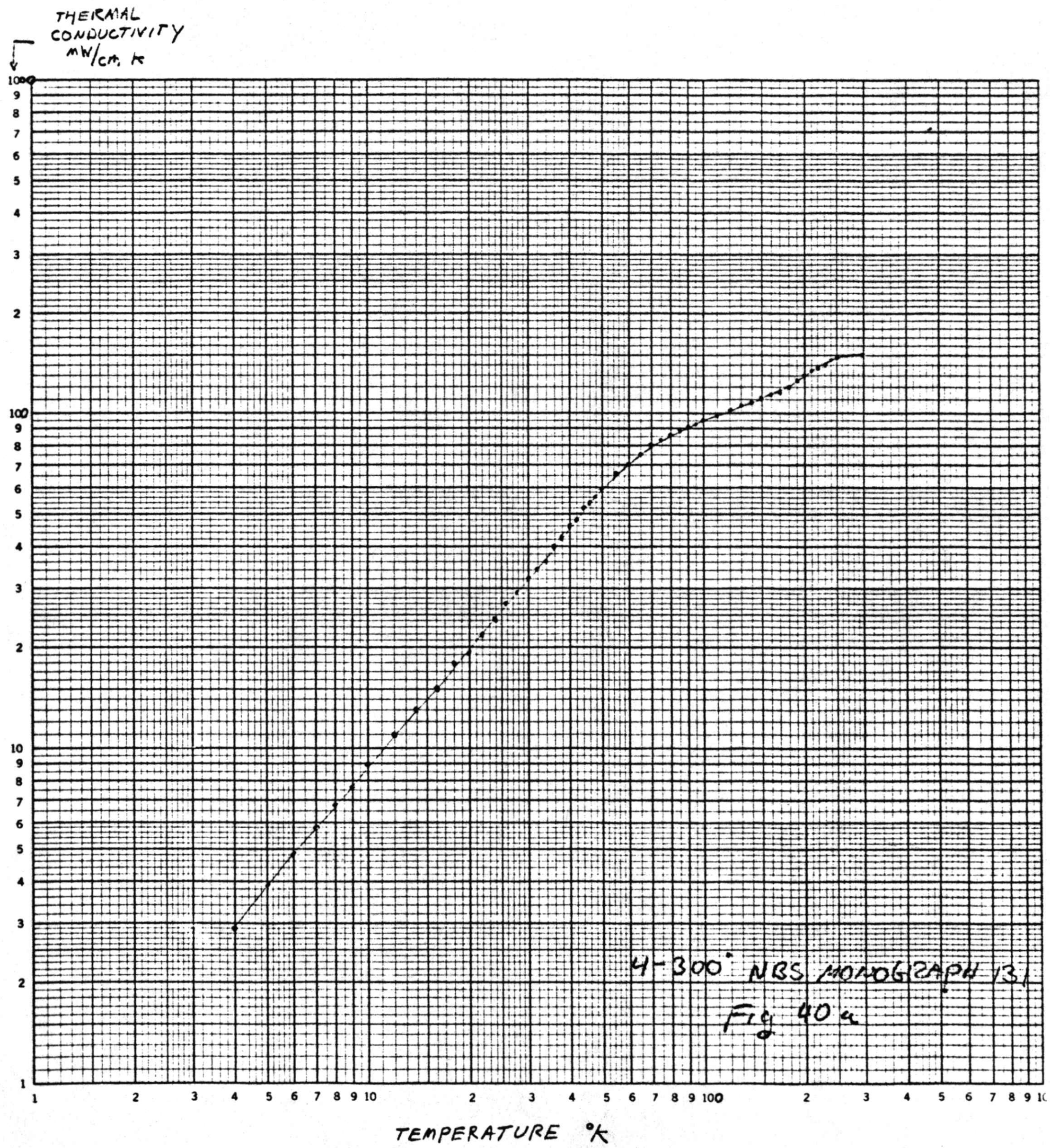

Copper
4-5.5 INTERPOLATION
5.5-90 NBS MONOGRAPH 131
90-300 R. Fisher Report p.21
TEMPERATURE °K
THERMAL CONDUCTIVITY W/cm K

COPPER TE

	TEMPERATURE KELVIN	CONDUCTI W/CM-
1	4	1.5
2	5	1.7
3	6	2.2
4	7	2.5
5	8	2.8
6	9	3.2
7	10	3.5
8	12	4.2
9	14	4.9
10	16	5.4
11	18	6.2
12	20	6.5
13	22	7
14	24	7.3
15	26	7.5
16	28	7.8
17	30	7.9
18	32	8
19	34	8
20	36	7.9
21	38	7.7
22	40	7.5
23	42	7.3
24	44	7.1
25	46	7
26	48	6.7
27	50	6.5
28	55	6
29	60	5.7
30	65	5.4
31	70	5.1
32	75	4.8
33	80	4.7
34	85	4.5
35	90	4.3
36	95	4.2
37	100	4.1
38	110	4
39	120	4
40	130	3.9
41	140	3.9
42	150	3.9
43	175	3.9
44	200	3.9
45	225	3.9
46	250	3.9
47	275	3.9
48	300	3.9

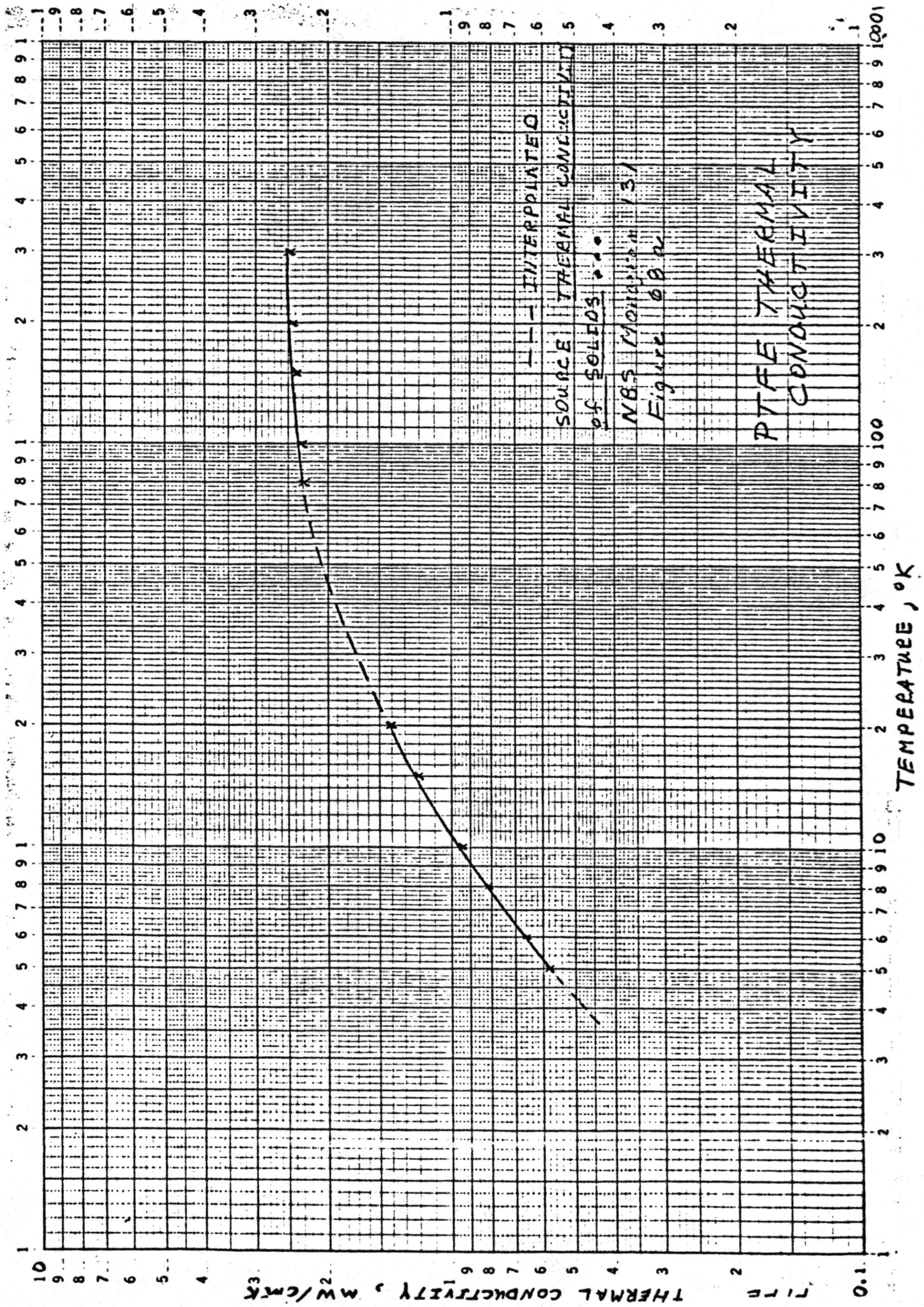
STAINLESS STEEL

NBS MONOGRAPH 131 p.257



STAINLESS STEEL

	TEMPERATURE KELVIN	CONDUCTIVITY W/CM-K
1	4	2.9E-03
2	5	3.9E-03
3	6	4.8E-03
4	7	5.8E-03
5	8	6.7E-03
6	9	7.6E-03
7	10	9E-03
8	12	.011
9	14	.013
10	16	.015
11	18	.018
12	20	.019
13	22	.022
14	24	.024
15	26	.027
16	28	.029
17	30	.032
18	32	.034
19	34	.036
20	36	.04
21	38	.042
22	40	.046
23	42	.048
24	44	.052
25	46	.054
26	48	.056
27	50	.059
28	55	.066
29	60	.07
30	65	.075
31	70	.08
32	75	.083
33	80	.086
34	85	.089
35	90	.091
36	95	.092
37	100	.095
38	110	.098
39	120	.102
40	130	.105
41	140	.107
42	150	.11
43	160	.112
44	170	.115
45	180	.12
46	190	.127
47	200	.13
48	210	.134
49	220	.138
50	230	.14
51	240	.145
52	250	.148
53	300	.15


PTFE THERMAL CONDUCTIVITY
TEMPERATURE, °K
THERMAL CONDUCTIVITY, mW/cm K

PTFE

	TEMPERATURE KELVIN	CONDUCTIVITY W/CM-K
1	4	4.75E-04
2	5	5.8E-04
3	6	6.6E-04
4	7	7.4E-04
5	8	8.2E-04
6	9	9E-04
7	10	9.6E-04
8	12	1.02E-03
9	14	1.19E-03
10	16	1.28E-03
11	18	1.35E-03
12	20	1.42E-03
13	22	1.5E-03
14	24	1.55E-03
15	26	1.61E-03
16	28	1.66E-03
17	30	1.71E-03
18	32	1.75E-03
19	34	1.8E-03
20	36	1.84E-03
21	38	1.9E-03
22	40	1.91E-03
23	42	1.96E-03
24	44	2E-03
25	46	2.02E-03
26	48	2.05E-03
27	50	2.1E-03
28	55	2.15E-03
29	60	2.2E-03
30	65	2.25E-03
31	70	2.26E-03
32	75	2.29E-03
33	80	2.3E-03
34	85	2.32E-03
35	90	2.33E-03
36	95	2.35E-03
37	100	2.38E-03
38	125	2.4E-03
39	150	2.45E-03
40	175	2.48E-03
41	200	2.5E-03
42	225	2.5E-03
43	250	2.5E-03
44	275	2.5E-03
45	300	2.5E-03

APPENDIX E

APPARATUS COMPONENT DATA

LAKE SHORE CRYOTRONICS

Sensor Type	Available Configuration (See Pages 6 and 7) 2 4 6 8 10 12 14	Sensing Element Material	Heat Dissipation (at 4.2K and recommended operating current)	Useful Temperature Range	Output Signal or Nominal Value at 4.2k	Sensitivity	Inter-changeability	Thermal Response (at 4.2K) (Configuration Dependent)	Repeatability (at 4.2K)	Magnetic Field Effect (Data taken ⊥ to field at 4 Tesla and 4.2K)	Reliability (Typical cycling life 300K to 4.2K)	Suggested Temperature or Signal Read Out Accuracy	REMARKS	Sensor Type
Diode Thermometry														Diode Thermometry
TG-100	4, 6, 8	Gallium Arsenide	15 uW at 10 uA	1 K to 380 K	1.45 V at 4.2 K / 0.7 V at 295 K	0.6 mV/K at 4.2 K / 2.75 mV/K at 77 K; See Fig. 2, 4	N.A.	100 K/sec	100 uV	-0.8 K; See Fig. 6	200 to 300 Cycles Nominally	100 uV	Useful in modest magnetic fields	TG-100
DT-500	2, 4, 6, 8, 14	Silicon	25 uW at 10 uA	1 K to 380 K	2.4 V at 4.2 K / 0.4 V at 295 K	50 mV/K at 4.2 K / 2.75 mV/K at 77 K; See Fig. 1, 4	±0.1 K @ 4.2 K ±1K @ 77 K ±1K @ 300 K (see remarks)	100 K/sec	50 uV	~5K; See Fig. 6	Excellent	100 uV	Sensors of same config.can be matched at LHe, LN, and room temperature. If quantities to be matched exceed 5, discuss applicaton with factory	DT-500
Capacitance Thermometry														Capacitance Thermometry
CS-400	12	Strontium Titanate	<10⁻¹⁰ W at 1 K Hz and 50 mv excitation	<1 K to 60 K / 70 K to 380 K	3 nF to 40 nF; See Fig. 3	250 pF/K at 4.2 K / 160 pF/K at 4.2 K (-FP only); See Fig. 3	N.A.	100 K/sec		No Effect; See Fig. 6	Excellent	±3 pF	Unaffected by magnetic fields to 18 T. Recommended for control purposes. Request detailed information from factory	CS-400
Resistance Thermometry														Resistance Thermometry
CGR-1	10	Carbon Glass	CGR-1 (2000) 0.2 uW 10 uA	1.4 K To 100 K (300 K) with several Elements	1000 ohm 1500 ohm 2000 ohm	See Figures 4, 5, 7	Consult Factory		<1 mK at 4.2 K	< 0.08 K; See Fig. 6	Excellent	0.005	Useful in Magnetic Fields. Large useful range, essentially no piezo-resistance, monotonic R vs T and dR/dT curves. 1000 ohm 1.5-100K (300K) 1500 ohm 2-100K (300K) 2000 ohm 2-100K (300K)	CGR-1
GR-200A and GR-200B	10	Germanium	GR-200A-1000 or GR-200B-1000 0.1 uW at 10 uA	GR-200A <0.03 K to 100 K with several elements GR-200B 1 K to 100 K with several elements	30 ohm* 50 ohm* 100 ohm* 250 ohm* 500 ohm 1000 ohm 1500 ohm 2500 ohm 5000 ohm* *Not available AS GR-200 B	See Figures 4, 5, 7	Limited, with Bridge Techniques		≤0.5 mK at 4.2 K	Not Recommended; See Fig. 6	Excellent	± 0.002 K at 4.2 K For R=1000Ω at 4.2 K	Recognized secondary standard 30 ohm 0.010-1.5K (4.2K)* 50 ohm 0.050-1.5K (4.2K)* 100 ohm 0.30-4.2K* 250 ohm 0.50-20K* 500 ohm 1-20K 1000 ohm 1.5-40K (100K) 1500 ohm 1.5-40K (100K) 2500 ohm 2-40K (100K) 5000 ohm 3-40K (100K)* *Not available as GR-200 B	GR-200A and GR-200B
RF-800		Rhodium with 0.5 atomic % Iron		2 K to 300 K	20, 47, or 100 ohms at 273.2 K (0°C)	90 uV/K at 4.2 K and 500 uA	No		0.3 mK at 4.2 K	– 0.3 K	Excellent	0.008 K or better	Model RF-802-Perf. is a perforated can version for gas or liquid use. Request detailed information from factory	RF-800
PT-100		Platinum		23 K to 873 K	100 ohms at 273.2 K (0°C)	0.00385/°C	± 0.3 K at 273.2 K	N.A.	N.A.	-9 K at 20 K	Excellent	100 µV	Ceramic Package Sizes Available: Dia. (mm) Length (mm) PT-101 — 3.1 .... 30.5; PT-102 — 2.0 .... 20.3; PT-103 — 1.8 .... 12.1	PT-100

ASK FOR BULLETIN "CRYOGENIC INSTRUMENTATION" FROM LAKE SHORE CRYOTRONICS, INC.

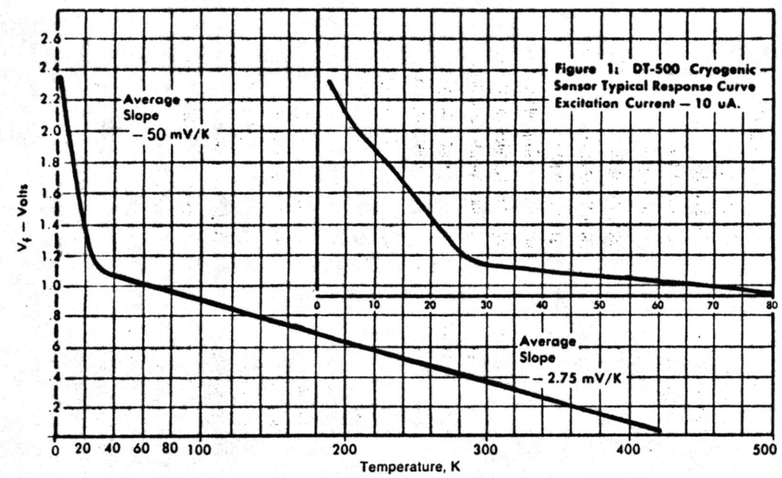


Figure 1 Detailed Response of DT-500 Silicon Diode Temperature Sensor

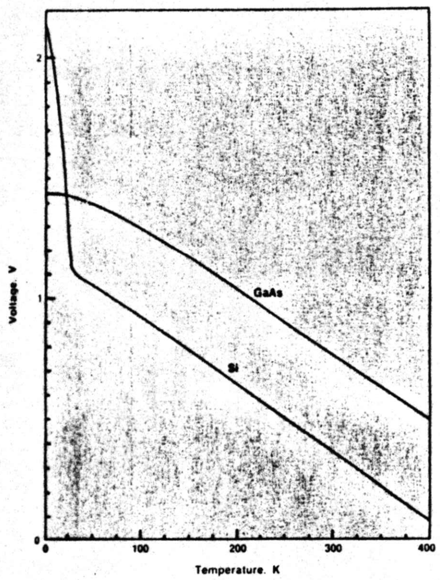


Figure 2

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

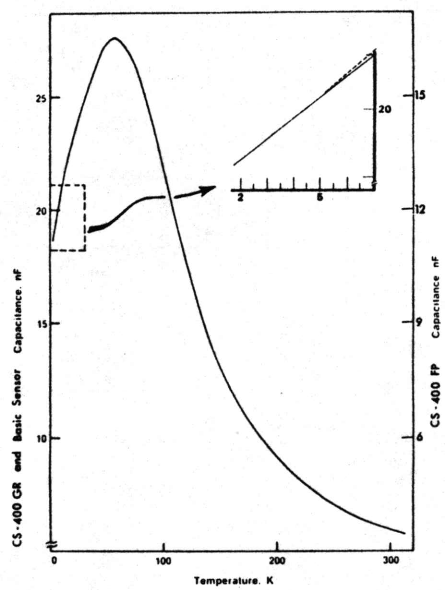


Figure 3

Typical capacitance temperature characteristics for $SrTiO_3$ capacitance thermometers.

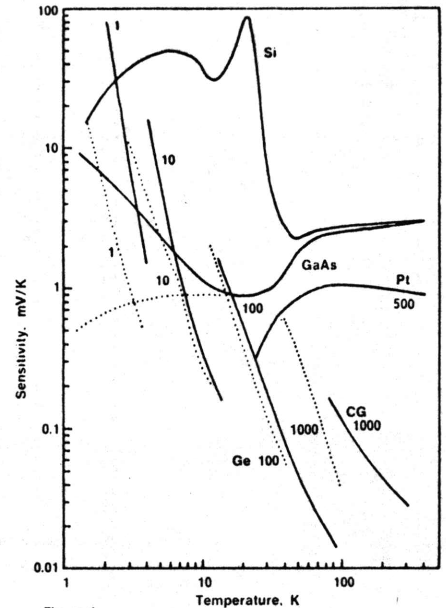


Figure 4

Temperature sensitivity of voltage (dV/dT) as a function of temperature for silicon (Si) and gallium arsenide (GaAs) diode (solid and dotted line) thermometers and carbon glass (CG) (solid line), germanium (Ge) (dotted line), and platinum (Pt) (R_0= 470 ohms) resistors. Numbers for resistors indicate current in microamperes. Diode thermometer data is at 10 microamperes.

Magnetic Field-Tesla	2.5	5	10	15
TG-100 GaAs	-.13	-.8	-3.25	N.R.*
DT-500 Silicon	-3.15	~-5	N.R.*	N.R.*
CS-400 $SrTiO_3$	0	0	0	0
CGR Carbon Glass	-.02	-.06	-.17	-.28
GR-200 Germanium	-.8	-1.6	-2.5	-3.

Figure 6

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

*N.R. — Not Recommended

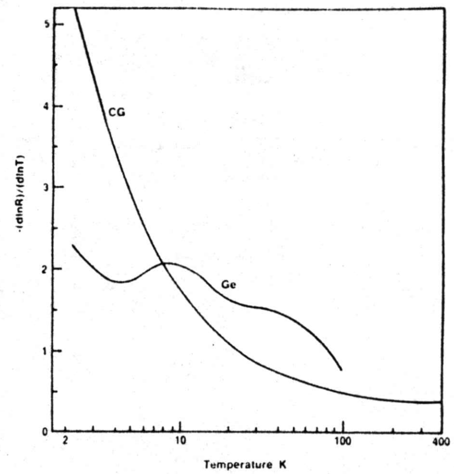


Figure 5

Relative sensitivity data (dlnR)/(dlnT) versus temperature for carbon glass (CG) and germanium (Ge) resistors.

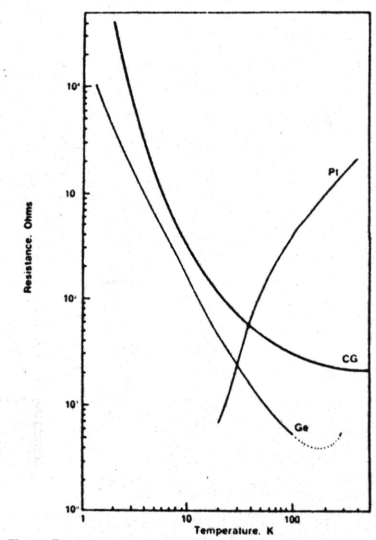
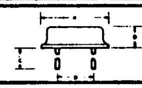
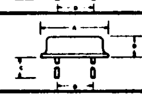
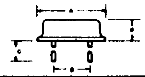
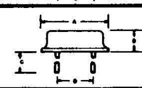
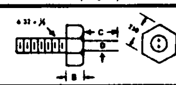
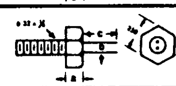
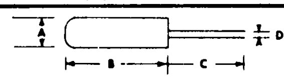
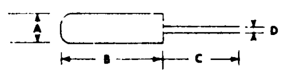
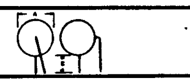
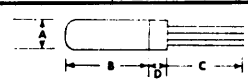
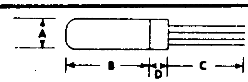
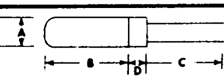
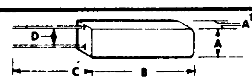
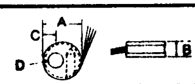


Figure 7

Resistance-temperature characteristics of the germanium (Ge), platinum (Pt) (R_0= 1380 ohms), and carbon glass (CG) resistors.

ASK FOR BULLETIN "INSTALLATION AND APPLICATION NOTES FOR CRYOGENIC SENSORS"

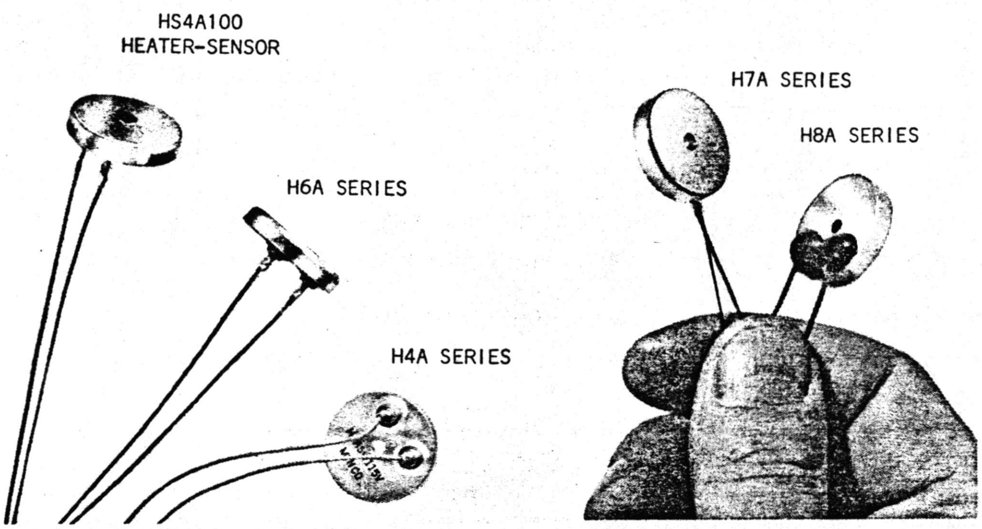
SENSOR SERIES DESIGNATION	REF. NO.	LEAD IDENT. AND ISOLATION	CONFIGURATION	DIMENSIONS: INCHES / MM. A	B	C	D	LEADS	LEAD DIAM.	WEIGHT	ENCAPSULATION MATERIALS	REMARKS
TG-100K DT-500K	1	Cathode is at case potential Tab index is anode		.23 5.8	.08 2	1.5 38	.10 2.5	2, Gold Plated Ni-Fe 3 DE	.019 .5	0.32 gr.	Gold Plated Kovar TO-46 Package	Thermal transfer thru body of unit one lead grounded
DT-500KL	2	Both leads isolated Tab index is anode		.23 5.8	.08 2	1.5 38	.07 1.8	2, Gold Plated Ni-Fe 3-DE	.019 .5	.3 gr.	Gold Plated Kovar TO-46 Package	Both leads isolated from case
TG-100KL	3	Both leads isolated Tab indax is anode		.23 5.8	.21 5.3	1.5 38	.07 1.8	2, Gold Plated Ni-Fe	.019 .5	0.38 gr.	Gold Plated Kovar TO-18 Package	Both leads isolated from case
TG-100P DT-500P	4	Cathode Is at casa potential anode is shorter lead		.15 3.8	.065 1.65	1.0 25.4	.06 1.5	2, Plat.— 10% Ir	.01 .25	.18 gr.	Platinum & Glass	No ferromagnetic materials ara utilized in the construction of these sansors
TG-100K-T05 DT-500K-T05	5	Cathoda is at case potential Tab index is anode		—	.137 3.5	1.5 38	.10 2.5	2, Gold Platad Ni-Fe 3-DE	.019 .5	1.37 gr.	Gold Plated Kovar TO-46 base set in a 6-32 x ⅜" copper alloy hex head cap scraw	TG-100K or DT-500K set into the top of a copper alloy hex head cap screw
TG-100KL-T05 DT-500KL-T05	8	Both leads isolatad Tab indax is anoda		—	.137 3.5	1.5 38	.07 1.8	2, Gold Plated Ni-Fe 3-DE	.019 .5	1.4 gr.	Gold Plated Kovar TO-46 base set in a 6-32 x ⅜" copper alloy hex head cap screw	TG-100KL or DT-500KL set into the top of a copper alloy hex head cap screw
DT-500P-GR-MIN/I DT-500 DRC	7	Standard version Sama as Ref #4		.06 1.5	.16 4.1	1.0 25.4	.01 .254	2, Plat.— 10% Ir	.005 .13	.045 gr.	Platinum, Brass, & Epoxy	DT-500 DRC is basic interchangeable sensor for DRC series instruments.
TG-100P-GR DT-500P-GR	8	Standard varsion Sama as Ref #4 – Short lead – Anode		.12 3.0	.35 8.9	1.0 25.4	.06 1.5	2, Plat.— 10% Ir	.01 .25	0.19 gr.	Platinum and glass header set into a gold plated copper cylinder	TG-100P or DT-500P set into gold plated copper cylinder
TG-100FP DT-500FP	9	Gold laad—anode Plat lead—cathoda		.06 1.5	—	1.0 25.4	—	1 gold, 1 plat.— 10% Ir	Anode .002 .05 Cathode .005 .13	25 mg.	Platinum, Gold and Epoxy	No ferromagnetic materials are utilized in the construction of these sensors
CGR-1, GR-200A	10	See Installation & Application Notas for Cryogenic Sensors		.120 3.05	.335 8.5	8 152	0-.025 0-.6	4 Phoaphor-Bronze	32 AWG Polylmida Insulated	0.36 gr.	BeO Ceramic header set into a gold plated copper cylinder & an epoxy lead strain relief	Sensor has ^{4}He in can to act as a heat transfer medium. ^{3}He and other gases are avail.
GR-200B	11	See Installation & Application Notes for Cryogenic Sensors		.093 2.36	.240 6.1	8 152	0-.025 0-.8	4 Phosphor-Bronze	.006 .15	0.16 gr.	BeO Ceramic header set into a gold plated copper cylinder & an epoxy lead strain relief	Sensor has ^{4}He in can to act as a heat transfer medium. ^{3}He and other gases are avail.
CS-400-GR	12	Interchangaable – Leads have no polarity		.125 3.18	.335 8.5	6 152	.1 2.5	2, Copper	36 AWG	0.64 gr.	Platinum, Glass and Epoxy	Sensor can is completely filled with sensor element, glass, and epoxy
CS-400FP	13	Interchangeable – Leads have no polarity		A=.107 2.7 A1=.044 1.1	.340 8.6	1.0 25.4	.06 1.5	2 Silver	.008 .2	0.13 gr.	Glass-dimensions are nominal, due to manufacturing constraints	No ferromagnetic materials are utilized in the construction of CS 400 sensors
DT-500-CU-36 DT-500-CU-DRC-36	14			.313 8	.130 3.3	.109 2.8	.10 2.5	4 Phosphor-Bronze 36" long	36 AWG	1.45 gr.	OFHC Copper, Epoxy and Phosphor-Bronze	Leads are Haat Sinked to Copper Block. DT-500 CU-DRC-36 Basic Inter-changeable Sensor for DRC Series Instruments.

OTHER CONFIGURATIONS ENGINEERED ON REQUEST

BULLETIN HB-1

H4A
H6A
H7A
H8A
SERIES

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 gyros, 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, gyros, 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.

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

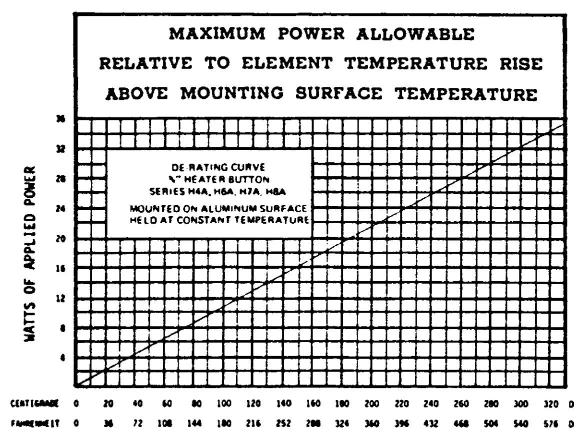
MINIATURE HEATER-BUTTONS

SPECIFICATIONS

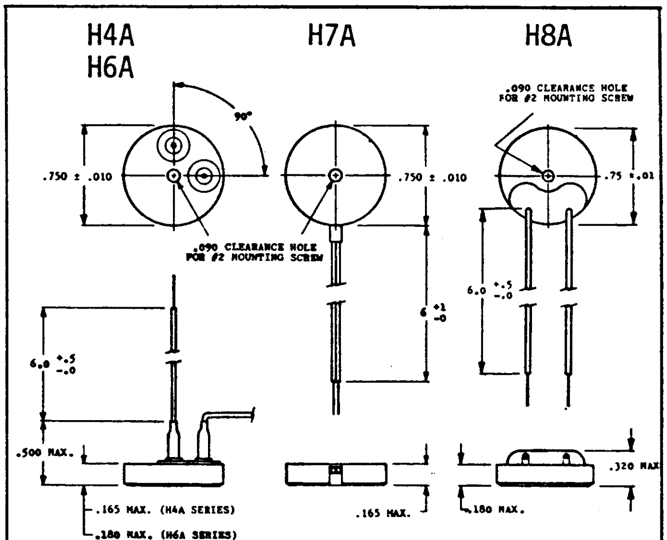
WATTAGE	MODEL NO. 115 Volts AC or DC				MODEL NO. 28 Volts AC or DC			
	STANDARD	ENV. SEALED	LOW PROFILE	ENV. SEALED LOW PROFILE	STANDARD	ENV. SEALED	LOW PROFILE	ENV. SEALED LOW PROFILE
2	H4A2W115	H6A2W115	H7A2W115	H8A2W115	H4A2W28	H6A2W28	H7A2W28	H8A2W28
5	H4A5W115	H6A5W115	H7A5W115	H8A5W115	H4A5W28	H6A5W28	H7A5W28	H8A5W28
10	H4A10W115	H6A10W115	H7A10W115	H8A10W115	H4A10W28	H6A10W28	H7A10W28	H8A10W28
15	H4A15W115	H6A15W115	H7A15W115	H8A15W115	H4A15W28	H6A15W28	H7A15W28	H8A15W28
20	H4A20W115	H6A20W115	H7A20W115	H8A20W115	H4A20W28	H6A20W28	H7A20W28	H8A20W28

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.



ELEMENT TEMPERATURE RISE
ABOVE MOUNTING SURFACE TEMPERATURE



POWER RATING DETERMINATION

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.

PHYSICAL SPECIFICATIONS

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

CASE: Nickel plated brass. Crimped closure on H4A Heaters, H7A Heaters, and HS4A Heater-Sensor. Crimped and solder-sealed closure on H6A and H8A Heaters.

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

TERMINALS: Glass-to-metal sealed feed-thru on H4A, H6A, and HS4A Models. Potted leads on H7A. Potted terminals on H8A Models.

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

[1] Balister, Michael. Temperature Readout Unit for the Lake Shore Cryo-Cryotronics Silicon Diode Sensors (DT-500 Series). Electronics Division Internal Report No. 204. Green Bank, WV: NRAO, 1980.

[2] Childs, G., L. Ericks and R. L. Powell. Thermal Conductivity of Solids at Room Temperature and Below. NBS Monograph 131. Boulder, Colorado: NBS, 1973.

[3] Fisher, J. R. Typical Heat Loads in a Cryogenic Receiver Dewar and a Discussion of the Refrigerator Principles of Operation. RPP 2311 (L): April 1979.