SRI-MME-92-564-7079

SRB THERMAL CURTAIN DESIGN SUPPORT

NOVEMBER 1992 FINAL REPORT TO

U.S. POLYMERIC
B.P. CHEMICALS
SANTA ANA, CALIFORNIA 92705

PURCHASE ORDER NUMBER 62550

PRIME CONTRACT NUMBER NAS8-38261

Southern Research Institute

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November 1992 Final Report

to

U.S. POLYMERIC
B.P. CHEMICALS
Advanced Materials Division
Fibers and Materials
700 East Dyer Road
Santa Ana, California 92705

Purchase Order Number 62550

Prime Contract Number NAS8-38261

by

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November 1992

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1.0 INTRODUCTION

This is the final report for work performed for B.P. Chemicals under purchase order number 62550, NASA prime contract NAS8-38261, "SRB Thermal Curtain Redesign Support". This report covers the period from 1 January 1990 to 31 December 1992.

The objective of the program during this time period was to evaluate candidate materials that could be used to design an improved Aft Skirt Thermal Curtain (ASTC) for both the Solid Rocket Booster (SRB) and Advanced Solid Rocket Booster (ASRB). The ASTC is a flexible, high temperature, cloth and insulation composite that is used to protect the hardware located inside the aft skirt of the shuttle solid rocket booster (Figure 1.1). The current ASTC consists of nine layers of insulating materials and is 2.58 inches thick (Figure 1.2). The ASTC is made up of twenty four segments. The segments are hand sewn together during installation on the aft skirt (Figure 1.3). The weight of the current ASTC is approximated at about six hundred pounds. This weight does not include the weight of the mounting hardware and ties required to install the twenty four ASTC segments (which is significant).

The effort entailed measuring the thermophysical properties of six candidate materials and then using these properties in a computer program to predict the thermal performance of various curtain configurations subjected to both SRB and ASRB heat fluxes. An optimum configuration was to be determined. The candidate materials under consideration were supplied by B.P. Chemicals and consisted of quartz, S-glass and Kevlar woven into nominal 0.25 inch thick layers by a unique process known as angle-interlock and polar-weave. The polar-weave material is a modification of the angle-interlock weave that has the advantage of being able to be woven about a radius. This type of weave would vastly simplify the construction of the ASTC by allowing for either a one-piece design or a smaller number of segments. Also, the presence of Kevlar would increase the strength of the ASTC making it less likely to tear from overpressure or flutter. Table 1.1 lists the physical characteristics of the six candidate materials supplied by B.P. Chemicals for thermophysical property measurements.

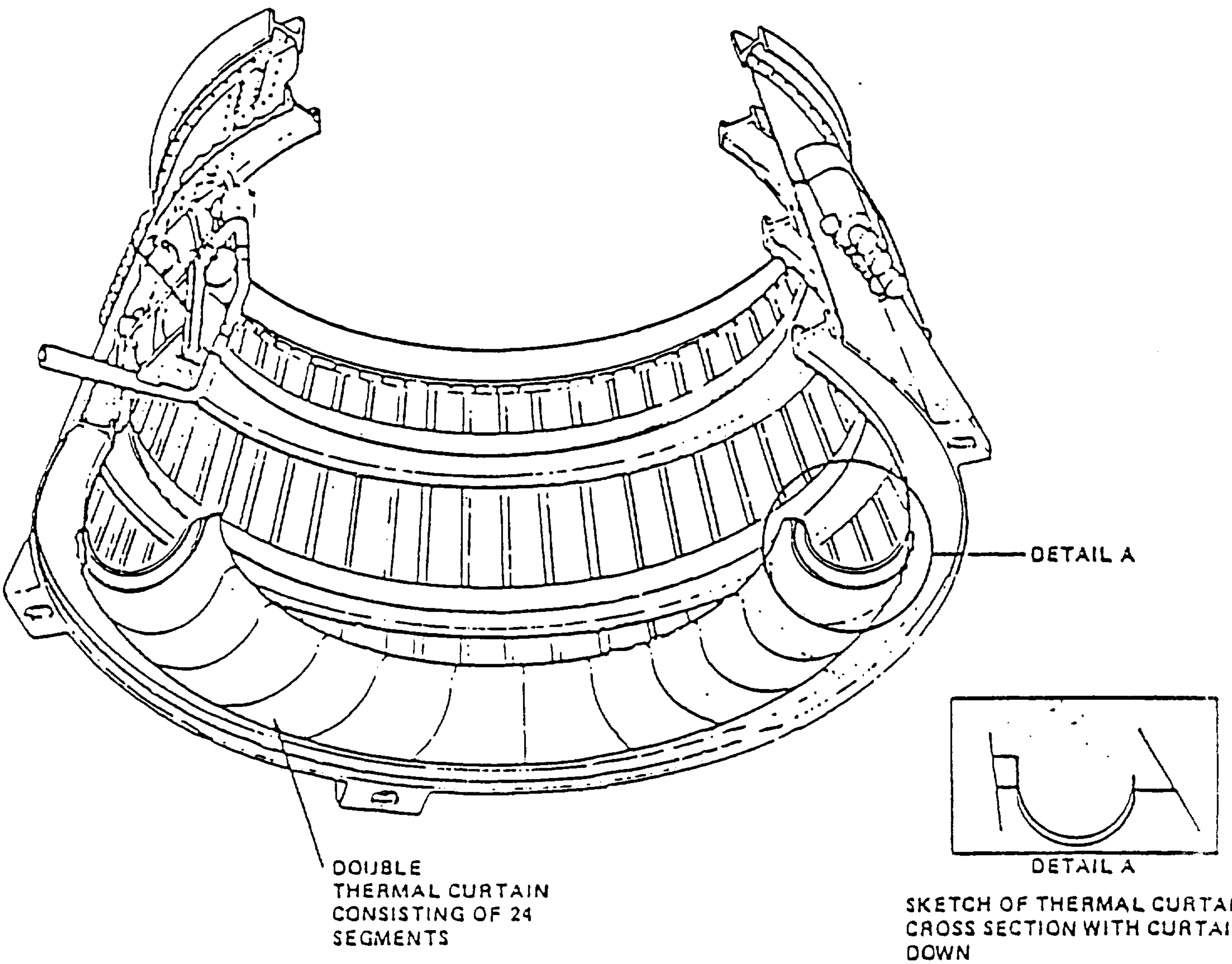


Figure 1.1. Location of Aft Skirt Thermal Curtain

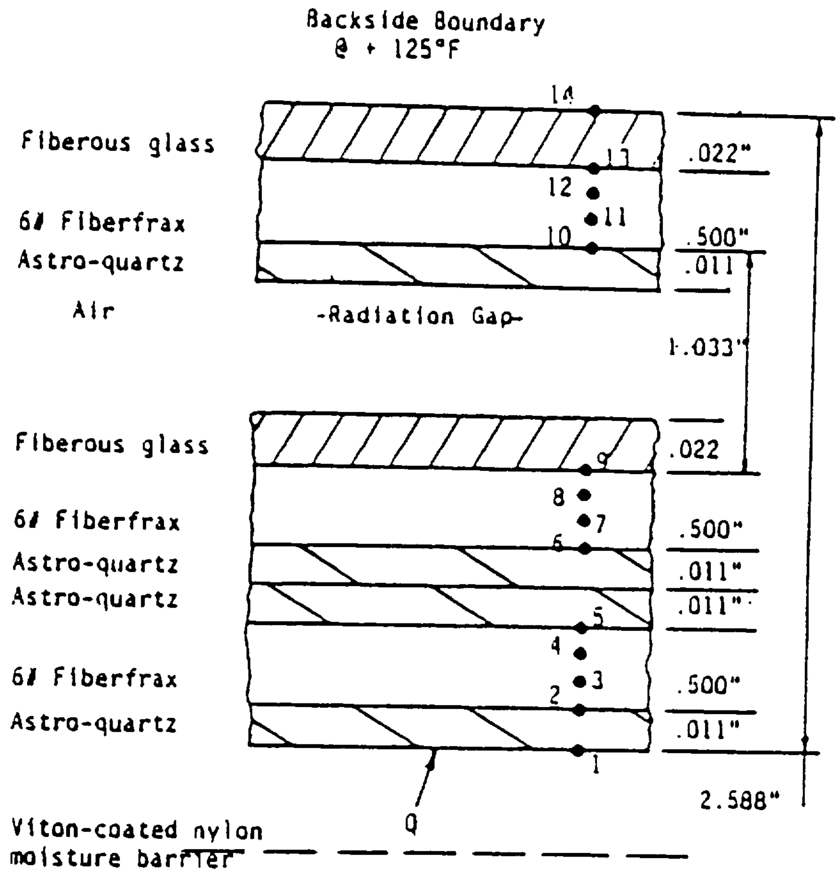
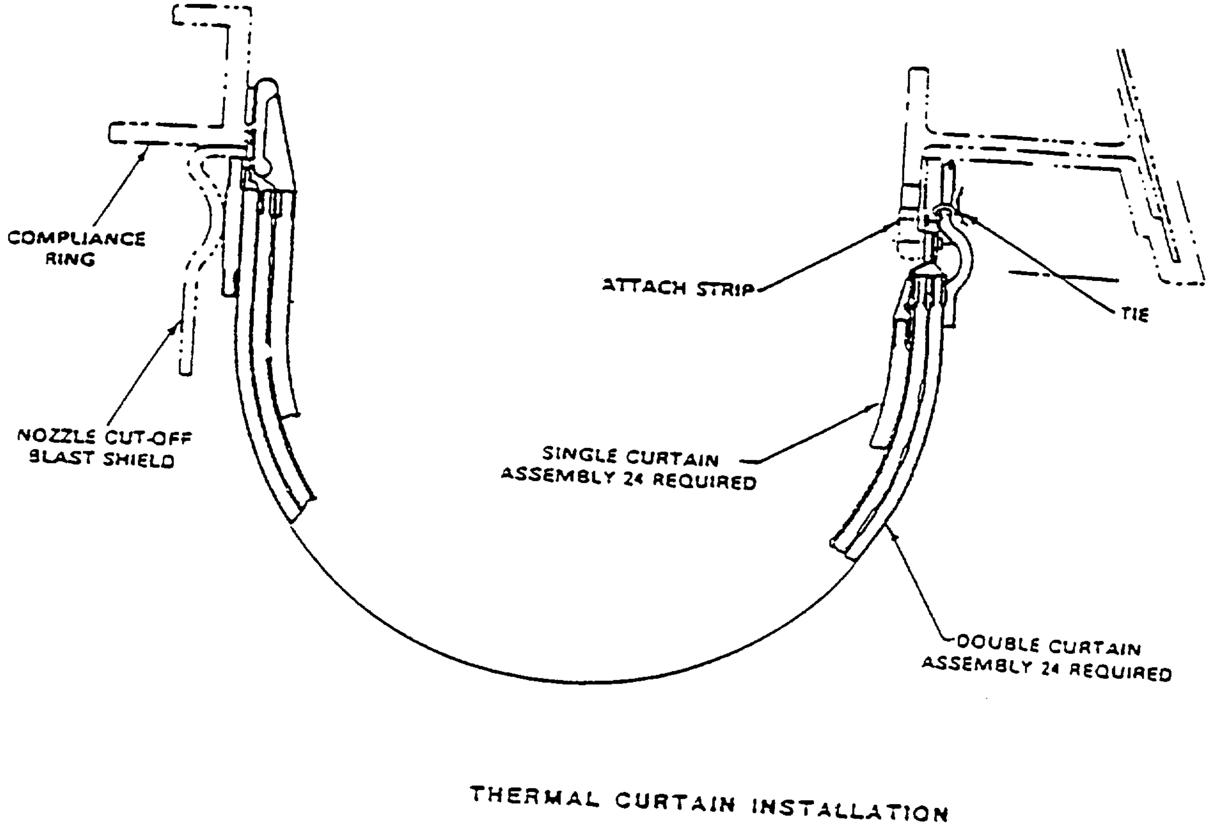


Figure 1.2. Aft Skirt Thermal Curtain Construction



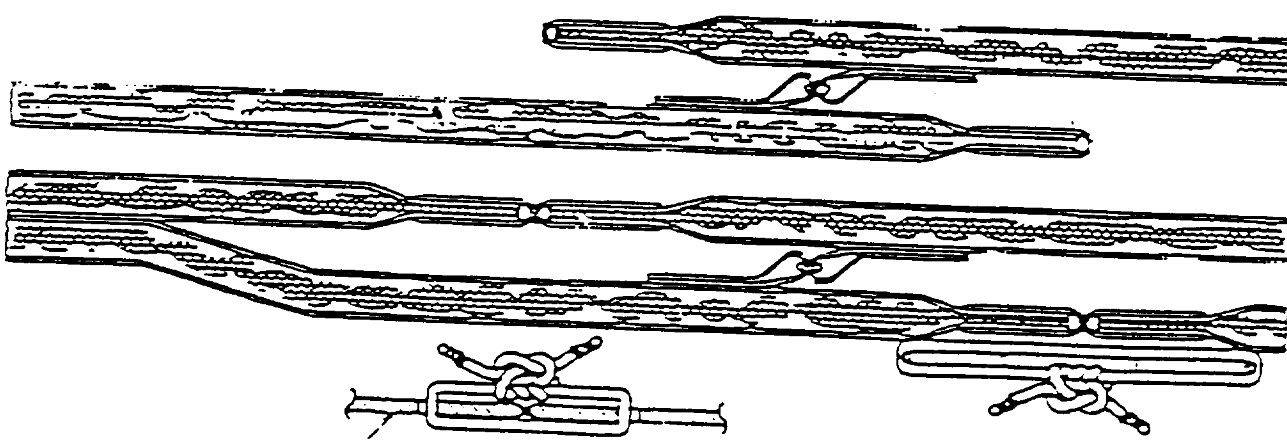


Figure 1.3. Aft Skirt Thermal Curtain Installation

Table 1.1. Physical Characteristics of Candidate ASTC Materials

Material	Warp Count (yarn/in.)	Fill Count (yarn/in.)	Areal Weight (gm/m^2)	Areal Weight ($oz.yd^2$)	Bulk Density (lb/ft3)	Construction
Angle-interlock fabric, Style ES-1742 Kevlar 29 3000 Denier, 12" wide 0.25" thick	117.0	96.0	3329.0	97.87	37.41	9 Warp x 8 Fill
Angle-interlock fabric, Style ES-2255 S-2CG 20-End Fiberglass, 12" wide 0.25" thick	117.0	96.0	6086.4	178.9	62.90	9 Warp x 8 Fill
Angle-interlock fabric, Style ES-2256 Quartz 300 2/4/4, 12" wide 0.25" thick	117.0	96.0	5458.6	161.0	53.88	9 Warp x 8 Fill
Polar Weave Fabric, Style ES-2317 Kevlar 29 3000 Denier, 12" wide, 4.5 ft. Radius 0.25" thick	117.0	96.0	3184.0	93.9	37.83	9 Warp x 8 Fill
Polar Weave Fabric, Style ES-2318 Quartz 300 2/4/4, 12" wide, 4.5 ft. Radius 0.25" thick	117.0	96.0	5221.0	154.0	54.69	9 Warp x 8 Fill
Polar Weave Fabric, Style ES-2319 20 End S-2 Glass 12" wide, 4.5 ft. Radius 0.25" thick	117.0	96.0	6802.0	200.6	61.93	9 Warp x 8 Fill

2.0 THERMOPHYSICAL MEASUREMENTS

Values of the specific heat for quartz, S-glass and Kevlar were obtained from literature[1]. Figures 2.1 through 2.3 are plots of specific heat versus temperature for the aforementioned materials. Tables 2.1 through 2.3 are tabulated recommended values of specific heat.

Low temperature thermal conductivity measurements (530 °R to about 1200 °R) were made utilizing the ASTM C-177 guarded hot plate technique described in Appendix A. Measurements were performed on all six materials and the collected data is contained in Appendix B. Figures 2.4 through 2.6 are the thermal conductivity versus temperature curves for the candidate materials. As can be seen, the thermal conductivity of the polar-weave fabric is slightly less than that of the angle-interlock fabric. This is fortunate, since the polar-weave fabric is desired for ASTC design. Tables 2.4 through 2.6 are tabulated recommended values of thermal conductivity. These tables also contain some extrapolated values that are necessary for the thermal analysis. These extrapolated values are explained in section 3.3 of this report.

Optical properties (transmittance, reflectance and emittance) were measured from 1.6 to 26 microns at 530 °R on the polar-weave quartz only. Transmittance data showed the polar-weave quartz to be opaque so no optical properties were required on the S-glass and Kevlar. Reflectance and emittance measurements were subcontracted to Surface Optics Corporation, San Diego, California. Reflectance measurements were taken at three incident angles in both the circumferential and radial orientations. Measurements were performed using a Cary-Integrating Sphere Reflectometer. Values of emittance were calculated from the transmittance and reflectance data. Table 2.7 summarizes the optical properties measurements. Appendix C contains the report from Surface Optics.

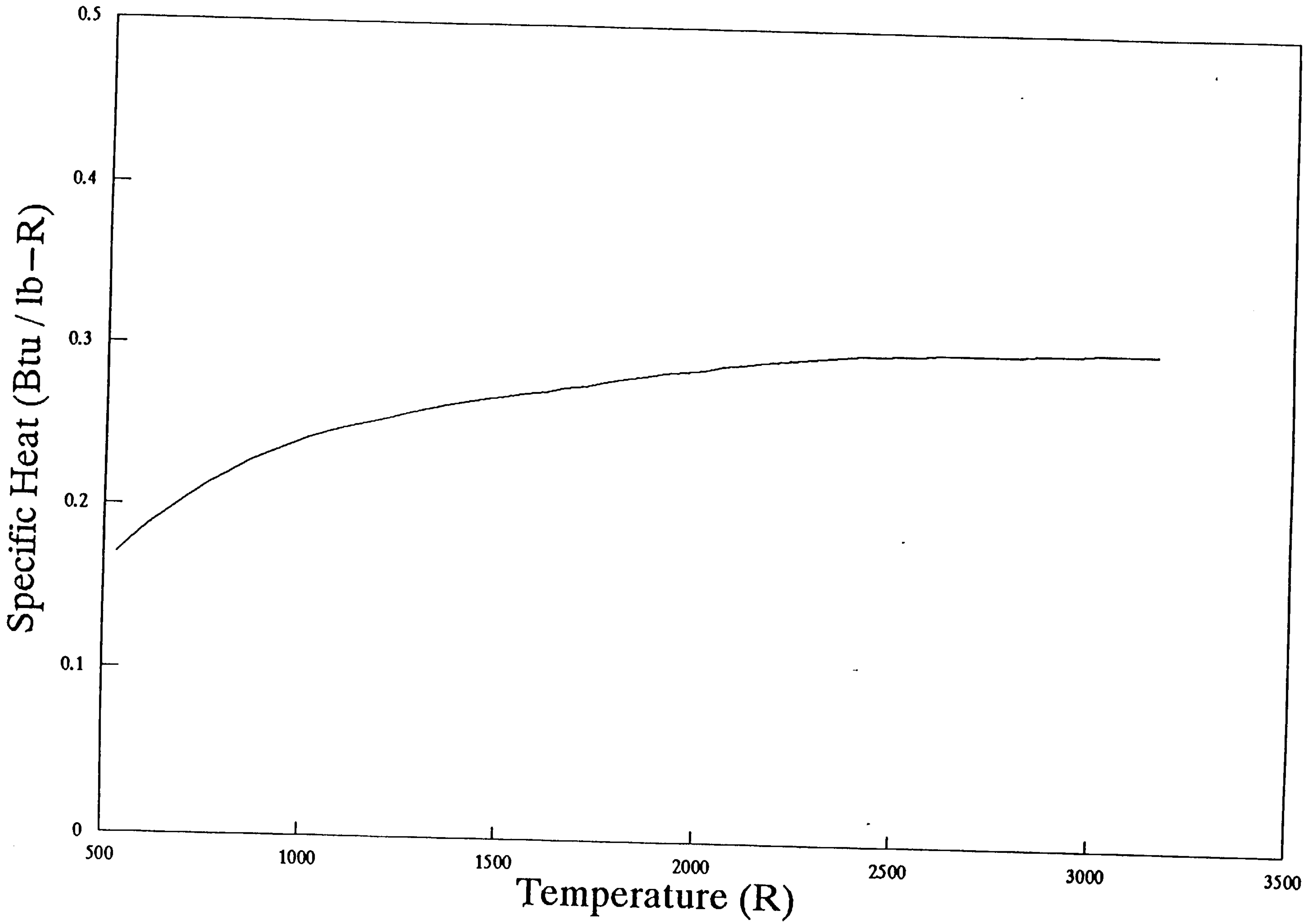


Figure 2.1. Specific Heat of Quartz Fabric

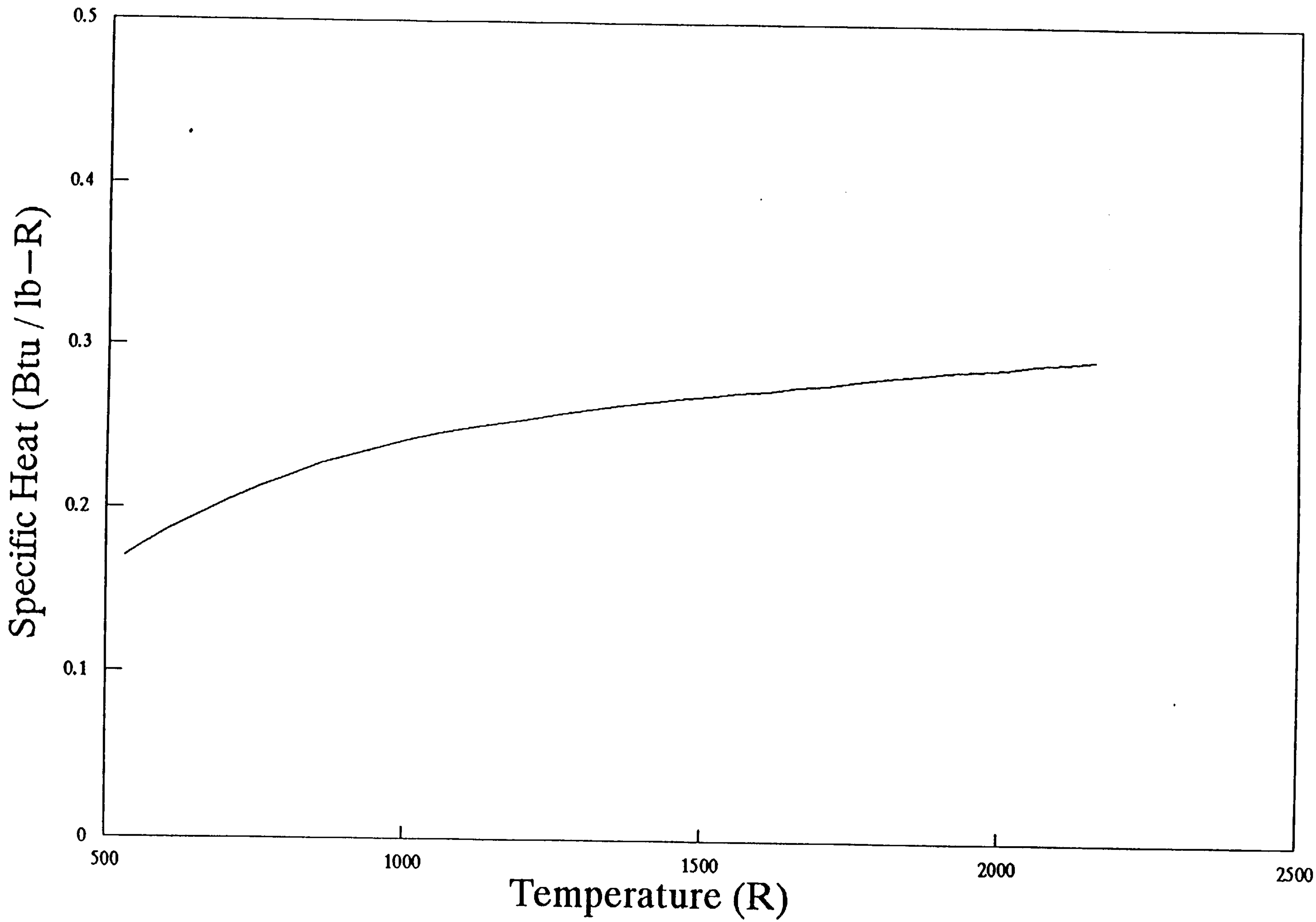


Figure 2.2. Specific Heat of S-Glass Fabric

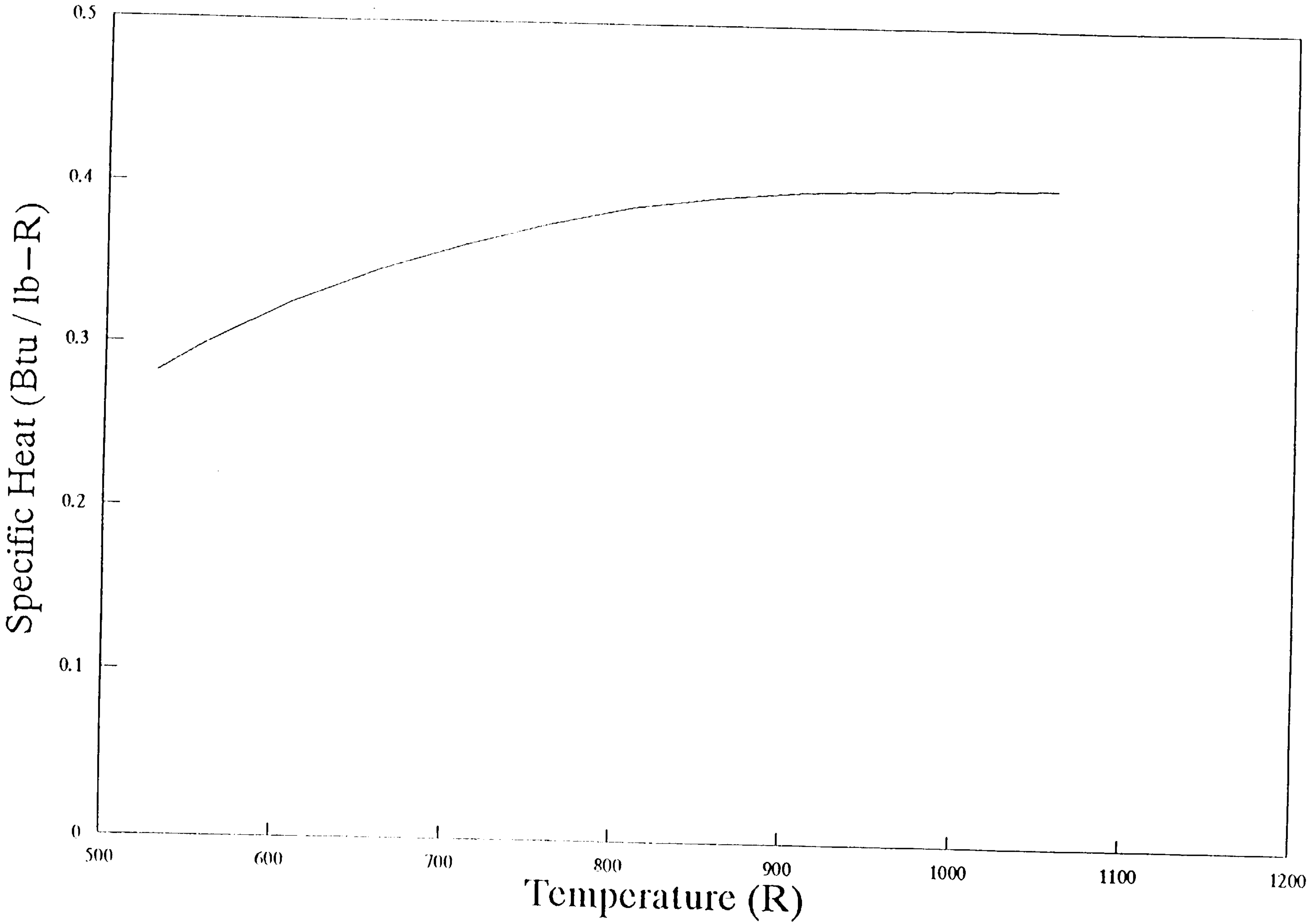


Figure 2.3. Specific Heat of Kevlar Fabric

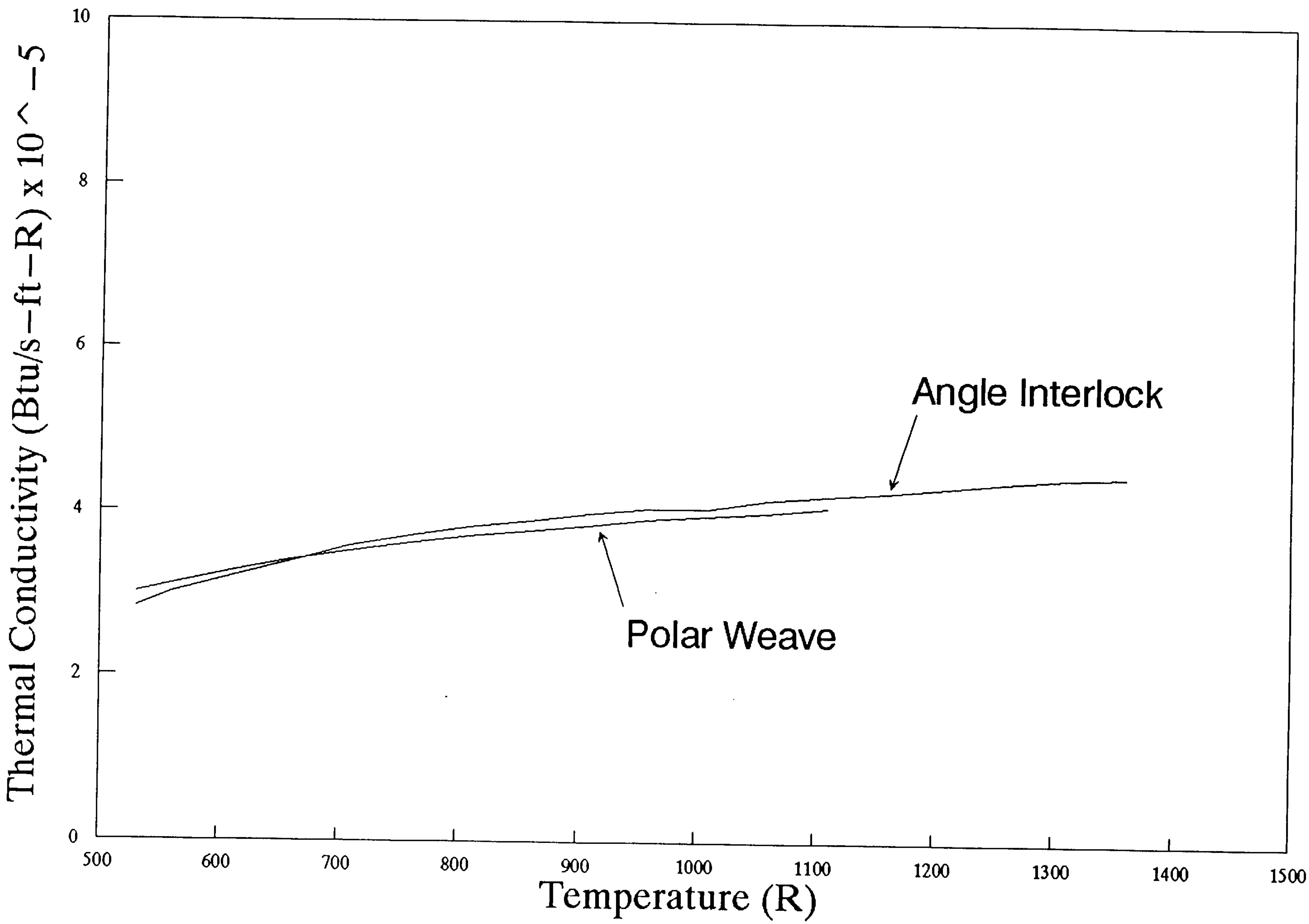


Figure 2.4. Thermal Conductivity of Quartz Fabric

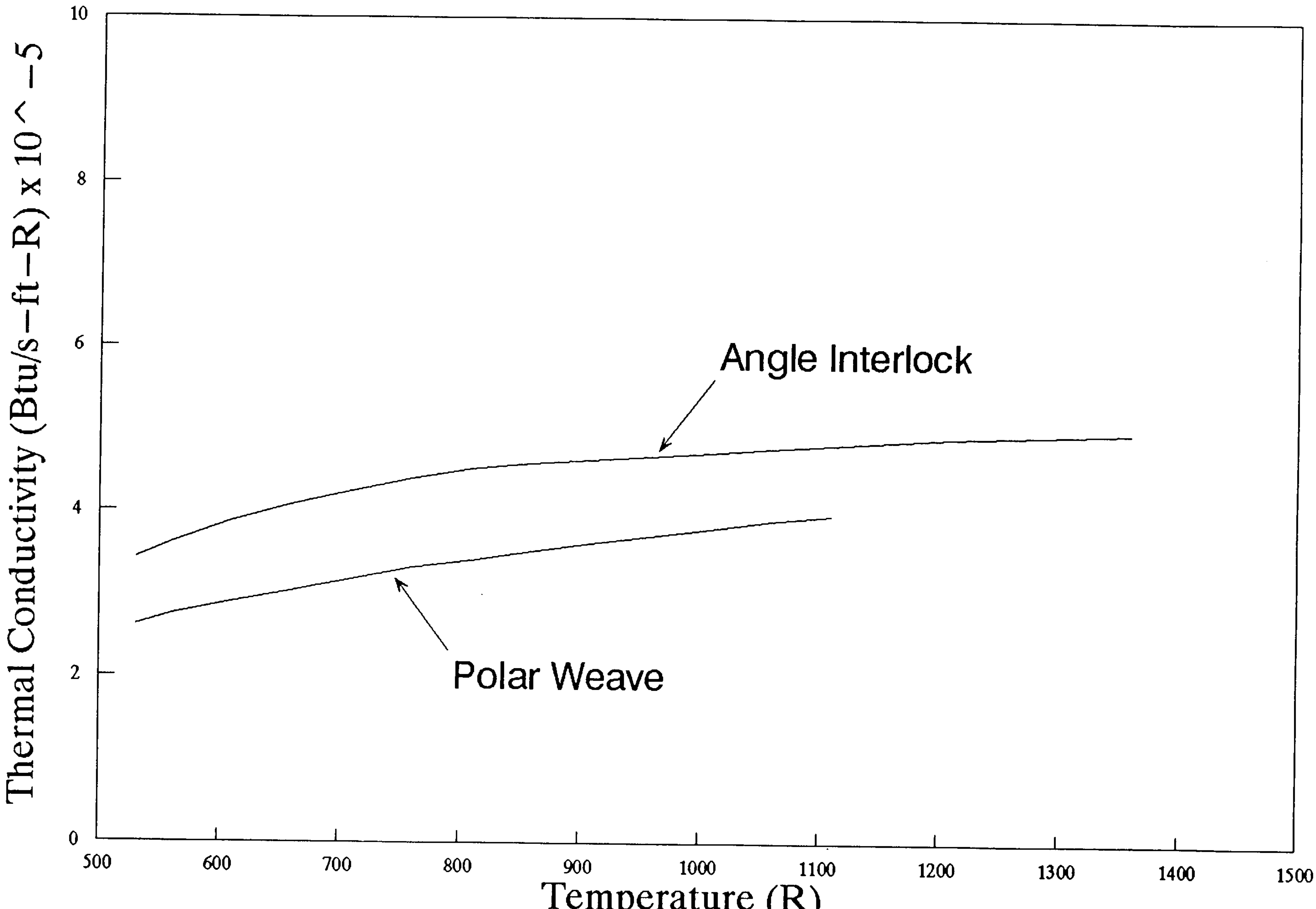


Figure 2.5. Thermal Conductivity of S-Glass Fabric

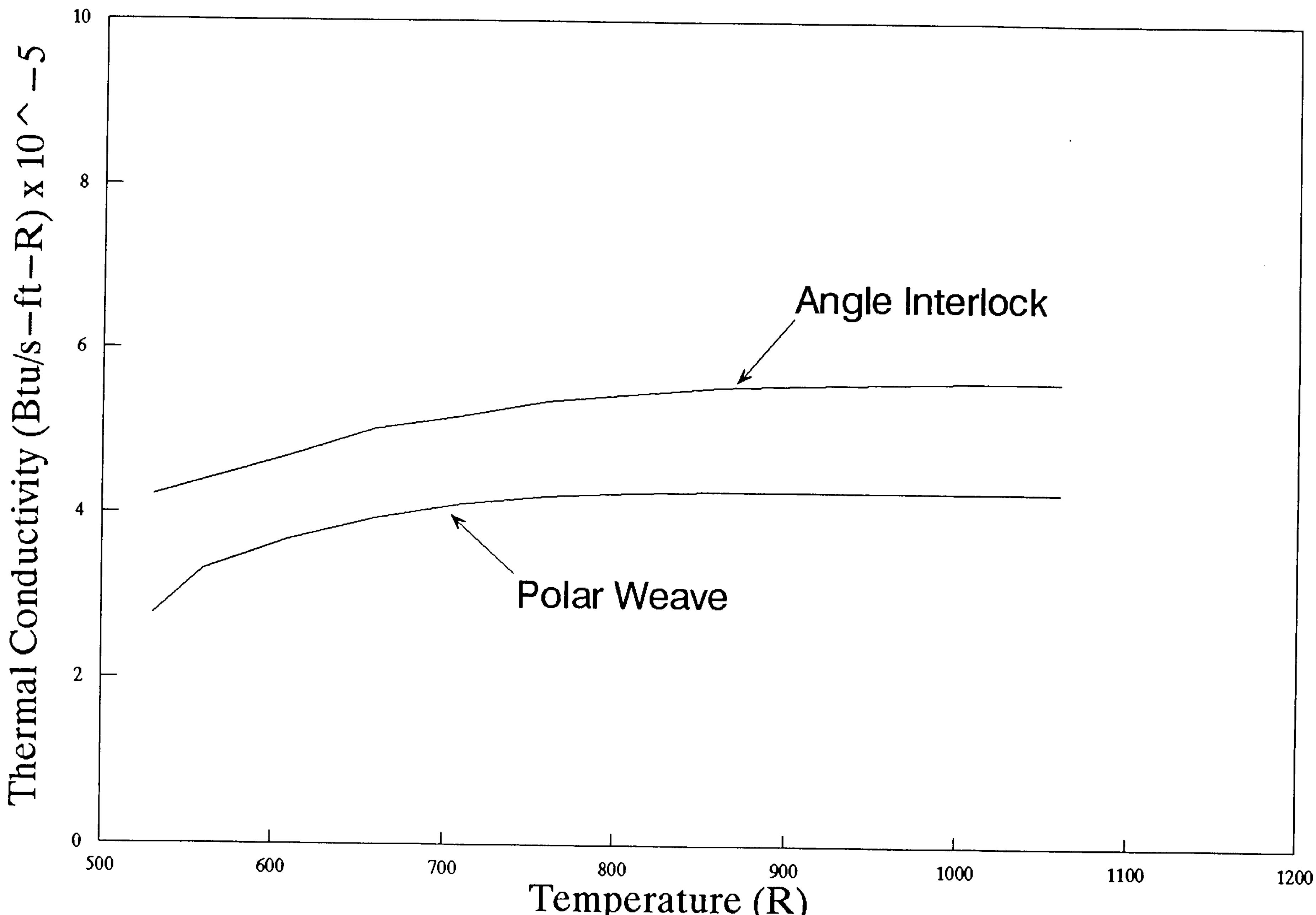


Figure 2.6. Thermal Conductivity of Kevlar Fabric

Table 2.1. Recommended Specific Heat of Quartz Fabric

Temperature (R)	Specific Heat (Btu/lb-R)
530	0.170
560	0.177
610	0.188
660	0.197
710	0.206
760	0.214
810	0.221
860	0.228
910	0.233
960	0.238
1010	0.243
1060	0.247
1110	0.250
1160	0.253
1210	0.256
1260	0.259
1310	0.262
1360	0.265
1410	0.267
1460	0.269
1510	0.271
1560	0.273
1610	0.274
1660	0.277
1710	0.278
1760	0.281
1810	0.283
1860	0.285
1910	0.287
1960	0.288
2010	0.289
2060	0.292
2110	0.293
2160	0.295
2210	0.296
2260	0.297
2310	0.298
2360	0.299
2410	0.300
2460	0.300
2510	0.301
2560	0.301
2610	0.302
2660	0.302
2710	0.302
2760	0.302
2810	0.302
2860	0.303
2910	0.303
2960	0.303
3010	0.304
3060	0.304
3110	0.304
3160	0.304

Table 2.2. Recommended Specific Heat of S-Glass Fabric

Temperature (R)	Specific Heat (Btu/lb-R)
530	0.170
560	0.177
610	0.188
660	0.197
710	0.206
760	0.214
810	0.221
860	0.228
910	0.233
960	0.238
1010	0.243
1060	0.247
1110	0.250
1160	0.253
1210	0.256
1260	0.259
1310	0.262
1360	0.265
1410	0.267
1460	0.269
1510	0.271
1560	0.273
1610	0.274
1660	0.277
1710	0.278
1760	0.281
1810	0.283
1860	0.285
1910	0.287
1960	0.288
2010	0.289
2060	0.292
2110	0.293
2160	0.295

Table 2.3. Recommended Specific Heat of Kevlar Fabric

Temperature (R)	Specific Heat (Btu/lb-R)
530	0.0293
560	0.0400
610	0.0336
660	0.0346
710	0.0362
760	0.0376
810	0.0387
860	0.0394
910	0.0398
960	0.0400
1010	0.0401
1060	0.0402

Table 2.4. Recommended Thermal Conductivity of Quartz Fabric

Temperature (R)	Polar Weave Thermal Conductivity (Btu/sec-ft-R x 10^{-5})	Angle-Interlock Thermal Conductivity (Btu/sec-ft-R x 10^{-5})
530	3.01	2.82
560	3.10	3.01
610	3.26	3.19
660	3.40	3.38
710	3.52	3.59
760	3.61	3.70
810	3.70	3.82
860	3.77	3.89
910	3.84	3.98
960	3.91	4.05
1010	3.96	4.05
1060	4.00	4.17
1110	4.07	4.21
*1160	*4.14	*4.26
1210	4.17	4.33
1260	4.21	4.40
1310	4.28	4.44
1360	4.35	4.47
1410	4.42	4.47
1460	4.49	4.49
1510	4.56	4.56
1560	4.63	4.63
1610	4.68	4.68
1660	4.75	4.75
1710	4.84	4.84
1760	4.93	4.93
1810	5.05	5.05
1860	5.19	5.19
1910	5.35	5.35
1960	5.51	5.51
2010	5.74	5.74
2060	6.02	6.02
2110	6.32	6.32
2160	6.60	6.60
2210	6.94	6.94
2260	7.29	7.29
2310	7.66	7.66
2360	8.06	8.06
2410	8.56	8.56
2460	9.05	9.05
2510	9.65	9.65
2560	10.21	10.21
2610	10.88	10.88
2660	11.46	11.46
2710	12.13	12.13
2760	12.73	12.73
2810	13.26	13.26
2860	13.87	13.87
2910	14.40	14.40
2960	14.98	14.98
3010	15.51	15.51
3060	16.11	16.11
3110	16.67	16.67
3160	17.29	17.29

*Data beyond this point extrapolated

Table 2.5. Recommended Thermal Conductivity of S-Glass Fabric

Temperature (R)	Polar Weave Thermal Conductivity (Btu/sec-ft-R x 10^{-5})	Angle-Interlock Thermal Conductivity (Btu/sec-ft-R x 10^{-5})
530	2.62	3.43
560	2.75	3.61
610	2.89	3.87
660	3.03	4.07
710	3.17	4.24
760	3.31	4.40
810	3.40	4.51
860	3.52	4.58
910	3.61	4.63
960	3.70	4.68
1010	3.80	4.72
1060	3.89	4.77
1110	3.96	4.81
*1160	*4.05	*4.86
1210	4.12	4.91
1260	4.19	4.93
1310	4.26	4.95
1360	4.35	4.98
1410	4.42	4.98
1460	4.49	5.02
1510	4.56	5.05
1560	4.63	5.12
1610	4.68	5.21
1660	4.75	5.30
1710	4.84	5.39
1760	4.93	5.51
1810	5.05	5.67
1860	5.19	5.83
1910	5.35	6.02
1960	5.51	6.20
2010	5.74	6.48
2060	6.02	6.74
2110	6.32	7.06
2160	6.60	7.43

*Data beyond this point extrapolated

Table 2.6. Recommended Thermal Conductivity of Kevlar Fabric

Temperature (R)	Polar Weave Thermal Conductivity (Btu/sec-ft-R x 10^{-5})	Angle-Interlock Thermal Conductivity (Btu/sec-ft-R x 10^{-5})
530	2.78	4.21
560	3.31	4.40
610	3.68	4.70
660	3.94	5.02
710	4.12	5.19
760	4.21	5.37
810	4.26	5.46
860	4.28	5.56
910	4.28	5.58
960	4.28	5.60
1010	4.28	5.63
1060	4.28	5.63

Table 2.7. Optical Properties Measurements at 530°R

Material	Wavelength Range	Zenith Angle (Degrees)	Transmittance	Average Emittance
Polar-Weave Quartz (Circumferential)	1.6-26 Microns	20(near normal)	0%	0.871
		45	0%	0.851
		75	0%	0.789
Polar Weave Quartz (Radial)	1.6-26 Microns	20(near normal)	0%	0.861
		45	0%	0.856
		75	0%	0.794

2.1 CONCLUSIONS

Since the polar-weave fabric was the fabric of choice for construction of an improved ASTC, and since the thermal conductivity of the polar-weave fabric was less than or comparable to the angle-interlock fabric, it was decided to perform all further tests and analysis on curtains employing the polar-weave constructions.

3.0 MODELLING

3.1 COMPUTER PROGRAM

A one-dimensional transient heat transfer computer program was developed to assist in the thermal analysis of the ASTC redesign.

An implicit, forward-differencing technique[2] was used with the nodal spacing taken at the interfaces of a multiple layer curtain configuration. Figure 3.1-1 shows a four node configuration for a proposed three-piece curtain.

The implicit technique involves evaluating an energy balance at a node (the heat flow into a node minus the heat flow out of a node is equal to the amount of heat stored in the node). Table 3.1-1 depicts the nodal equations for a simple four node system. Since the internal nodes are actually composed of two materials the energy storage term is adjusted to reflect an average value. Table 3.1-2 is the matrix form of the nodal equations. Table 3.1-3 lists the matrix coefficients. Gauss-Jordan upper triangularization[3] is used to solve the matrix. Radiant heat flux is varied as a function of time. The SRB and ASRB heat flux curves used (Figures 3.1-2 and 3.1-3)[4] were obtained from NASA thermal design data. Radiation heat transfer at node 1 is approximated by using the emittance at the surface to reduce the net heat flux accordingly.

Although Tables 3.1-1 through 3.1-3 reflect only a four node system the computer program will adjust the matrix according the to the number of layers selected for the configuration.

The current computer program is called "ASTC version 4.0". The program is very user friendly. All user inputs are described in detail on the prompt screens. A copy of the program on a 5-1/4" diskette is attached to the end cover of this report and the source code is contained in Appendix D. An IBM compatible, 386 PC with color VGA is recommended to run this program. To use the program create a directory called "ASTC4" on the PC hard drive. Change to the ASTC4 directory. Copy all programs from the diskette to the ASTC4 directory. To run the program type "astc4" and follow the instructions on the screen.

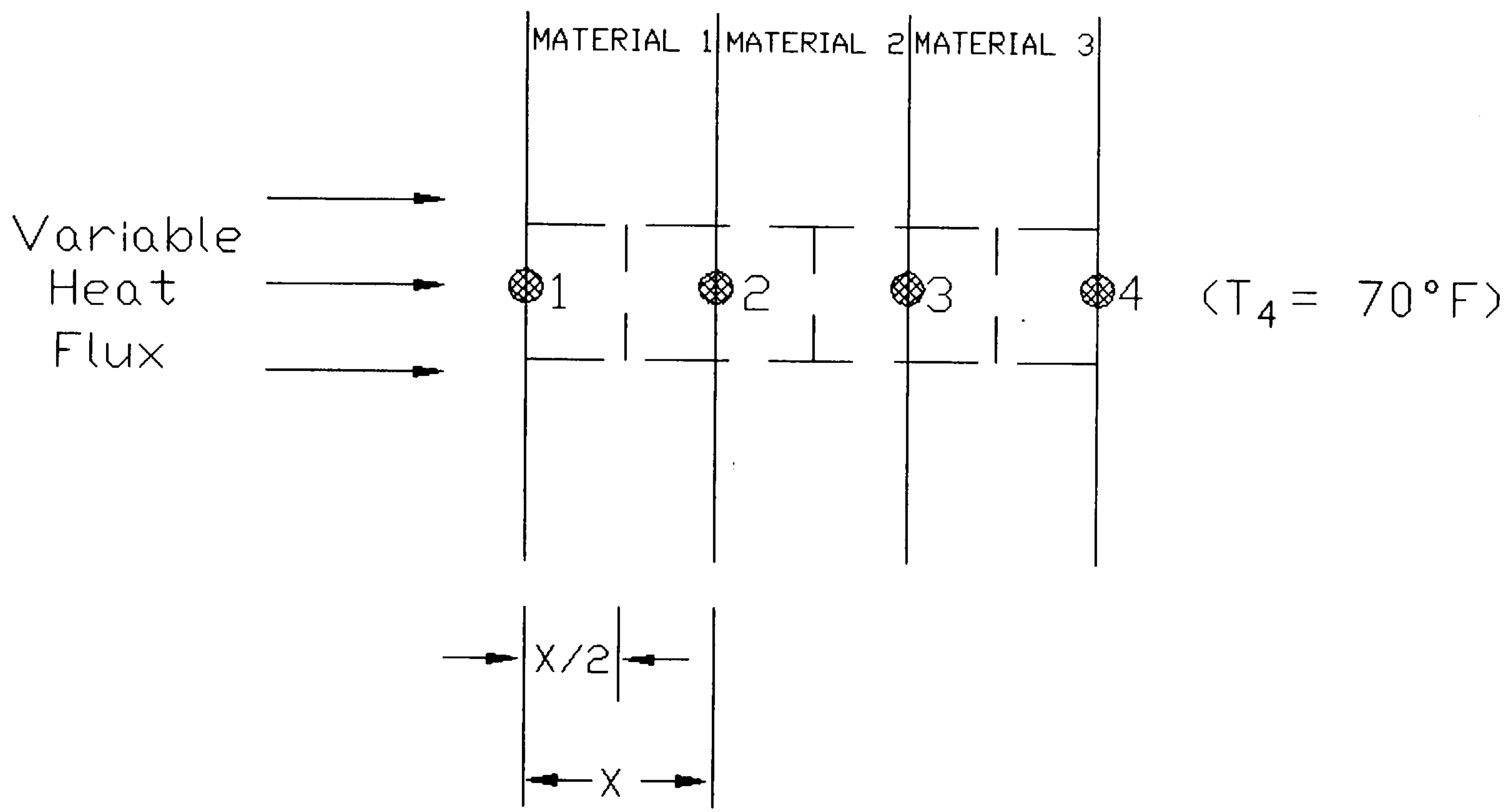


Figure 3.1-1. Four Node Configuration

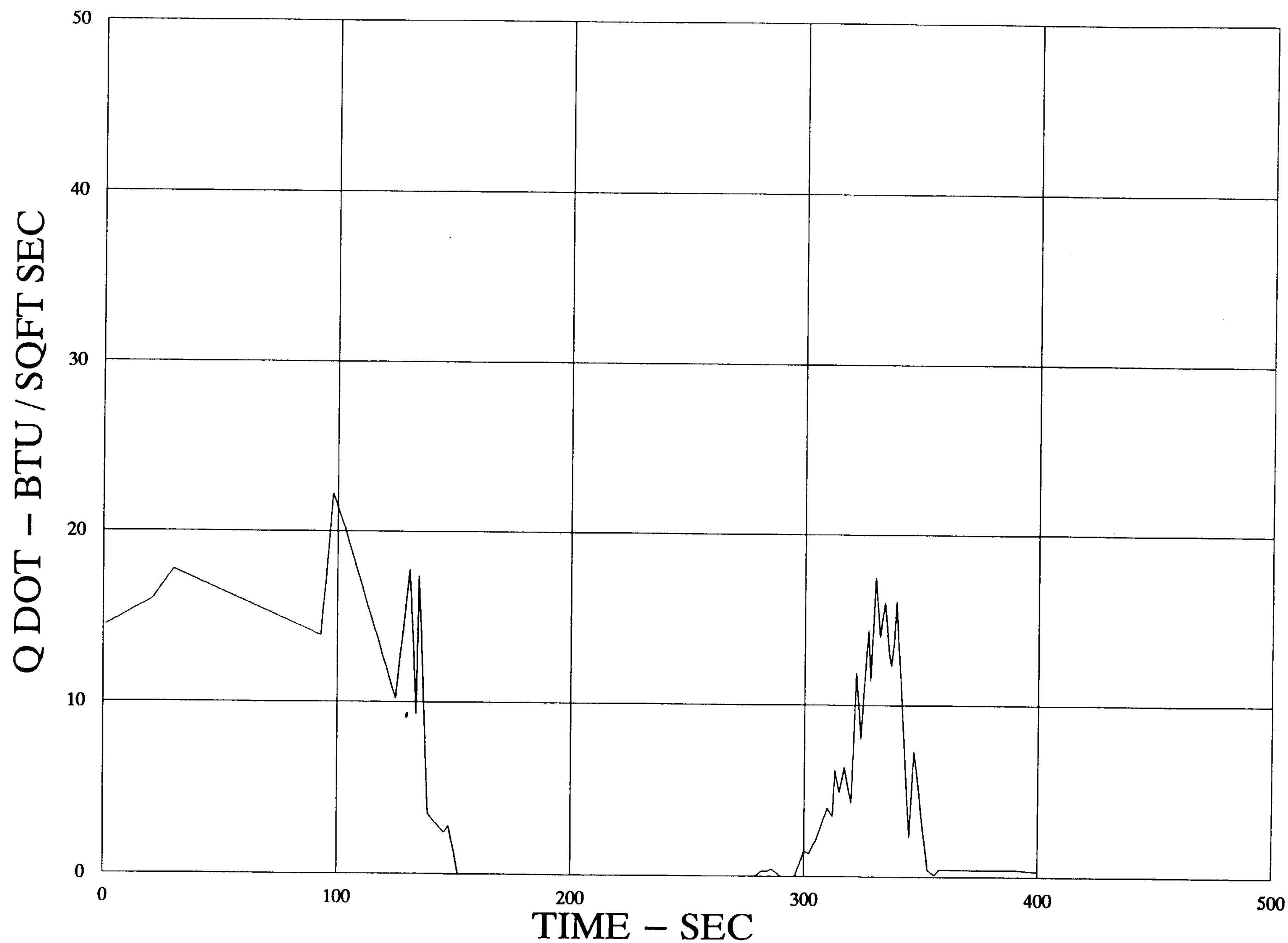


Figure 3.1-2. SRB Heat Flux Input as a Function of Time

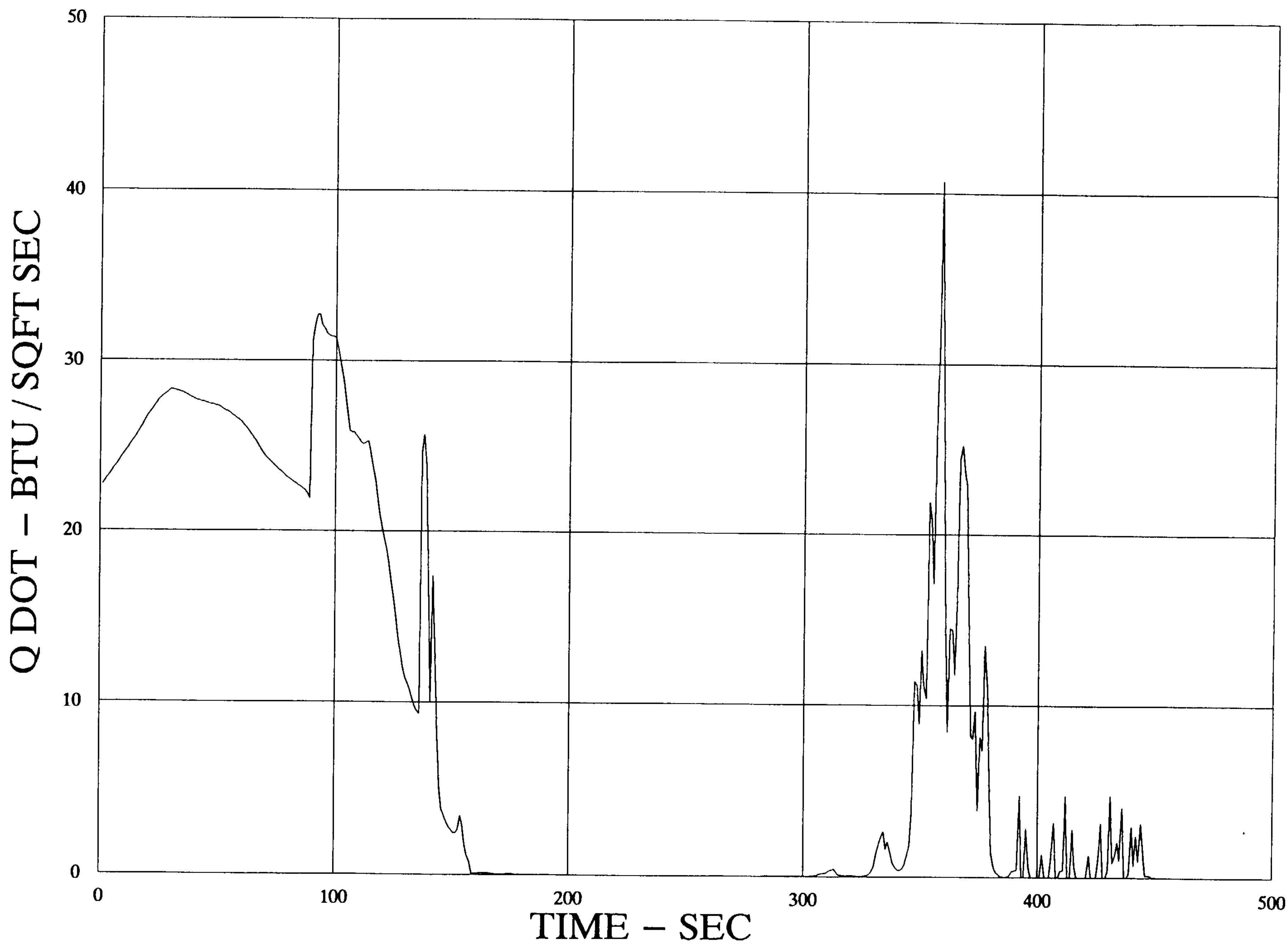


Figure 3.1-3. ASRB Heat Flux Input as a Function of Time

Table 3.1-1

Nodal Equations

Node 1 (given Q)	$\left[1 + \frac{2K_1\Delta t}{\rho_1 C_1 \Delta X^2}\right] T_1{}^1 - \frac{2K_1\Delta t}{\rho_1 C_1 \Delta X^2} T_2{}^1 = \frac{2Q\Delta t}{\rho_1 C_1 \Delta X} + T_1$
Node 2 (Composite)	$\frac{K_1}{\Delta X}\left[T_1{}^1 - T_2{}^1\right] + \frac{K_2}{\Delta X}\left[T_3{}^1 - T_2{}^1\right] = \left[\frac{\rho_1 C_1 + \rho_2 C_2}{2}\right] \frac{\Delta X}{\Delta t}\left[T_2{}^1 - T_2\right]$
Node 3	$\frac{K_2}{\Delta X}\left[T_2{}^1 - T_3{}^1\right] + \frac{K_3}{\Delta X}\left[T_4{}^1 - T_3{}^1\right] = \left[\frac{\rho_2 C_2 + \rho_3 C_3}{2}\right] \frac{\Delta X}{\Delta t}\left[T_3{}^1 - T_3\right]$
Node 4	Fix at some T_4

Table 3.1-2

Matrix Form of Nodal Equations

Node 1 $$\left[1+\frac{2K_1\Delta t}{\rho_1 C_1 \Delta X^2}\right] T_1{}^1 - \left[\frac{2K_1\Delta t}{\rho_1 C_1 \Delta X^2}\right] T_2{}^1 = \left[\frac{2Q\Delta t}{\rho_1 C_1 \Delta X}\right] + T_1$$

Node 2 $$-\left[\frac{2K_1\Delta t}{(\rho_1 C_1+\rho_2 C_2)\Delta X^2}\right] T_1{}^1 + \left[\frac{2\Delta t}{(\rho_1 C_1+\rho_2 C_2)\Delta X}\right]\left[\frac{K_1+K_2}{\Delta X}+\frac{(\rho_1 C_1+\rho_2 C_2)\Delta X}{2\Delta t}\right] T_2{}^1 - \left[\frac{2K_2\Delta t}{(\rho_1 C_1+\rho_2 C_2)\Delta X^2}\right] T_3{}^1 = T_2$$

Node 3 $$-\left[\frac{2K_2\Delta t}{(\rho_2 C_2+\rho_3 C_3)\Delta X^2}\right] T_2{}^1 + \left[\frac{2\Delta t}{(\rho_2 C_2+\rho_3 C_3)\Delta X}\right]\left[\frac{K_2+K_3}{\Delta X}+\frac{(\rho_2 C_2+\rho_3 C_3)\Delta X}{2\Delta t}\right] T_3{}^1 - \left[\frac{2K_3\Delta t}{(\rho_2 C_2+\rho_3 C_3)\Delta X^2}\right] T_4{}^1 = T_3$$

Table 3.1-3

Matrix Coefficients

$$A_{11} = [1 + 2K_1 \Delta T/\rho_1 C_1 \Delta X^2]$$

$$A_{12} = -[2K_1 \Delta t/\rho_1 C_1 \Delta X^2]$$

$$A_{21} = -[2K_1 \Delta t/(\rho_1 C_1 + \rho_2 C_2)\Delta X^2]$$

$$A_{22} = [(2\Delta t/(\rho_1 C_1 + \rho_2 C_2)\Delta X) \ (K_1 + K_2/\Delta X + (\rho_1 C_1 + \rho_2 C_2)\Delta X/2\Delta t)]$$

$$A_{23} = -[2K_2 \Delta t/(\rho_1 C_1 + \rho_2 C_2)\Delta X^2]$$

$$A_{32} = -[2K_2 \Delta t/(\rho_2 C_2 + \rho_3 C_3)\Delta X^2]$$

$$A_{33} = [(2\Delta t/(\rho_2 C_2 + \rho_3 C_3)\Delta X) \ (K_2 + K_3/\Delta X + (\rho_2 C_2 + \rho_3 C_3)\Delta X/2\Delta t)]$$

$$A_{34} = -[2K_3 \Delta t/(\rho_2 C_2 + \rho_3 C_3)\Delta X^2]$$

$$A_{43} = -[2K_3 \Delta t/(\rho_3 C_3 + \rho_4 C_4)\Delta X^2]$$

3.2 ANALOG TEST FACILITY

A quartz lamp thermal flux facility was developed to perform actual tests on curtain configurations constructed by B.P. Chemicals. Figure 3.2-1 is a schematic of this test facility. A sample curtain 12"x12" can instrumented with thermocouples on the surface and between layers and then exposed to either an SRB or ASRB flux shown in Figures 3.1-2 and 3.1-3. A calibrated heat flux transducer can be used to control the flux from the quartz lamps. Data is recorded continuously by a data acquisition system. Data are presented in the form of temperature-time plots.

Some analog testing was also performed independently at NASA/MSFC although only for the SRB flux. A schematic of NASA's analog test setup is shown in Figure 3.2-2. Two blankets are run simultaneously in the NASA facility with thermocouples placed on both the right and left sides of each blanket. The NASA facility does not possess the capability to simulate the SRB flux. Instead, the area under the SRB flux curve is determined and a lower flux is applied for sufficient time to achieve the same integral area. Figure 3.2-3 is the flux applied in the NASA test. Note that the heat flux feedback is measured with the blanket in place while the heat flux reference is measured by a radiation transducer without the blanket. NASA's test setup also allows simulation of the change in pressure the ASTC would experience as the booster climbs through the upper atmosphere (Figure 3.2-4). Data are recorded via an acquisitioner and include incident heat flux, pressure, and temperature as functions of time.

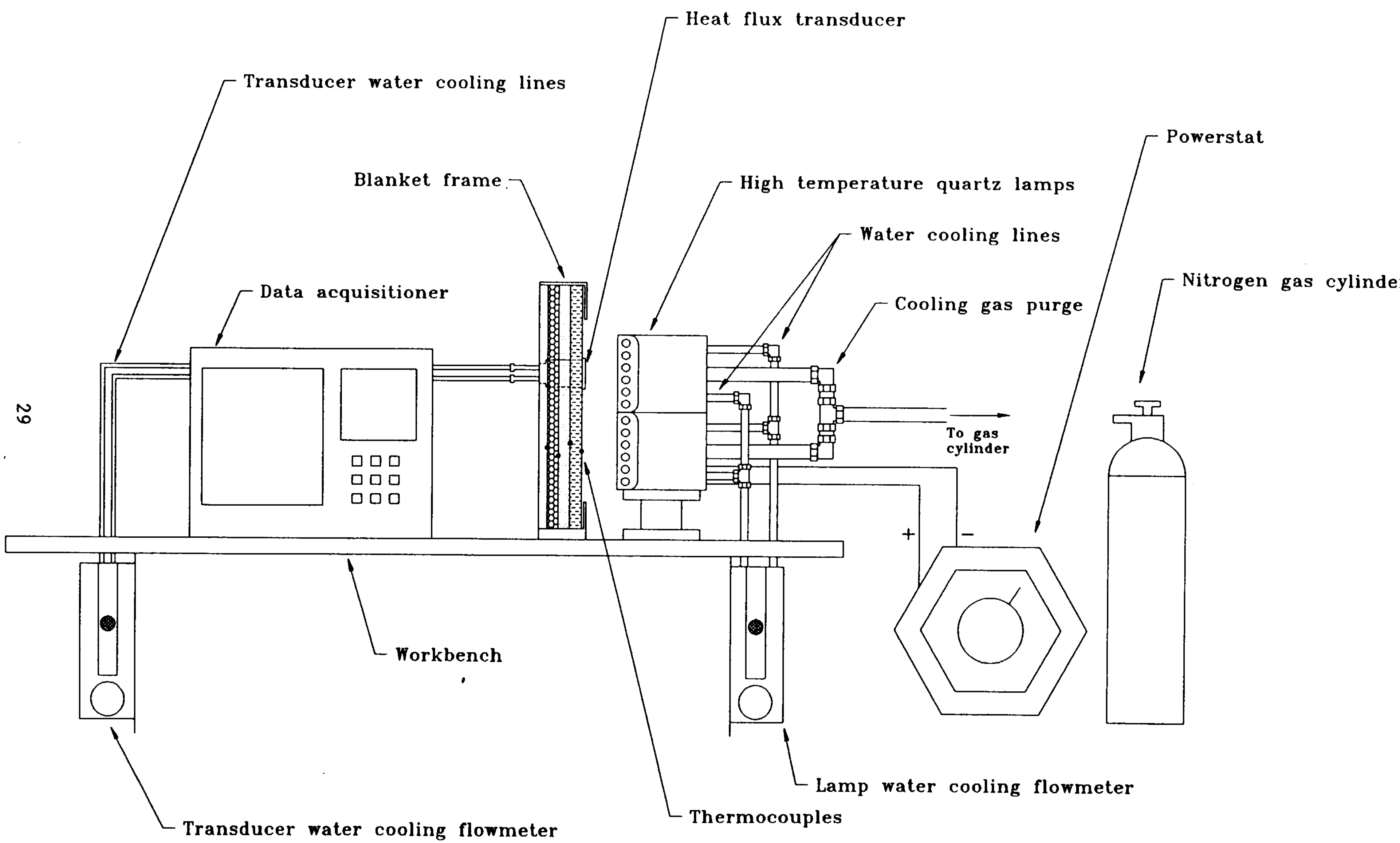
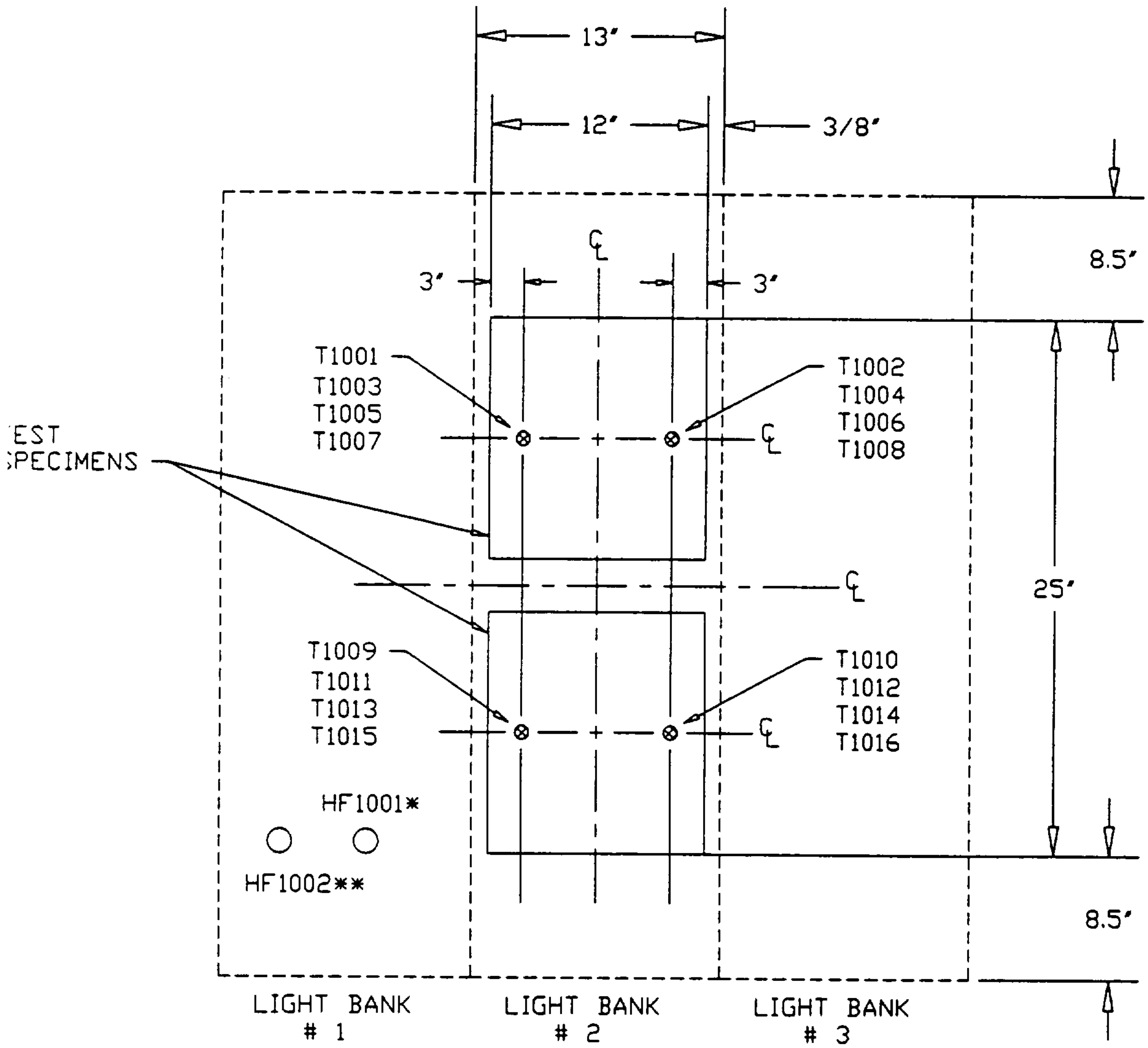


Figure 3.2-1. Schematic of Quartz Lamp Thermal Flux Facility

TEST CONFIGURATION FOR ALTERNATE THERMAL CURTAIN MATERIAL TEST



FACING EAST INSIDE CHAMBER

NOTE: TEST SPECIMEN 6 IN. FROM LAMPS
* HF1001-FEEDBACK
** HF1002-REFERENCE

NOTES:

1. THERMOCOUPLES ARE STAGGERED ± .5' ABOUT VERTICAL CENTERLINE
2. THERMOCOUPLE LEADS FOR 'TOP' THERMOCOUPLES ARE FED BETWEEN 2ND AND 1ST LAYERS WITH THERMOCOUPLE BEAD PROTRUDING THROUGH TOP LAYER

Figure 3.2-2. NASA/MSFC Analog Test Setup

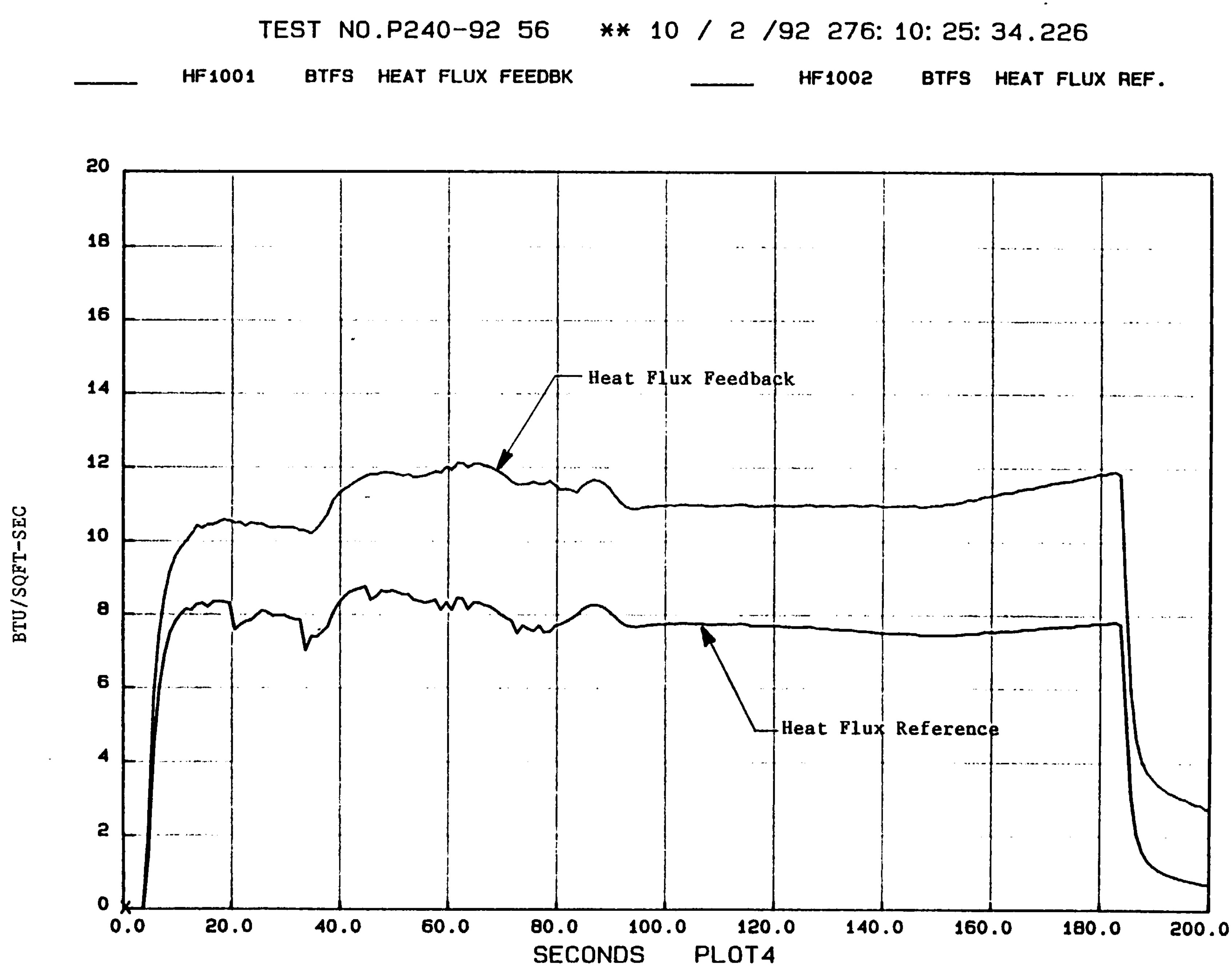


Figure 3.2-3. Incident Heat Flux for NASA Analog Test

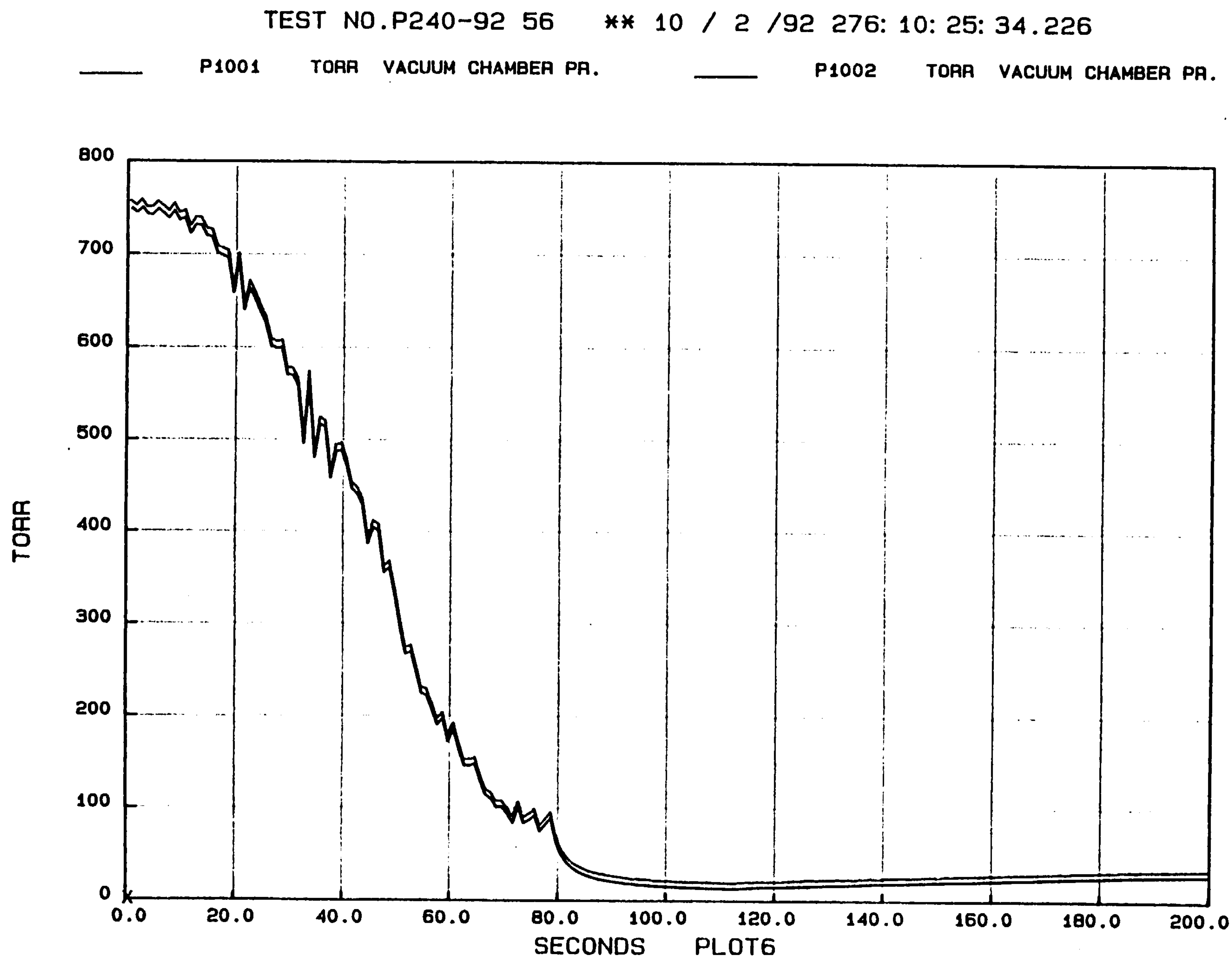


Figure 3.2-4. Vacuum Pressure versus Time for NASA Analog Test

3.3 RESULTS AND CONCLUSIONS

Samples of polar-weave quartz, S-glass and Kevlar, cut 12"x12", were sewn together to form a three-piece curtain for testing in the quartz lamp facility. Although this curtain design is twice as heavy as the current ASTC design (about 1150 lbs versus 600 lbs, not considering hardware installation tradeoffs) the analog data from this particular design can be used to validate the computer program. The sample was instrumented with three thermocouples and exposed to both SRB and ASRB design fluxes for 120 seconds. Three tests were run. Figures 3.3-1 and 3.3-2 show the average thermal response with exposure to SRB and ASRB fluxes, respectively.

Figures 3.3-3 through 3.3-6 show the temperature-time data collected in the NASA facility and Figures 3.3-7 and 3.3-8 compare SRI to NASA data. NASA's surface data is considerably lower than SRI's up to 120 seconds. However, NASA's incident flux was much lower than the SRB flux used in SRI's test and surface temperature variations are to be expected. Note that NASA's surface temperature reached about the same maximum as SRI's but took longer due to the lower flux levels. NASA's data is in excellent agreement with SRI's data for the interior and rear face positions up to around 120 seconds. NASA's maximum temperatures for these positions are somewhat higher than those reached in the SRI experiment. However, due to the lower flux level, NASA's test duration must be considerably longer than SRI's in order to achieve the same area under the flux curve. This additional time allows the blanket to heat longer and is probably the cause of the higher temperatures. Overall, NASA's test would seem to confirm the data taken in SRI's analog test.

Next, the computer program was used to perform a thermal analysis on the three-piece curtain for each flux. Since elevated temperature thermal conductivity was required on the quartz and S-glass an approximation had to be made for these values. Figures 3.3-9 and 3.3-10 represent the approximations selected for the most probable high temperature thermal conductivity of the quartz and S-glass. These values are marked with asterisks in Tables 2.4 and 2.5.

It was estimated that the incident radiation on the ASTC from the rocket motor plume would be approximately 45 degrees[5]. Therefore, an emittance value of 0.85 was selected (see Table 2.7) for the analysis.

Figure 3.3-11 presents the results of the thermal analysis for SRB flux and Figure 3.3-12 shows for the ASRB flux. Figures 3.3-13 and 3.3-14 compare the analog test data and the thermal analysis data for each flux. The surface temperature predictions are within about 20% of the analog data. Considering the limitations of the finite-differencing techniques used, plus some necessary simplifying assumptions made by the program (constant surface emissivity, constant rear face temperature), this is reasonable agreement. The analog interface temperatures were much lower than the predicted temperatures. The computer program has no provision for inputting interfacial resistances that are present in the analog test which probably accounts for the discrepancies.

The surface and rear face temperatures are the controlling design parameters for the ASTC. The computer program yields a conservative result for the surface temperature. However, caution must be exercised in examining the assumption that the rear face will remain at 530 °R. The program predicts that for thinner blankets, the surface and internal temperatures will be lower while the rear face remains at 530 °R. This is not the case. For thinner blankets, the surface and internal temperatures will indeed be lower, but the rear face will experience a greater temperature rise (see section 4.0 for an example). For a very thin blanket, it is possible that the program would indicate an acceptable design when the rear face temperature actually rises above acceptable levels.

The computer program appears to be a viable tool for the preliminary screening of possible ASTC configurations. For a more accurate determination of the configuration's rear face response, analog testing or a finite element analysis is recommended.

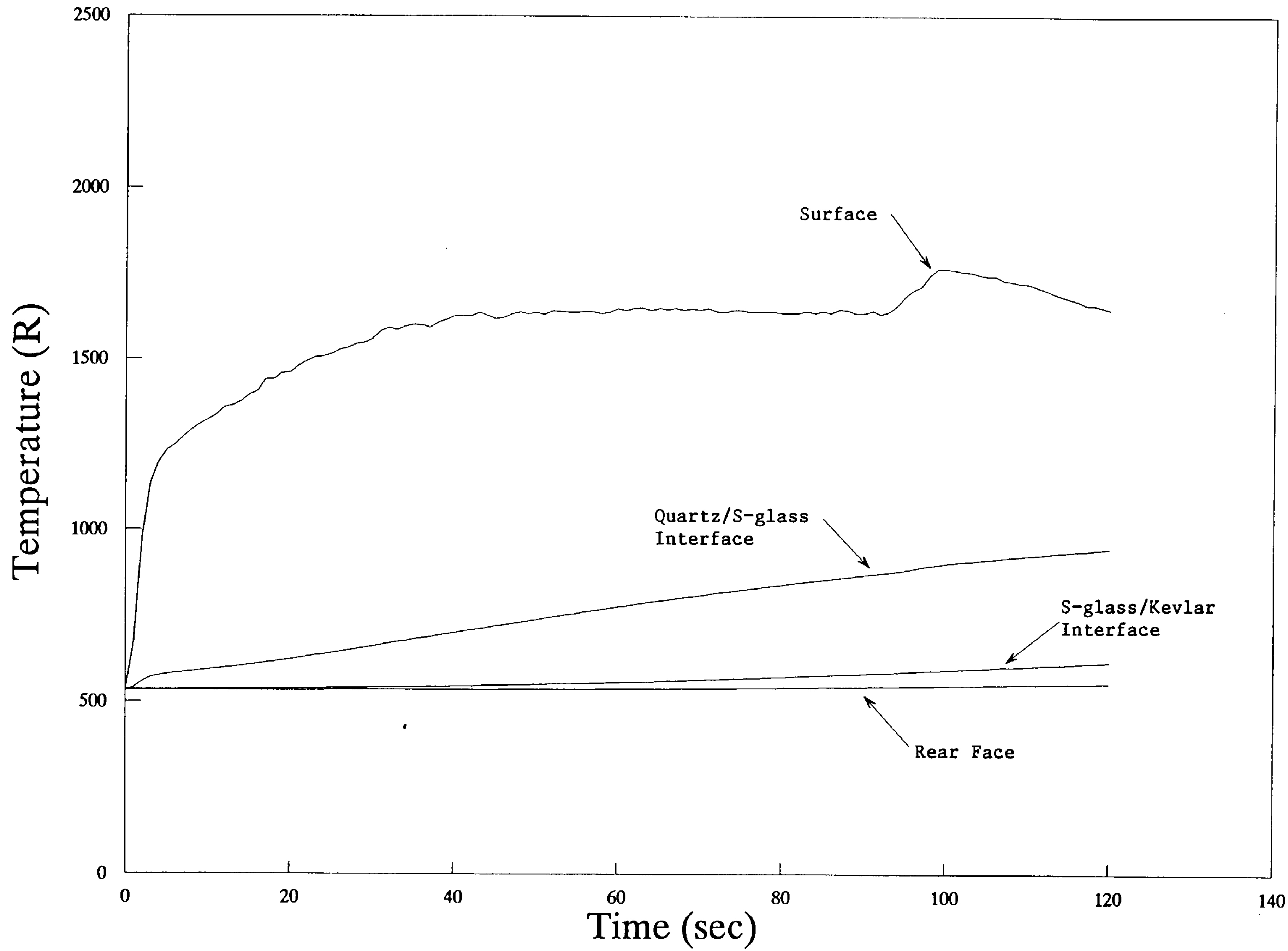


Figure 3.3-1. Analog Test Data for Quartz/S-glass/Kevlar Configuration Exposed to SRB Flux

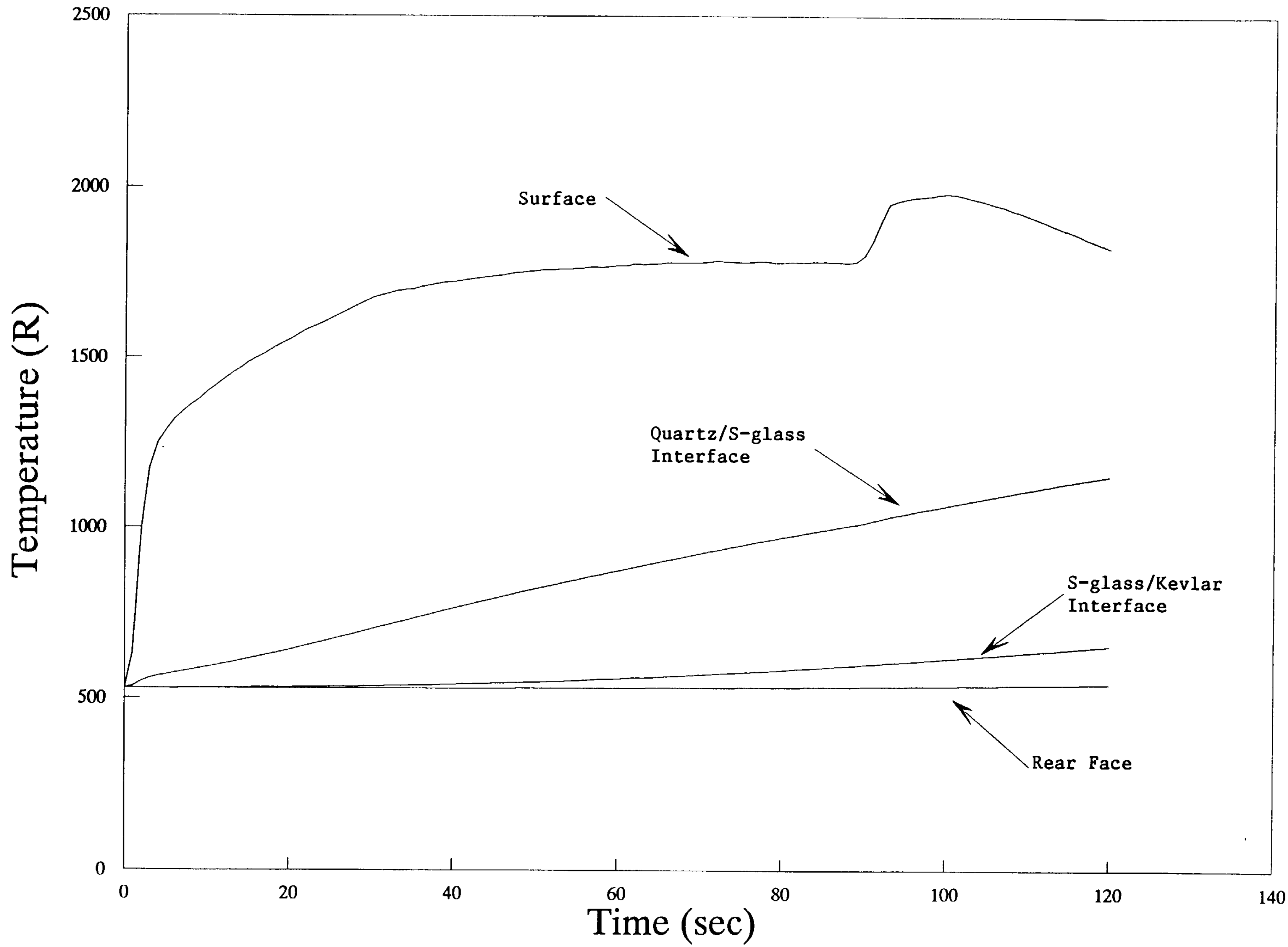


Figure 3.3-2. Analog Test Data for Quartz/S-glass/Kevlar Configuration Exposed to ASRB Flux

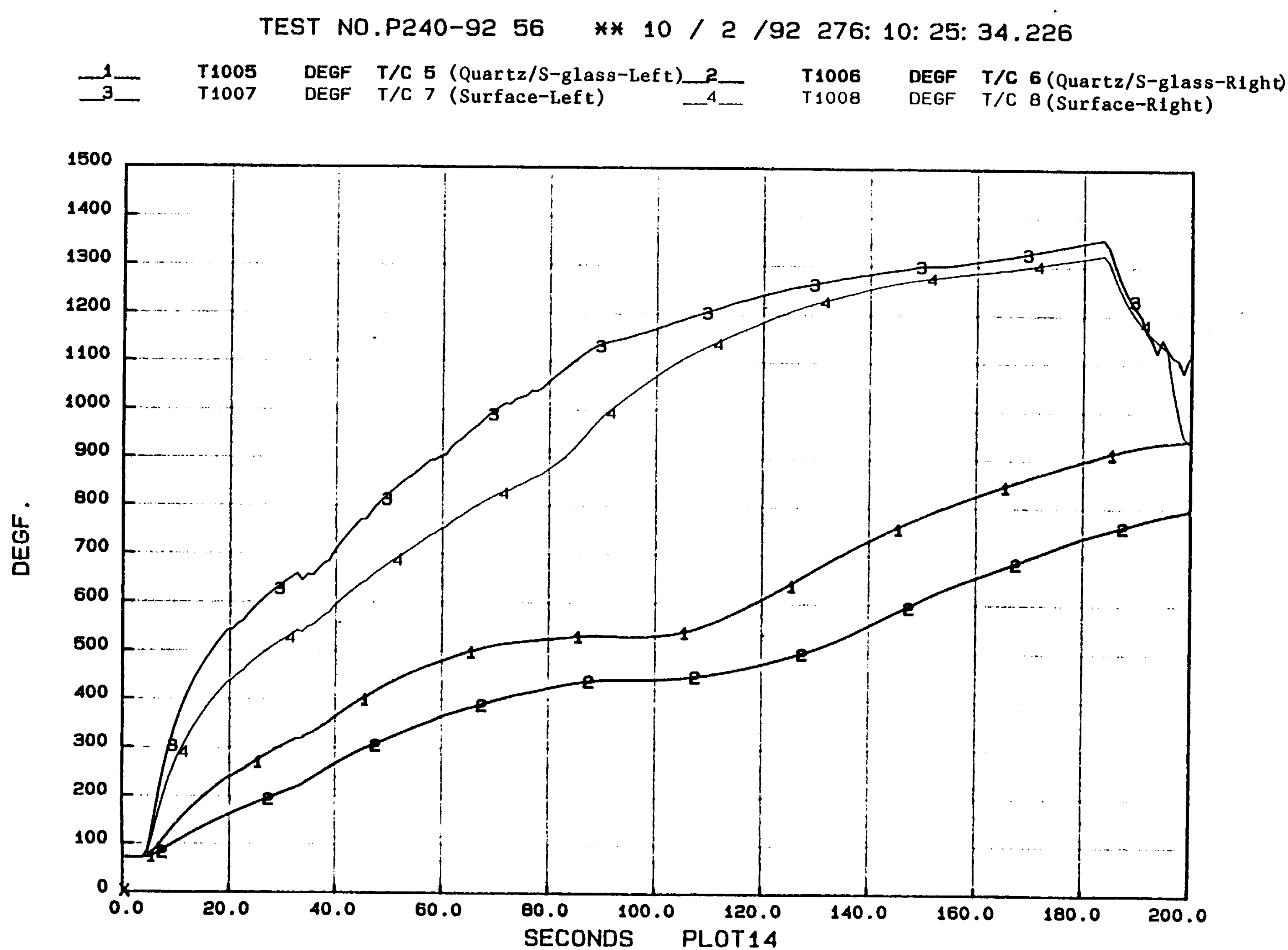


Figure 3.3-3. NASA Analog Test Data for Quartz/S-glass/Kevlar Configuration (Top Specimen)

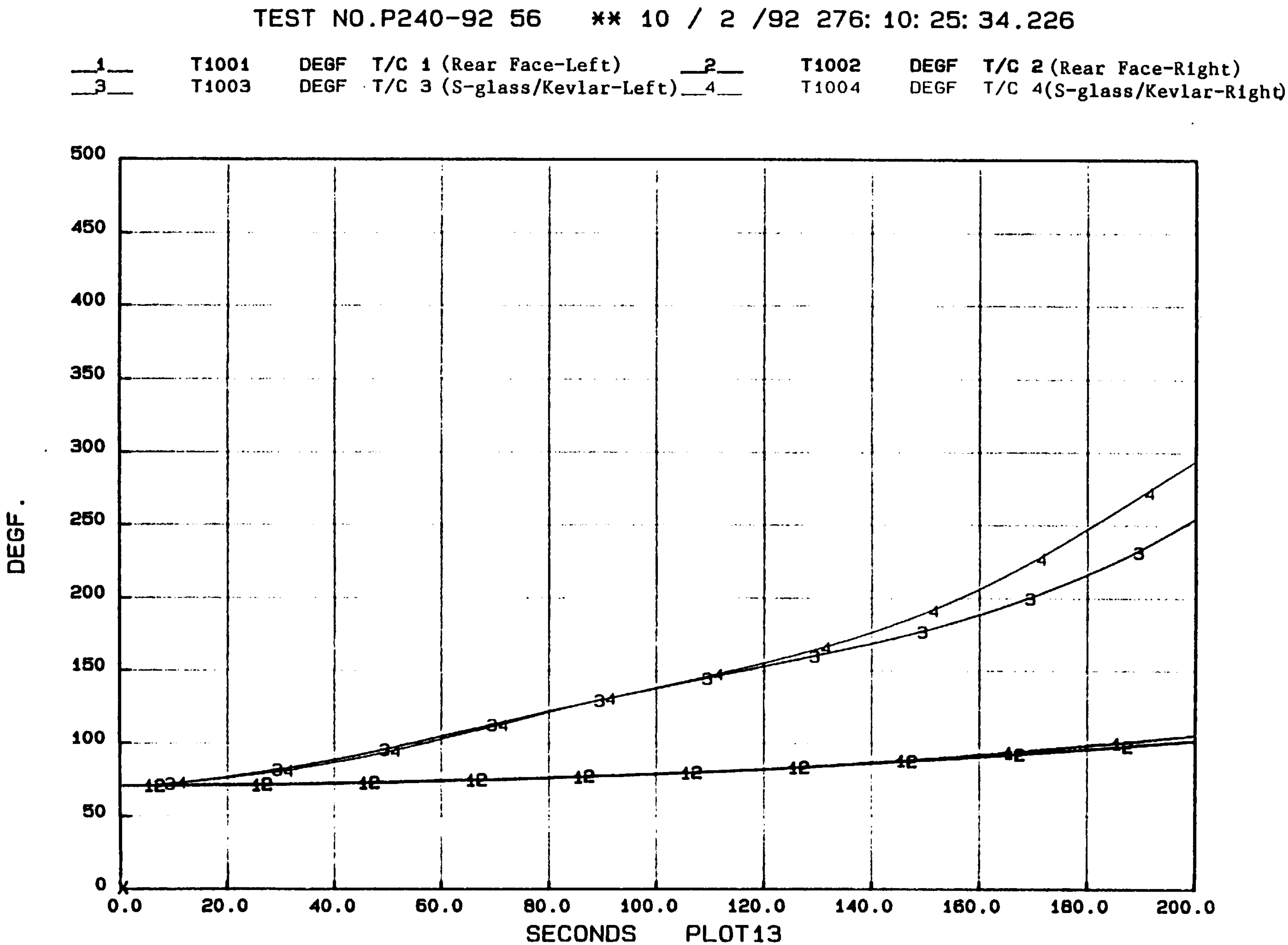


Figure 3.3-4. NASA Analog Test Data for Quartz/S-glass/Kevlar Configuration (Top Specimen)

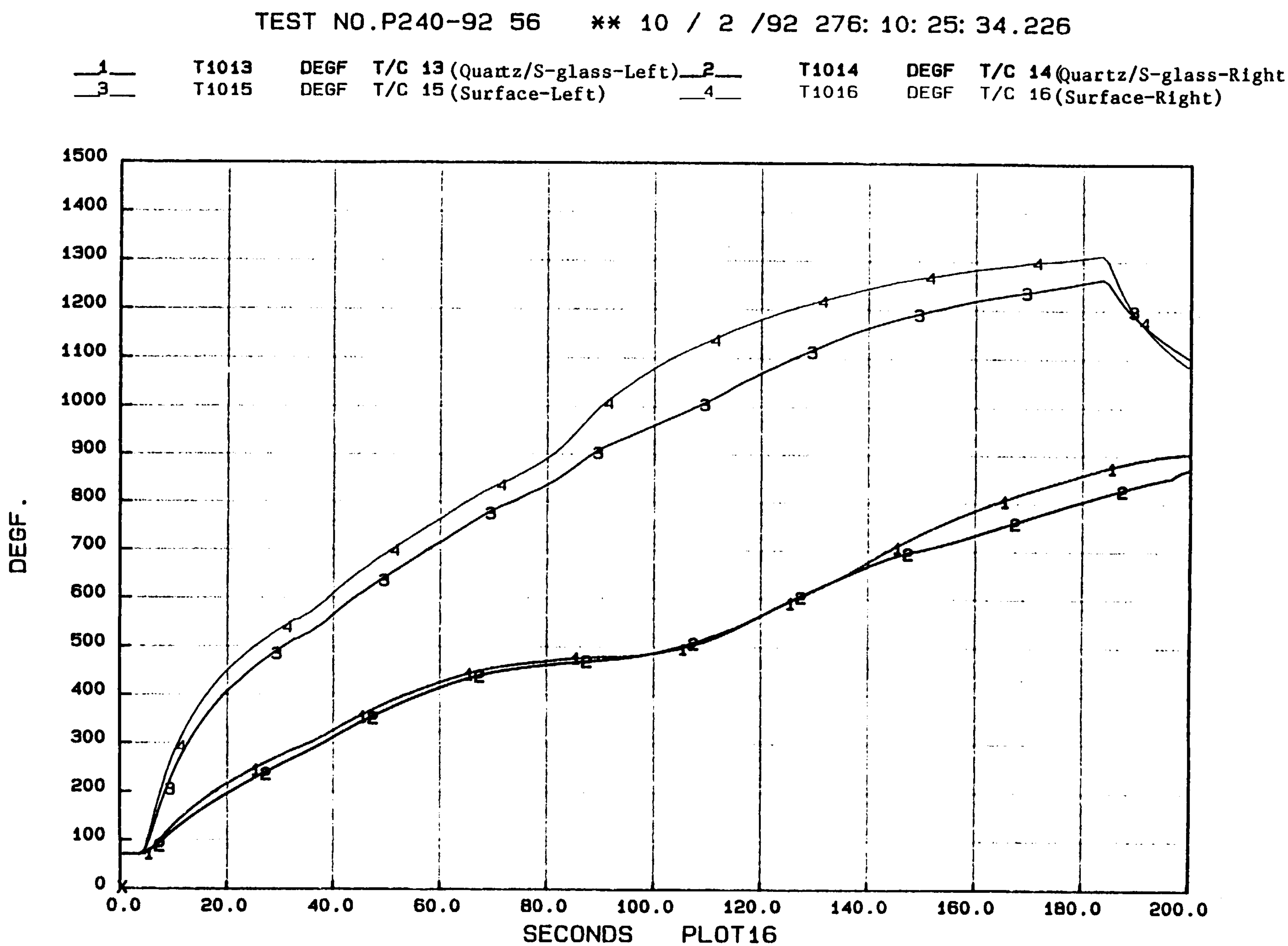


Figure 3.3-5. NASA Analog Test Data for Quartz/S-glass/Kevlar Configuration (Bottom Specimen)

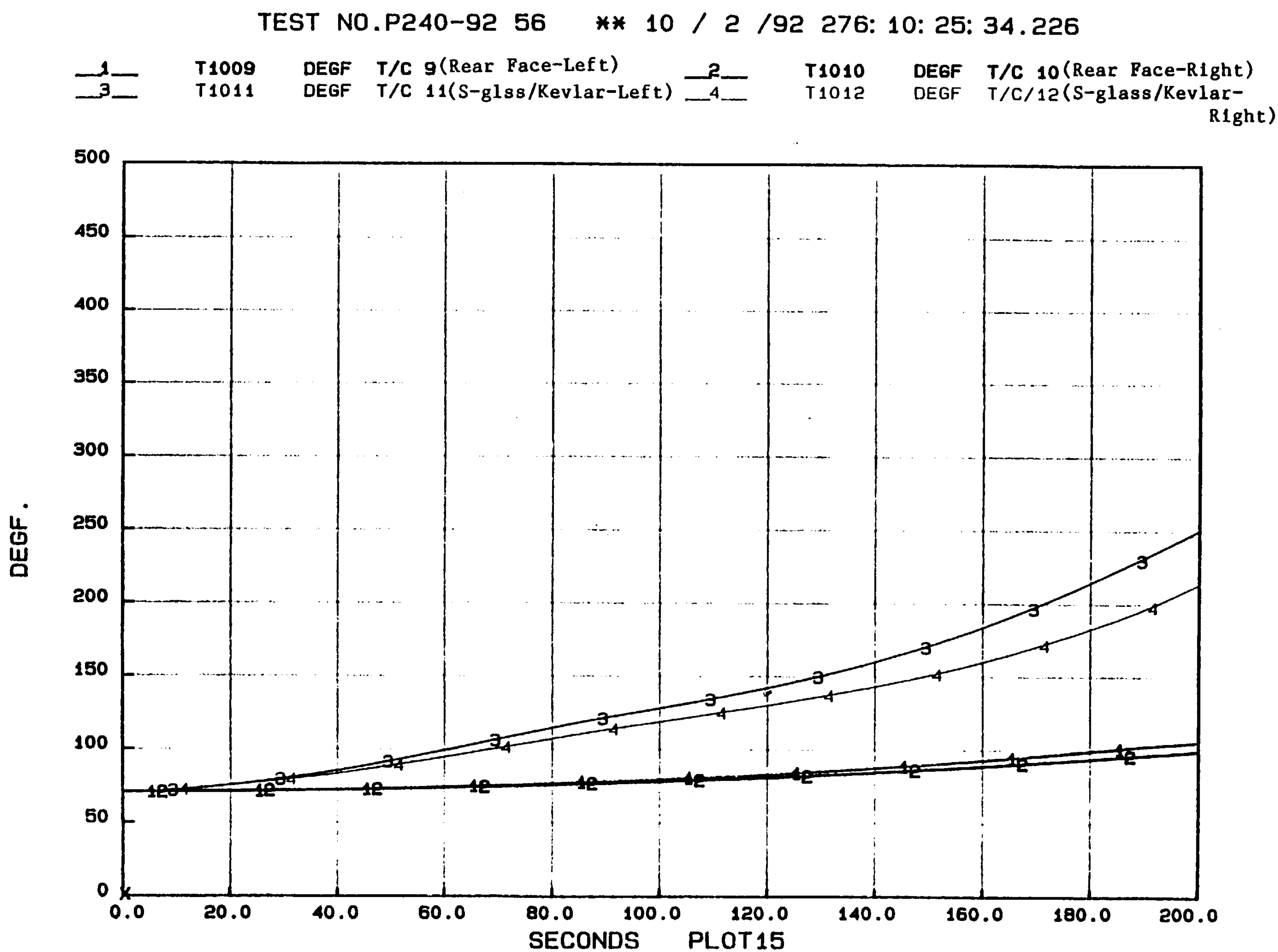


Figure 3.3-6. NASA Analog Test Data for Quartz/S-glass/Kevlar Configuration (Bottom Specimen)

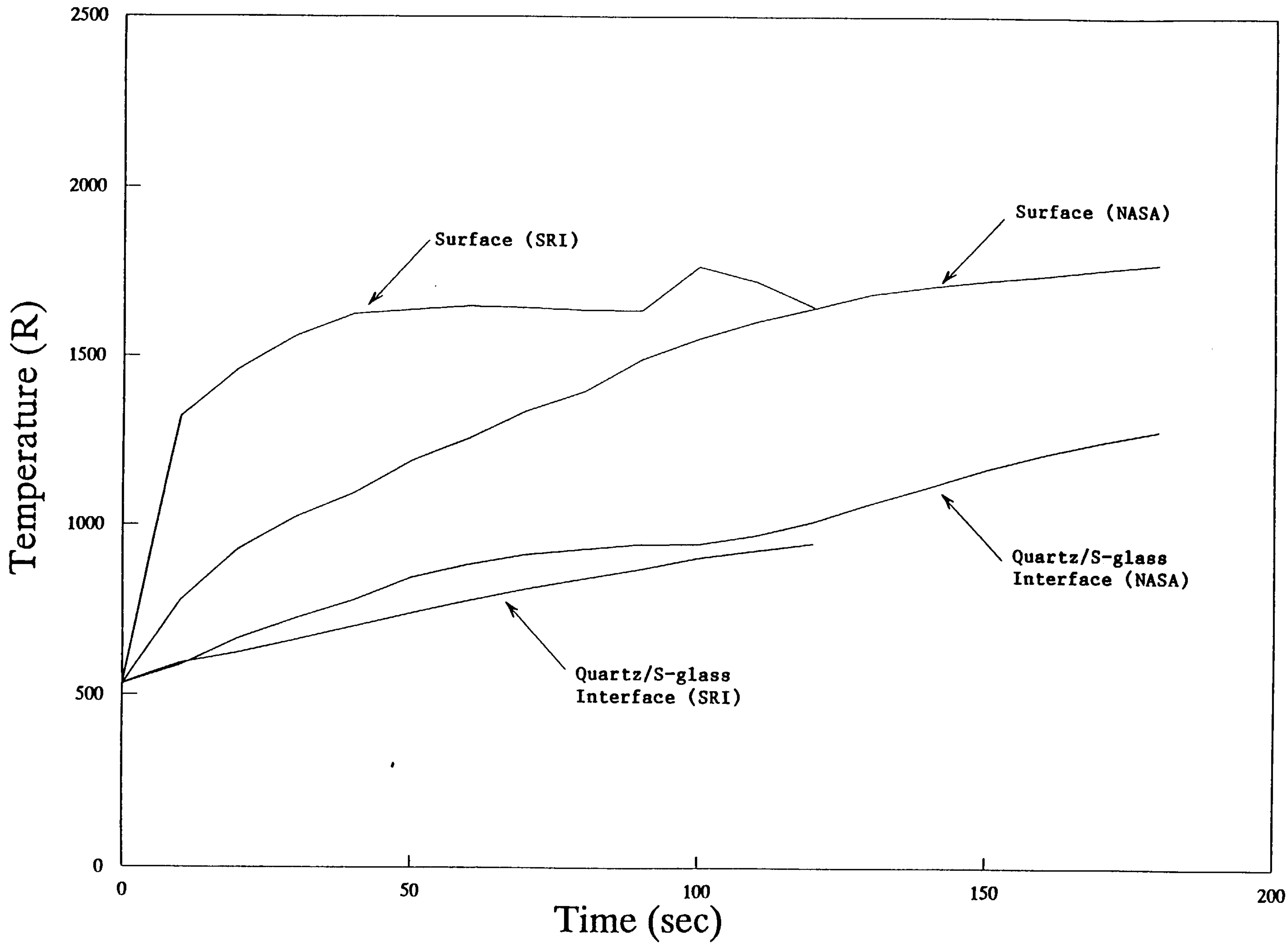


Figure 3.3-7. Comparison of SRI and NASA Analog Test Data for Front Layers of Quartz/S-glass/Kevlar Configuration

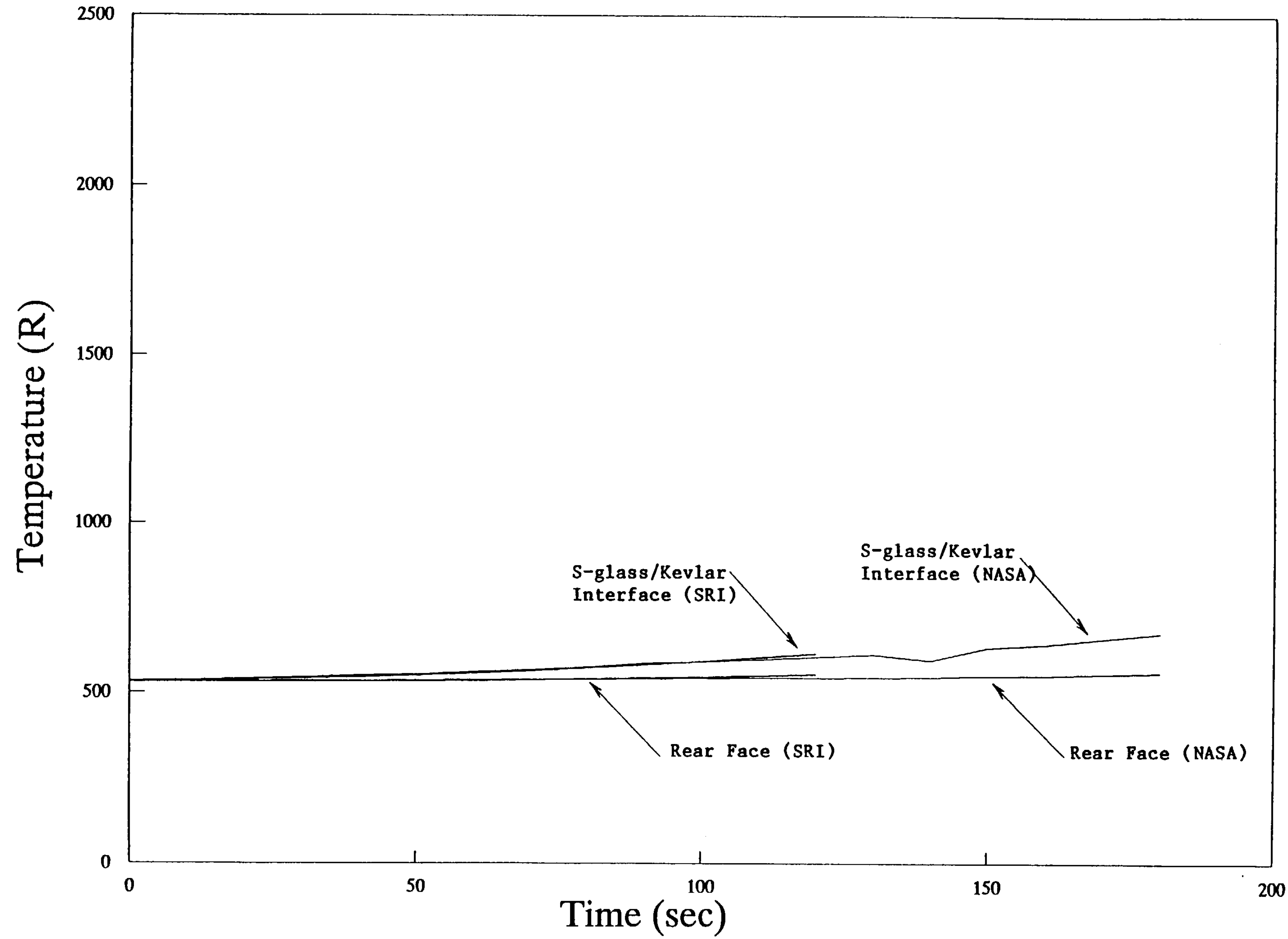


Figure 3.3-8. Comparison of SRI and NASA Analog Test Data for Rear Layers of Quartz/S-glas/Kevlar Configuration

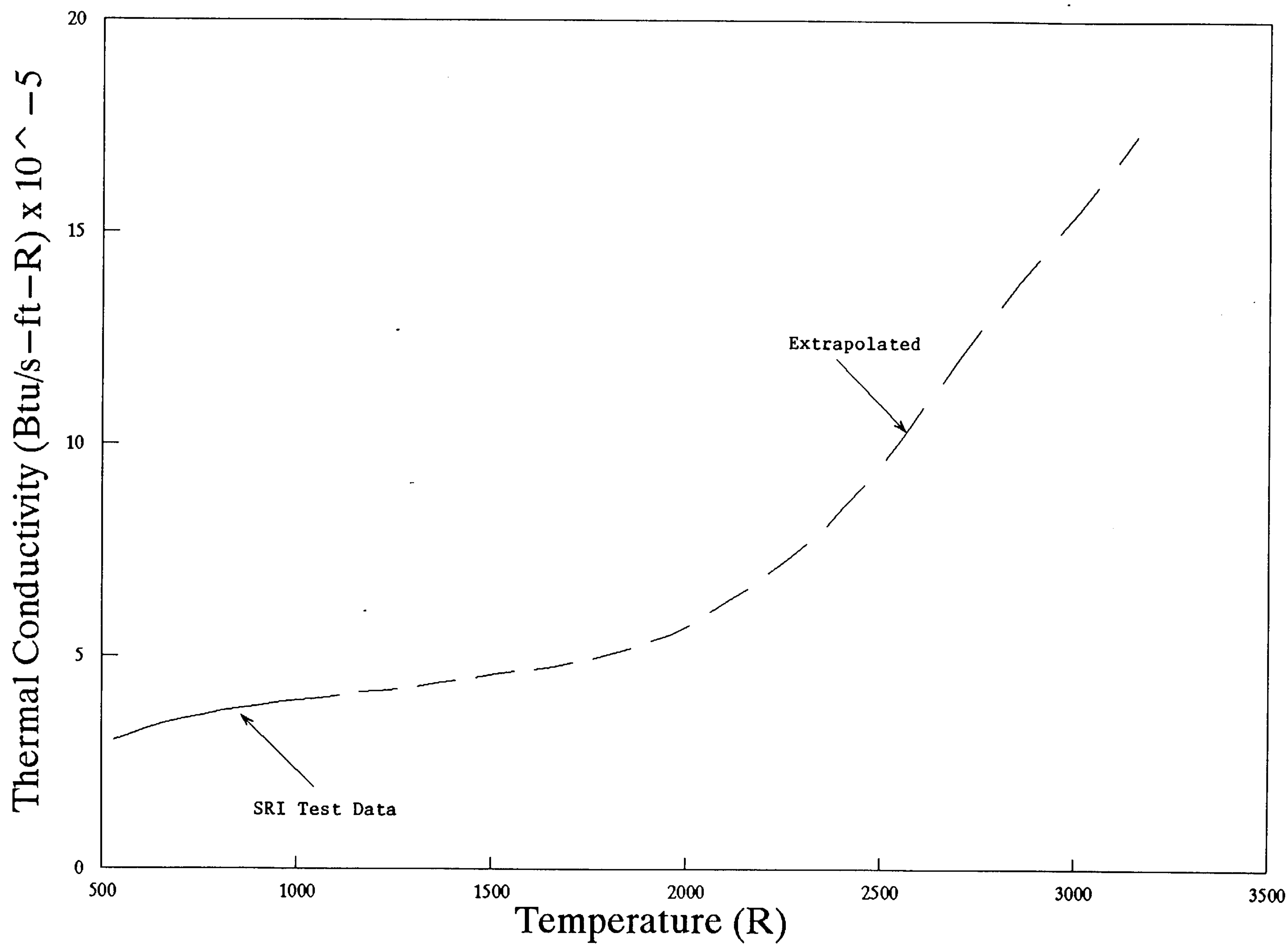


Figure 3.3-9. Extrapolated Thermal Conductivity of Polar Weave Quartz

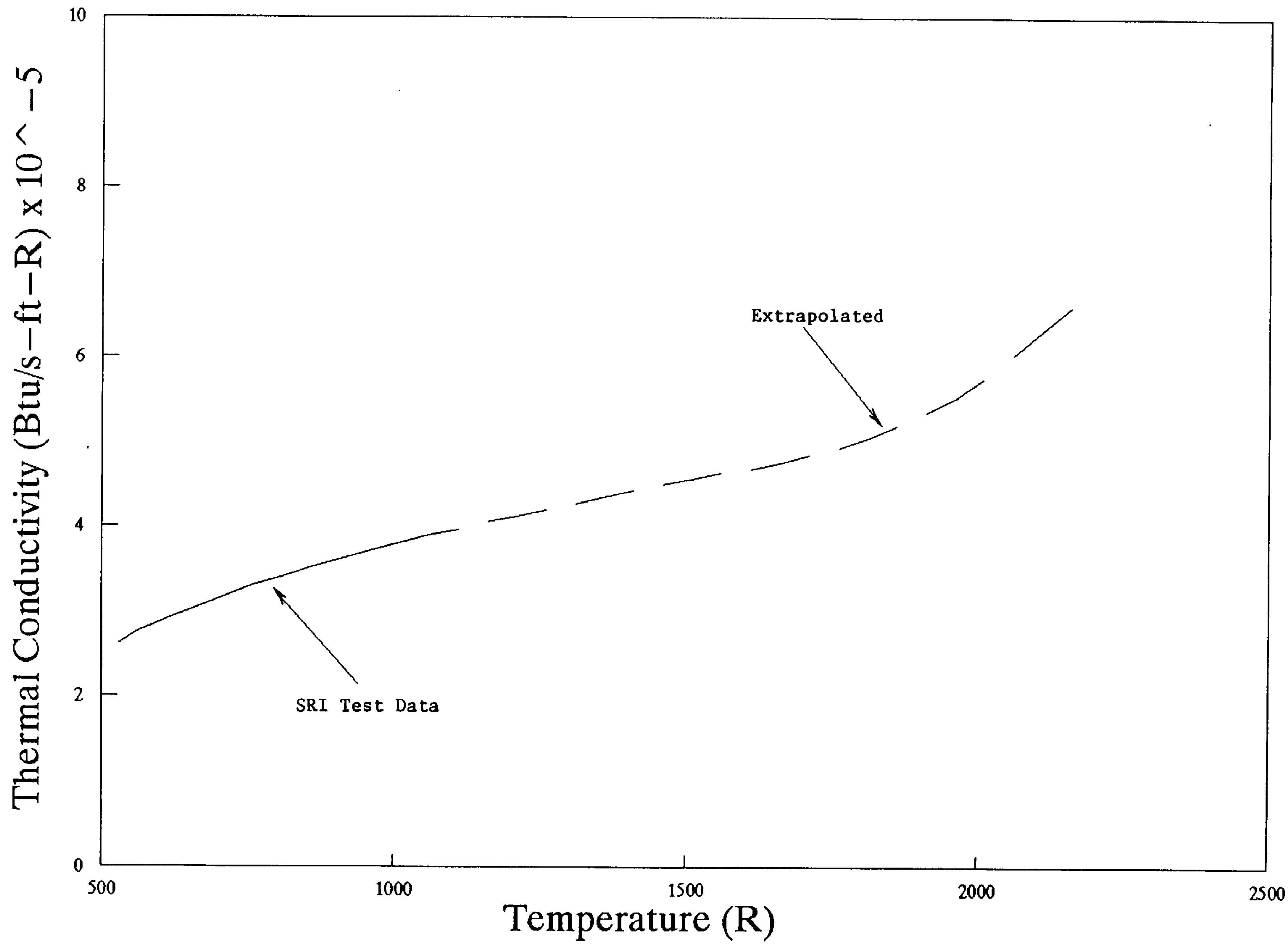


Figure 3.3-10. Extrapolated Thermal Conductivity of Polar Weave S-Glass

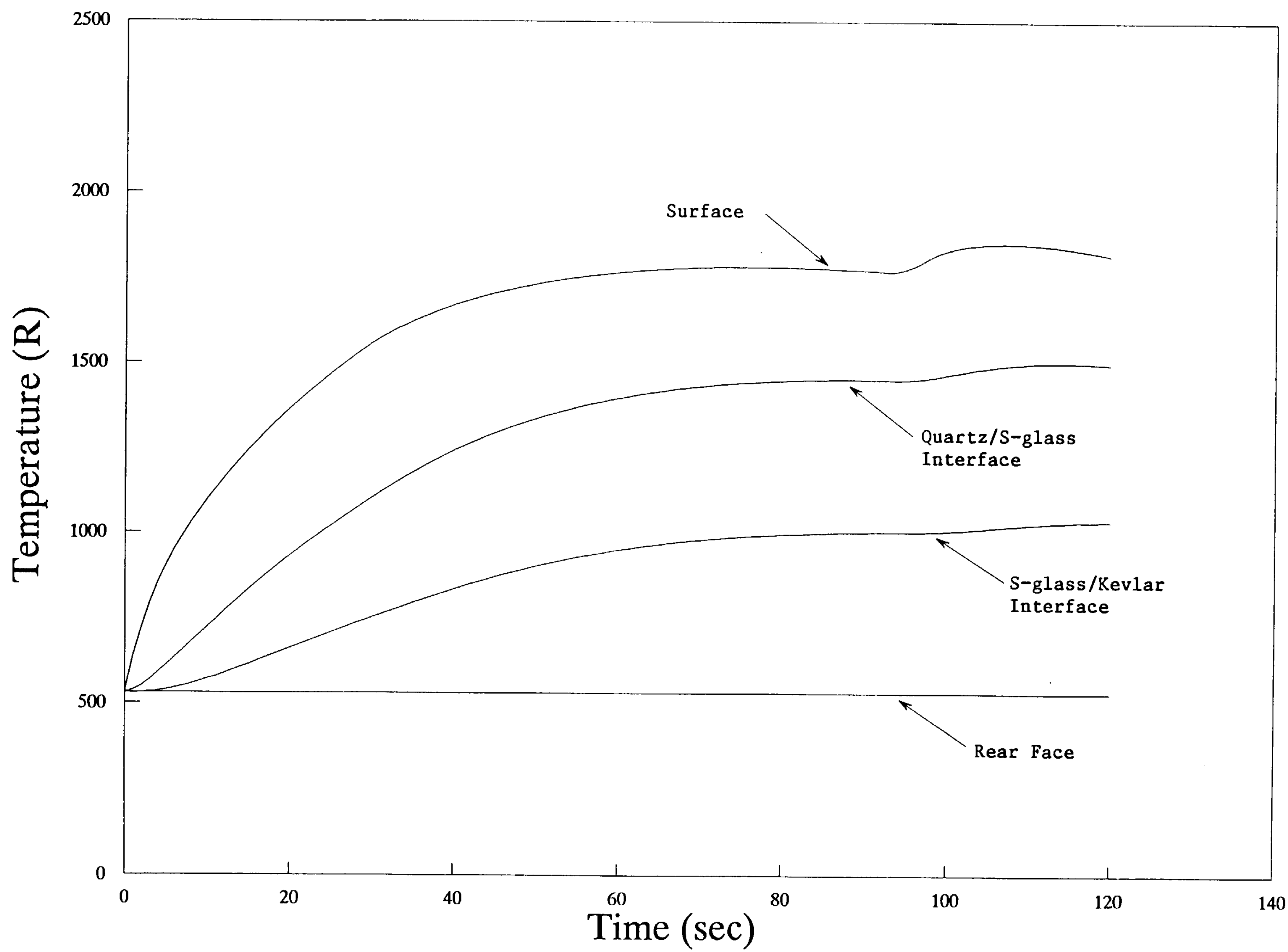


Figure 3.3-11. Thermal Analysis of Quartz/S-glass/Kevlar Configuration Exposed to SRB Flux

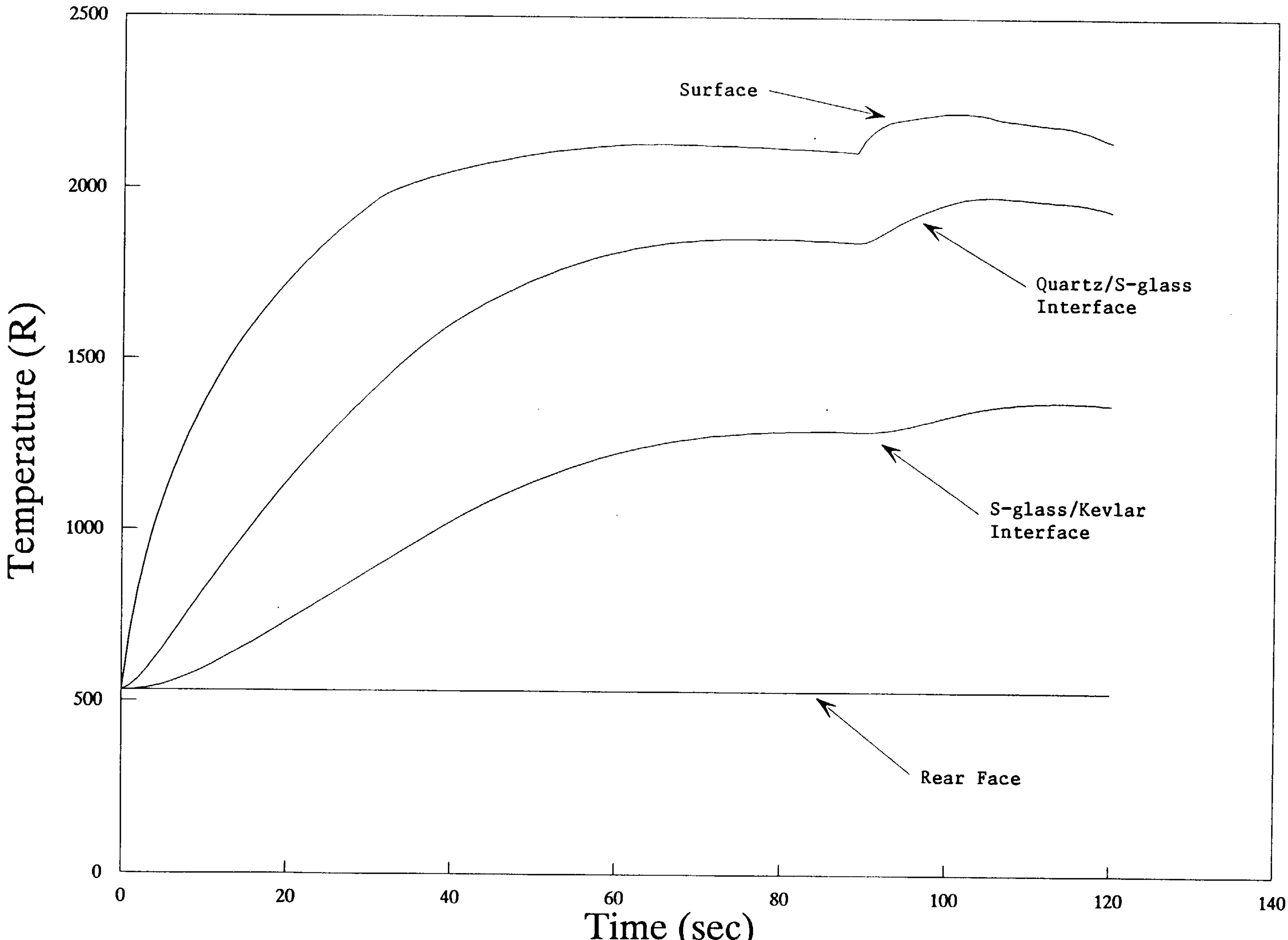


Figure 3.3-12. Thermal Analysis of Quartz/S-glass/Kevlar Configuration Exposed to ASRB Flux

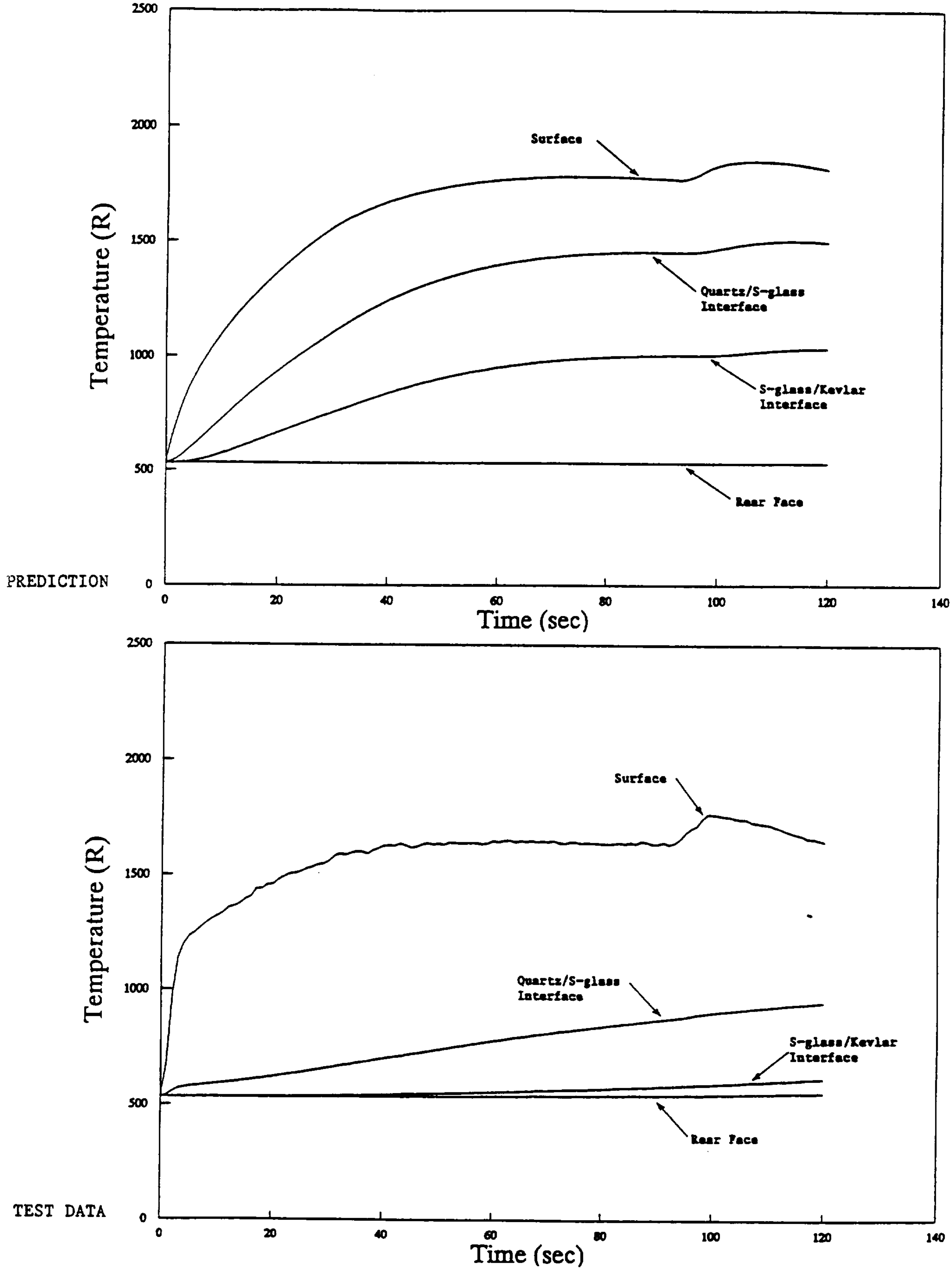


Figure 3.3-13. Comparison of Analog Test Data and Thermal Analysis Predictions for Quartz/S-glass/Kevlar Configuration Exposed to SRB Flux

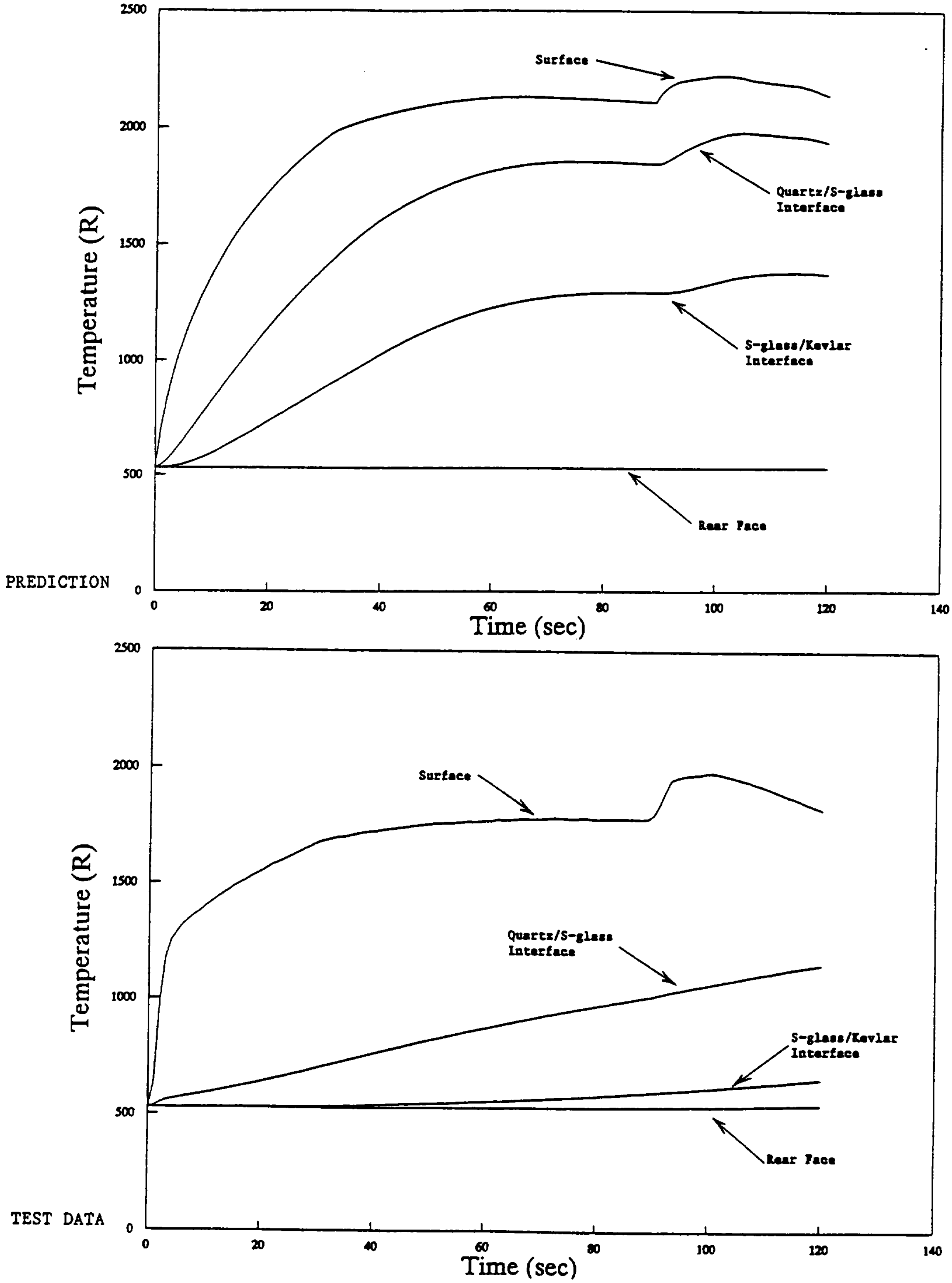


Figure 3.3-14. Comparison of Analog Test Data and Thermal Analysis Predictions for Quartz/S-glass/Kevlar Configuration Exposed to ASRB Flux

4.0 DESIGN OPTIMIZATION

As stated in the previous section, the 3-piece (quartz, S-glass, Kevlar) design is about 90% heavier than the current ASTC not considering hardware tradeoffs. The rear face temperatures measured in the analog facility, however, did not rise more than 20 °R for either the SRB or the ASRB flux. That much thermal protection is excessive. A design rear face temperature rise of 100 - 150 °R is more realistic. This would allow the blanket configuration to be thinner and thus weigh less.

Several thinner configurations were analyzed using the computer program. The simplest and most appealing means of reducing the blanket thickness was to remove one of the layers. A blanket consisting of 1 quartz layer and 1 Kevlar layer (both 0.25" nominal thickness) was selected. This configuration has the advantage of being much lighter than the 3-piece design (1.9 lb/ft^2 vs 3.2 lb/ft^2) since the densest material (S-glass) was removed. The cost would also be less since only two materials are required.

Figures 4.1 and 4.2 present the thermal analysis of this configuration for both the SRB and ASRB fluxes. The program predicts that the front face of the Kevlar layer will be heated beyond its service temperature. However, based on the program's tendency to overestimate the internal temperatures of the blankets, analog tests were run to verify the program's conclusion.

Figures 4.3 and 4.4 show the analog test data for the quartz/Kevlar blanket exposed to SRB and ASRB fluxes. As expected, the Kevlar layer did not reach predicted temperatures. Some slight scorching did occur on the front surface of the Kevlar layer but was not sufficient to damage the blanket. The rear face temperatures rose only 75 °R for the SRB flux and 100 °R for the ASRB flux. These are within acceptable limits for the ASTC. This configuration has an areal density of 1.9 lb/ft^2 and will weigh approximately 690 pounds without hardware. This compares favorably with the current ASTC design.

Further refinements of the design may be possible by reducing the thickness of either the quartz or Kevlar layers to reduce weight.

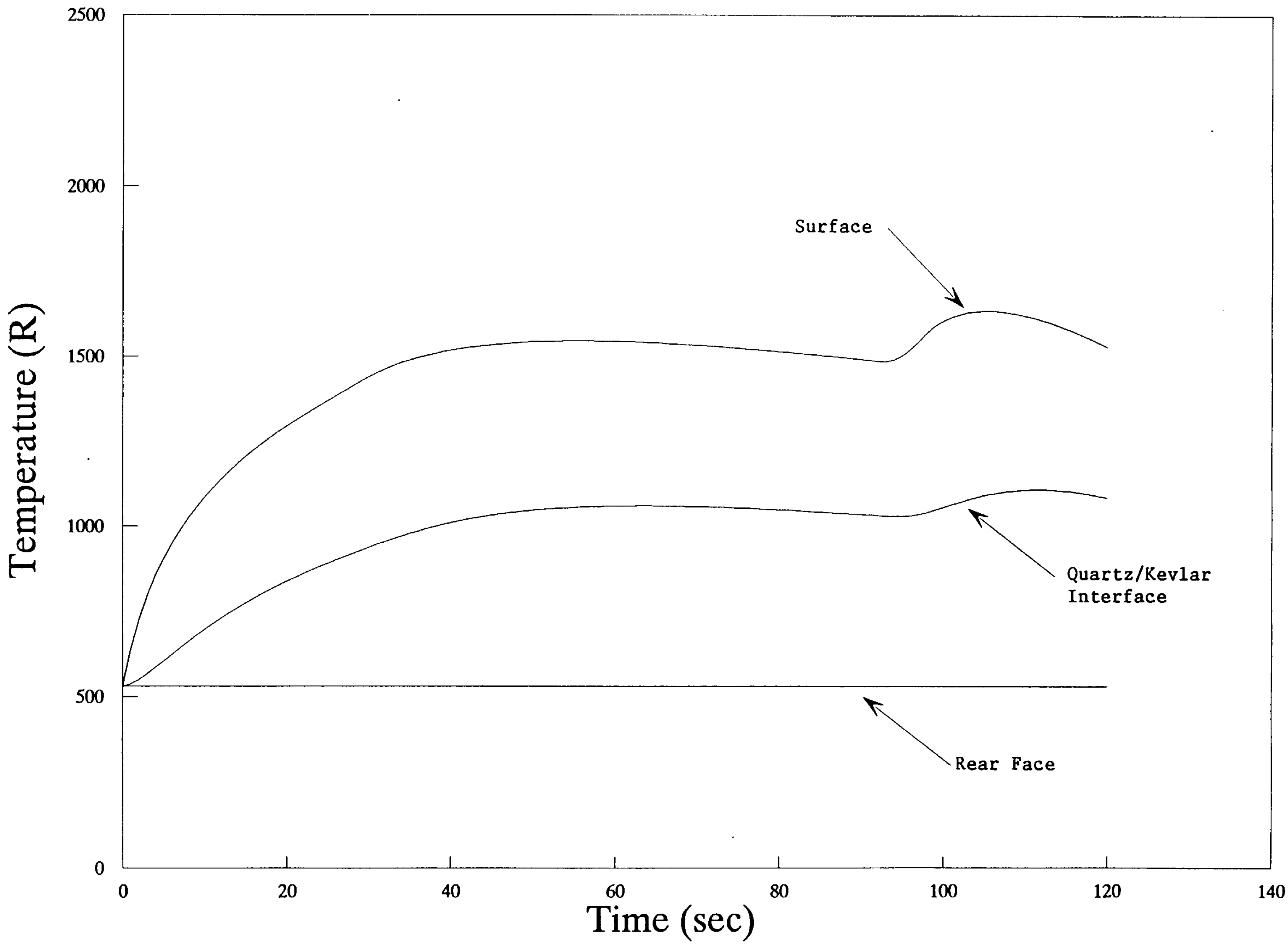


Figure 4.1. Thermal Analysis of Quartz/Kevlar Configuration Exposed to SRB Flux

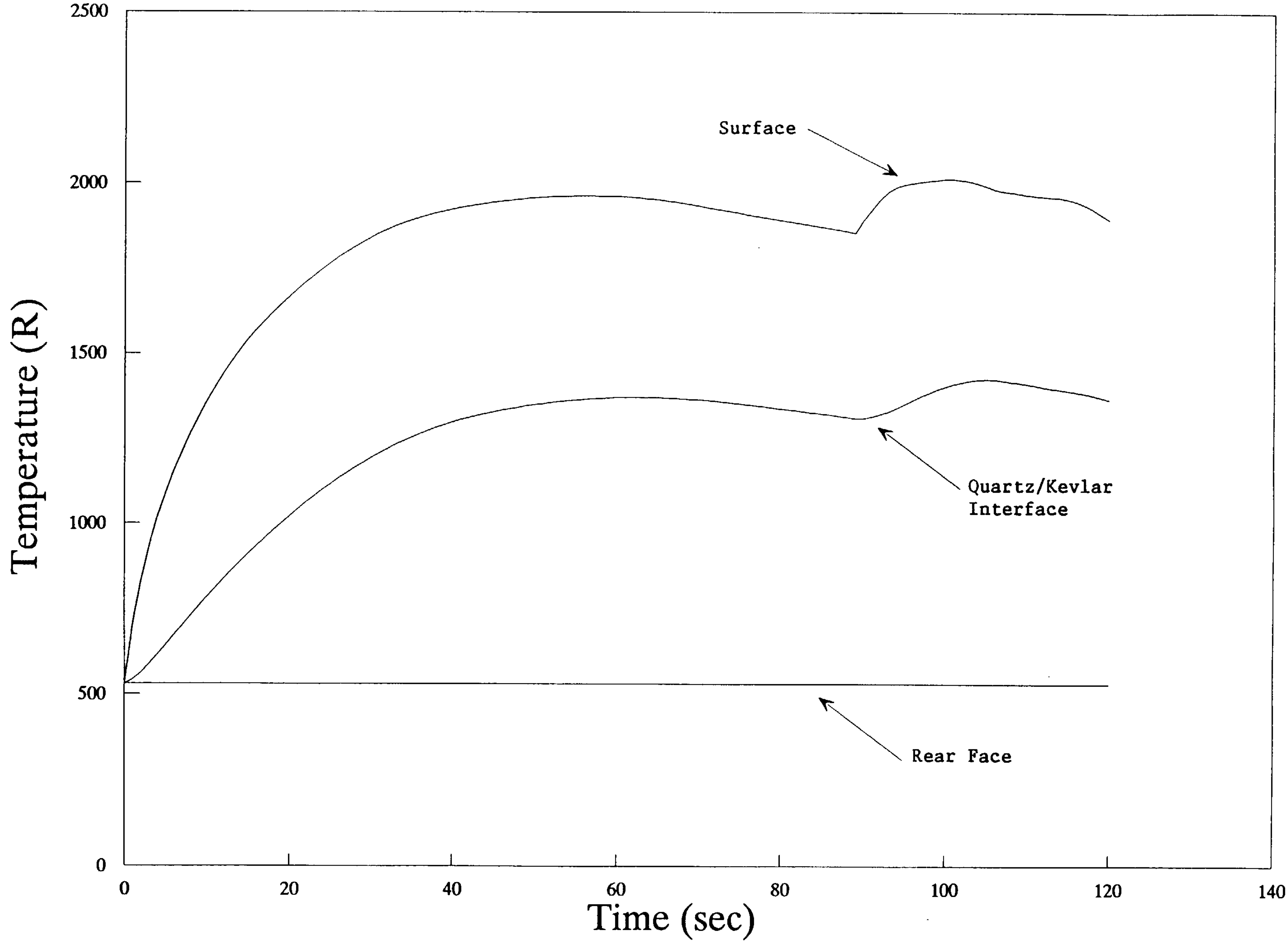


Figure 4.2. Thermal Analysis of Quartz/Kevlar Configuration Exposed to ASRB Flux

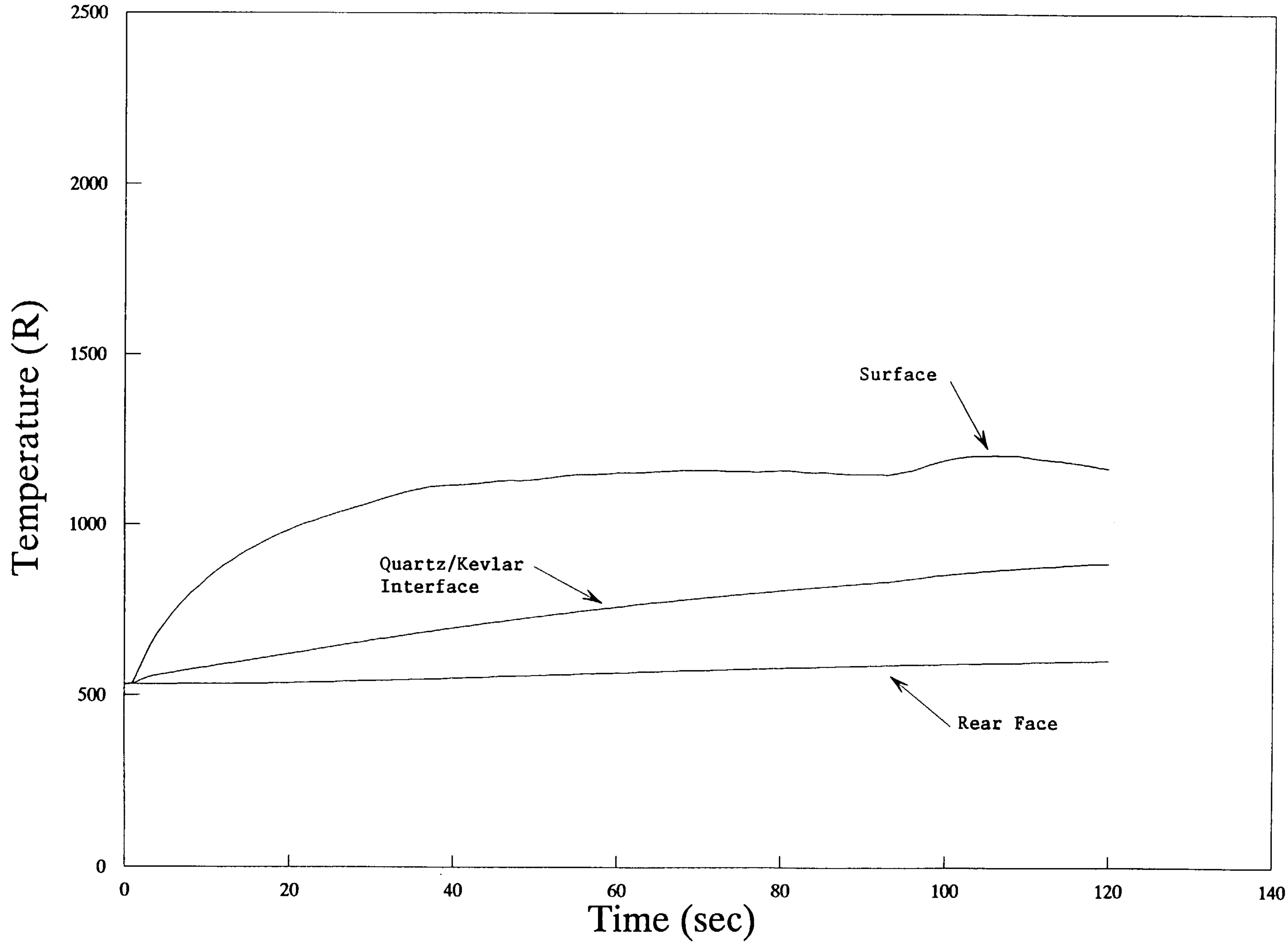


Figure 4.3. Analog Test Data for Quartz/Kevlar Configuration Exposed to SRB Flux

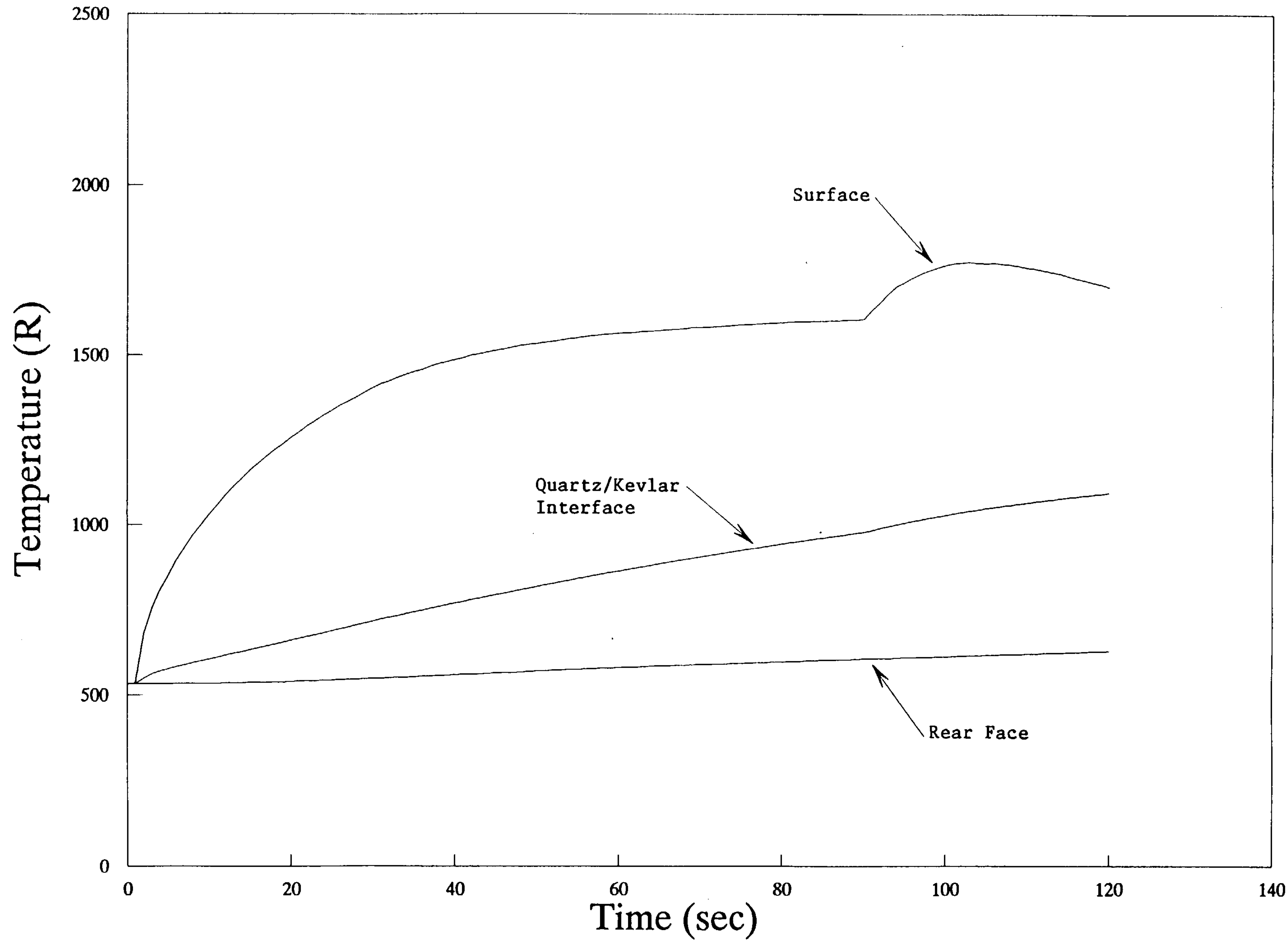


Figure 4.4. Analog Test Data for Quartz/Kevlar Configuration Exposed to ASRB Flux

4.1 COST CONSIDERATIONS

Textile Technologies Incorporated (TTI) is the current manufacturer of the polar weave materials evaluated in this program. TTI can weave the ASTC blanket in a single-piece (5 feet wide on a 18 foot inner diameter). However, the 0.25" thickness poses a major problem for the fabricator in that the number of the ends or fiber tows that must be drawn into the loom is excessive, over 7000 ends. This large quantity drives up the cost in the extremely large number of man-hours required to draw the fibers into the loom. Safety and quality control also become problematical. Therefore, TTI has suggested weaving blankets roughly one-third the original thickness, then sewing the layers together to reach the 0.25" thickness desired. The number of ends yarns would then be only around 2500 and the weaving much simplified. The proposed blanket layers dimensions are 5 feet wide, 0.065 inches thick on an 18 foot inner diameter.

This multi-ply approach will actually achieve a better thermal performance in that there will be a greater number interfacial resistances to impede the heat flow in the curtain. Estimated prices for the fabrics having a total thickness of 0.25" (based upon an annual requirement of 6 ASTCs per year) are as follows:

Quartz 300	$93,000
S-2 Glass	$14,800
Kevlar 29	$22,000

The proposed quartz/Kevlar configuration would cost $115,000 per ASTC.

5.0 CONCLUSIONS

A two-piece quartz/Kevlar (0.25" thick layers) design seems to be a desirable configuration for a new ASTC. This configuration weighs about the same as the current design, provides adequate thermal protection, and can be constructed as a single piece thus greatly simplifying installation.

Some further weight reduction may be gained by further reducing the thickness of the layers and allowing the rear face temperature to increase more, although the screening process may need to be fine-tuned. Several options are available for further refinement of the screening process. The computer program can be modified to accept interfacial resistance inputs. The analog test setup can include additional thermocouples to determine the interfacial resistances actually present. A finite element model can be built to better analyze the thermal performance of the candidate configurations. Finally, new blanket thickness can be woven for evaluation in the analog test facility.

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2. Incropera, DeWitt, "Fundamentals of Heat and Mass Transfer", 3rd. ed., John Wiley & Sons, New York, 1990.
3. O'Neil, "Advanced Engineering Mathematics", 3rd. ed., Wadsworth, California, 1991.
4. NASA/MSFC, "SRB Thermal Design Databook" Rev. D., September 1987.
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LIST OF APPENDICES

APPENDIX A

THERMAL CONDUCTIVITY MEASUREMENT TECHNIQUES

Thermal Conductivity Measurement Techniques

Southern Research has three basic type of apparatuses that can be used to measure the thermal conductivity of a material.

For very low density materials (materials expected to have a very low thermal conductivity) Southern has available a 7-inch guarded hot plate which is a slightly modified ASTM C177-85 design. This unit is capable of obtaining conductivity values in the temperature range of -200 °F to 600 °F. Examples of materials that are tested using this apparatus are; insulating foams, graphite foams and fibrous insulations, low density ceramic insulations, cloths and rubbers. A smaller 3-inch hot plate apparatus is also available. This hot plate is more applicable to the higher conductivity materials. Its temperature operating range is also -200 °F to 600 °F. Temperatures up to 800 °F are possible under certain circumstances. Thick rubbers and elastomers (.125" to .250" thick) are ideally suited to the three inch apparatus.

The 7-inch guarded hot plate can be operated in a vacuum down to 10^{-5} torr (10^{-6} torr if the material is clean).

Figure 1 is a typical assembly for the hot plate apparatus.

The apparatus consists of a central heater plate surrounded by a guard heater, each separately controlled. The guard ring is maintained at the same temperature as the central heater so that all of the heat flow is normal to the specimen surfaces. The temperature differences between the guard and central sections are measured by means of differential thermocouple junctions connected in series. The 7-inch apparatus contains eight differential junctions, whereas the 3-inch apparatus contains four. The heater plate is sandwiched between layers of interfacial material, the hot-face thermocouples, the specimen, cold-face thermocouples, interfacial material, and finally a cold source to dissipate the heat. In addition to the thermocouples in contact with the specimen, thermocouples are located in the central heater and the outer copper cold plates.

To provide intimate contact at all interfaces, the entire sandwich assembly is pressed firmly together by spring loading with the total load application desired, which is usually 600 pounds. For fragile specimens spacers are used to maintain specimen thickness. Spacers maintain a fixed distance between the heater and the cold plate.

The thermocouples used on very thin specimens (less than .125" thick) are made from 0.005" diameter chromel-alumel wire that is flattened to less than 0.0025". The thermocouple is then electrically insulated with 0.003" Teflon tape. The junction is made by connecting the wires to a small metal square called a "getter". The Teflon insulated leads are sandwiched between the specimen and filler material. This arrangement insures that there is no air film between the specimen and thermocouples, and that good, intimate contact exists at all interfaces.

For specimens greater than 0.250" thick internal thermocouples are used. These thermocouples consist of 0.005" diameter wire in a 0.040" double bore alumina tube. Figure 2 is a typical 0.250" thick specimen design.

To obtain mean sample temperatures above room temperature, water is circulated through the cooling section. For mean sample temperatures below room temperature, cold trichloroethylene or liquid nitrogen is pumped through the cooling plates. Equilibrium conditions are obtained before readings are taken.

Thermal conductivity values are calculated from the expression:

$$k_s = Ql_s/A\Delta t$$

where Q = total heat flow - Btu/hr

l_s = average thickness of specimens - inches

A = area of central heater section - square feet

Δt = sum of temperature drop across each sample - °F

Theoretically, Q, the heat input, should split, with exactly half of the input flowing through each sample. The temperature drops indicate that this condition rarely exists. Instead, there is a slight unbalance in the heat flow. The above formula then permits a calculation of the arithmetic average for the two panels. In this calculation the temperatures are measured directly at the faces of the specimen by the "getters", resulting in a direct method.

When measuring the thermal conductivity of materials with expected values greater than 2 Btu-in./hr-ft^2-F the comparative rod apparatus (CRA) may be used. This apparatus can be used to measure thermal conductivity from -200 °F to 2000 °F (2200 °F on certain metal alloys). This apparatus, shown schematically in Figure 3, consists basically of two cylindrical reference pieces of known thermal conductivity stacked in series with a cylindrical specimen. Heat is introduced to one end of the rod, composed of the references and specimen, by a small electrical heater. A cold sink or heater is employed at the opposite end of the rod as required to maintain the temperature drop through the specimen at the preferred level. Insulators may be inserted in the rod assembly to assist in controlling the temperature drop. Radial losses are minimized by means of radial guard heaters surrounding the rod. The annulus between the rod and the guard heaters is filled with diatomaceous earth, thermatomic carbon, bubbled alumina or zirconia powder. Surrounding the guard is an annulus of diatomaceous earth enclosed in an aluminum shell.

Specimen configurations are shown in Figure 4. Thermocouples located in radially drilled holes measure the axial temperature gradients. Thermocouples located at matching points in each guard heater are used to monitor guard temperatures, which are adjusted to match those at corresponding locations in the test section.

In operation, the apparatus is turned on and allowed to reach steady state. The guard and rod heaters are adjusted to minimize radial temperature gradients between the rod and guard sections consistent with maintaining equal heat flows in the references.

The thermal conductivity of the specimen is calculated from the relation:

$$K_s = \frac{K_1 \Delta T_1 + K2 \Delta T_2}{2 \Delta T_s} \left[\frac{\Delta X_s}{\Delta X_r} \right]$$

where K_1 and K_2 are the thermal conductivities of the upper and lower references, ΔT_1, ΔT_2 and ΔT_s are the temperature differences in the upper and lower references and specimen, respectively; ΔX_s and ΔX_r are the distances between thermocouples in the specimen and references.

Note that for purely axial heat flow, the products $K_1 \Delta T_1$ and $K_2 \Delta T_2$ should be equal. Due to imperfectly matched guarding and other factors, this condition is seldom attained in practice; therefore, the average of the two values is used in the calculations. Their difference is maintained as small as possible, usually within 5 percent.

Generally, measurements with the comparative rod apparatus are performed in an inert environment. The apparatus can also be operated in vacuum and at gas pressure of up to 100 psig. Southern has had experience operating under all conditions.

The primary reference materials are Code 9606 Pyroceram and Armco iron for measurements on materials with low and high thermal conductivities, respectively. Primary standard reference sets are kept and are used to calibrate other references made from the same materials.

In addition to Code 9606 Pyroceram and Armco iron several other materials have been used as references. These include copper for high conductivity specimens, 316 stainless steel for specimens of intermediate thermal conductivity and Silica or Pyrex for low conductivity materials.

Copper references have been calibrated against Armco iron and excellent agreement with literature data has been obtained.

Calibrations indicate that for materials with moderate to high thermal conductivities the apparatus operates with a precision of about ±5 percent at temperatures above 0 °F. Below 0 °F, the precision achieved to date has been about ±7 percent with a total uncertainty of about ±10 percent.

High temperature thermal conductivity measurements (1500 °F to 5000 °F) can be made using the radial inflow apparatus (RIA). This apparatus can be used to measure the high temperature thermal conductivity of graphite or carbon lightweight insulations, graphites, carbon-carbons and charred composites. Figure 5 shows a cross-sectional view of the RIA facility. Water from the calorimeter enters at 32 °F at the bottom and passes through the insulation, the specimen, and more insulation, leaving the apparatus at the top. Two thermocouples placed one-half inch apart measure the temperature rise in the water stream as it passes through the gage section of the specimen. A flowmeter in the external water circuit measures the flow rate, which can be adjusted by a control valve. Vertical sight tubes run down through the upper insulation material and align with holes in the specimen, so that thermocouple measurements or optical pyrometer readings can be taken of the specimen temperature. Vertical holes are drilled to the center of the specimen to determine the temperatures across a known distance. Figure 6 shows a top view of the RIA specimen configuration. A specimen is actually composed of four parts typically 0.70" x 0.70" x 2.50" (see Figure 7). It is possible to run specimens as thin as 0.250". This configuration is shown in Figure 8. Data taken from the four parts are averaged together.

The thermal conductivity values are computed from the relation:

$$K = \frac{QL}{A\Delta T}$$

where Q = the heat flow measured by the calorimeter

L = the gage length over which the specimen ΔT is measured

A = area

ΔT = temperature drop across specimen

Based on an extensive error analysis and calibrations on homogeneous isotropic materials of known thermal conductivities, such as Armco iron and ATJ graphite, the precision (coefficient of variation) in the measurements has been established at ±7 percent over the temperature range of 1500 °F to 5000 °F.

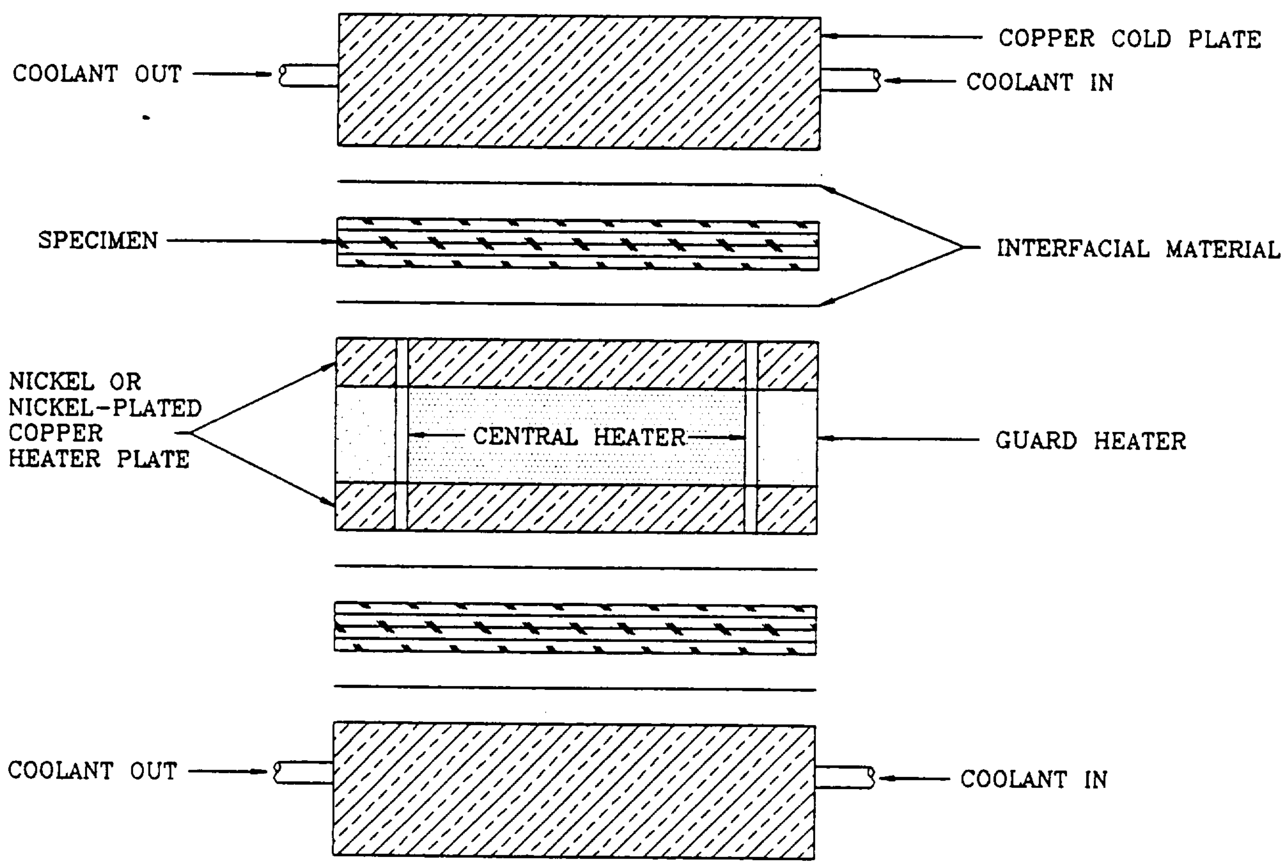

Figure 1. Typical Assembly for Thermal Conductivity Hot Plate Apparatus

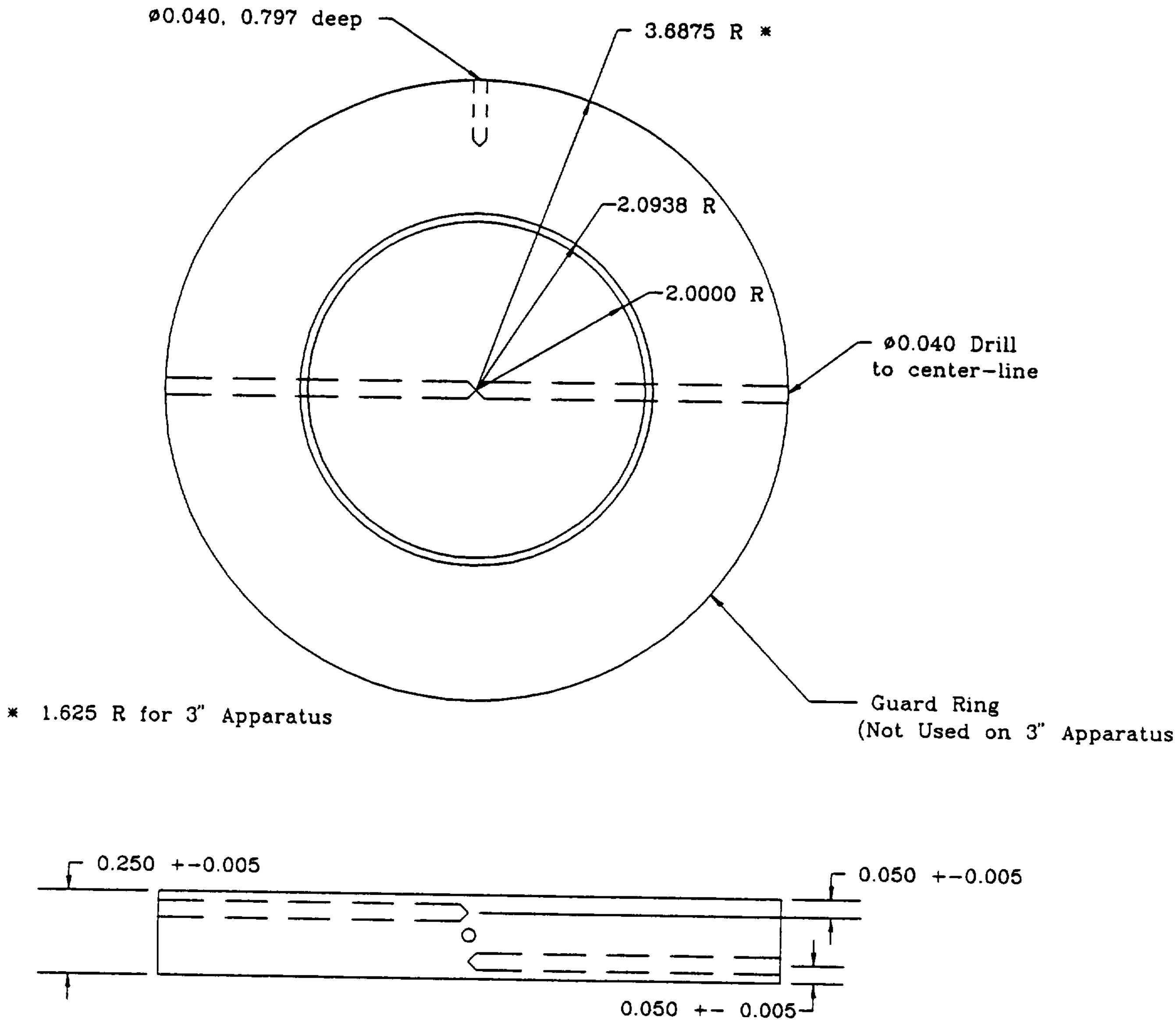

Figure 2. A Typical 0.250" Thick Hot Plate Apparatus Specimen

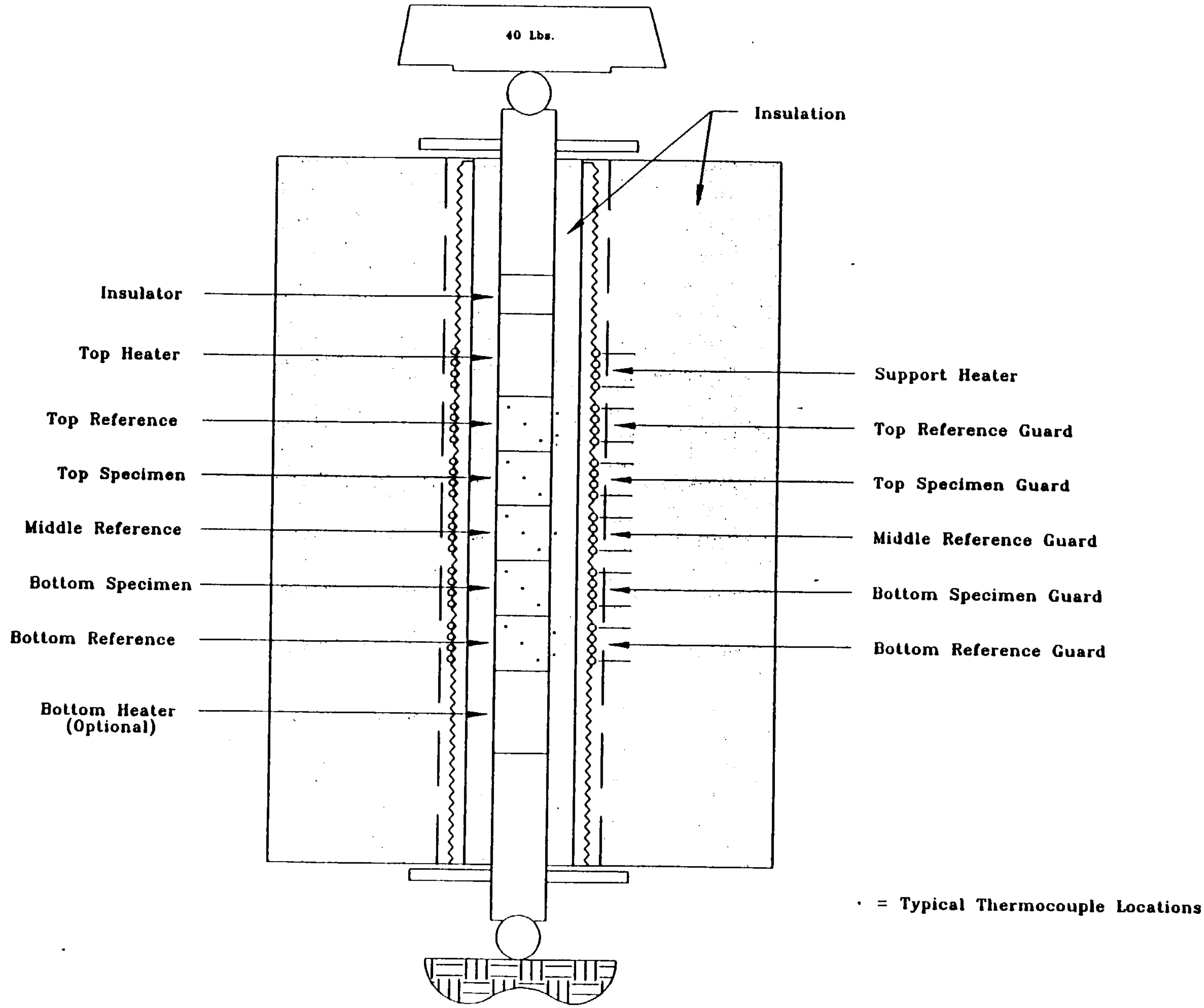

Figure 3. Cross Section of Comparative Rod Apparatus

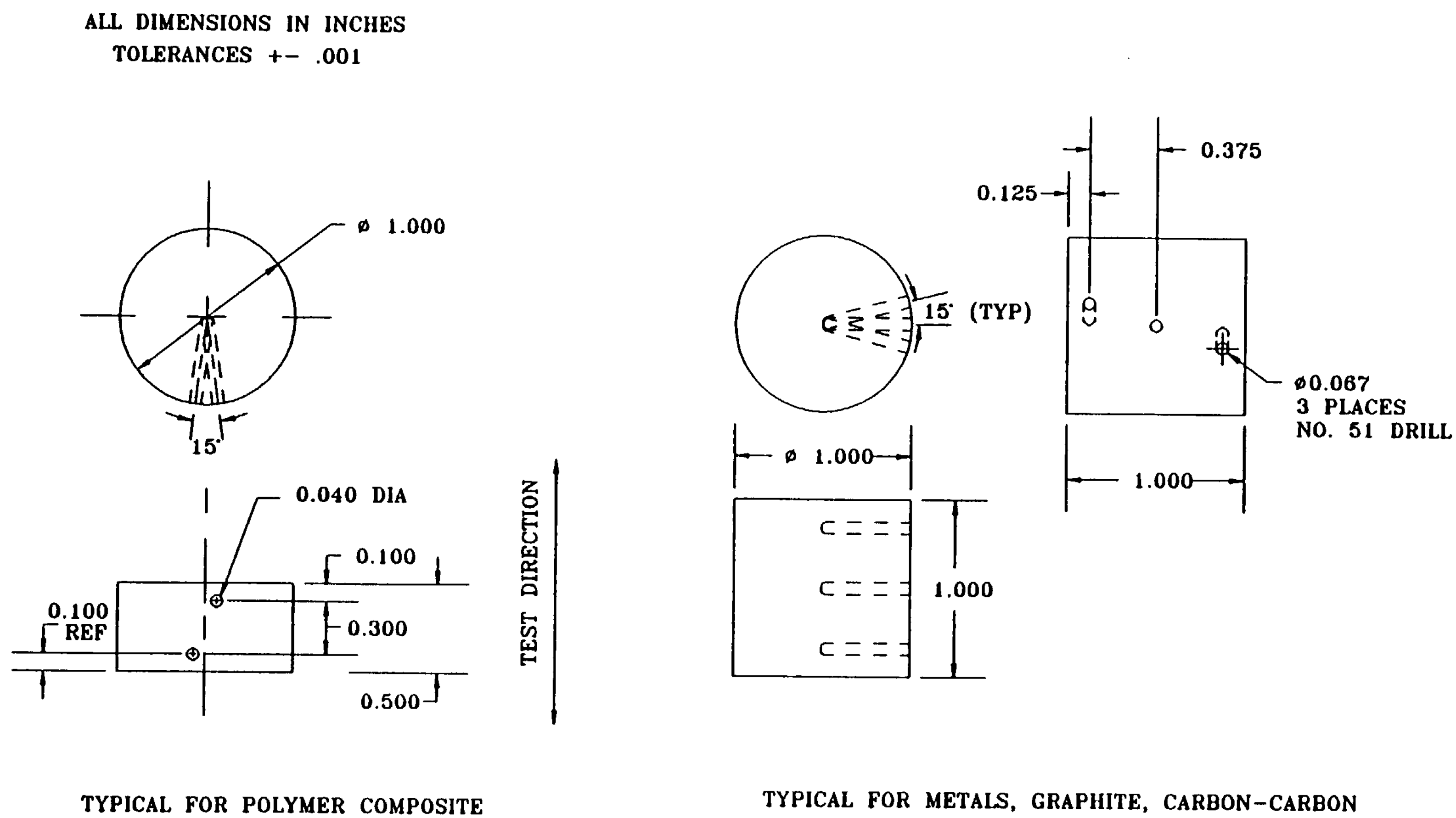

Figure 4. Comparative Rod Apparatus Specimen Configuration

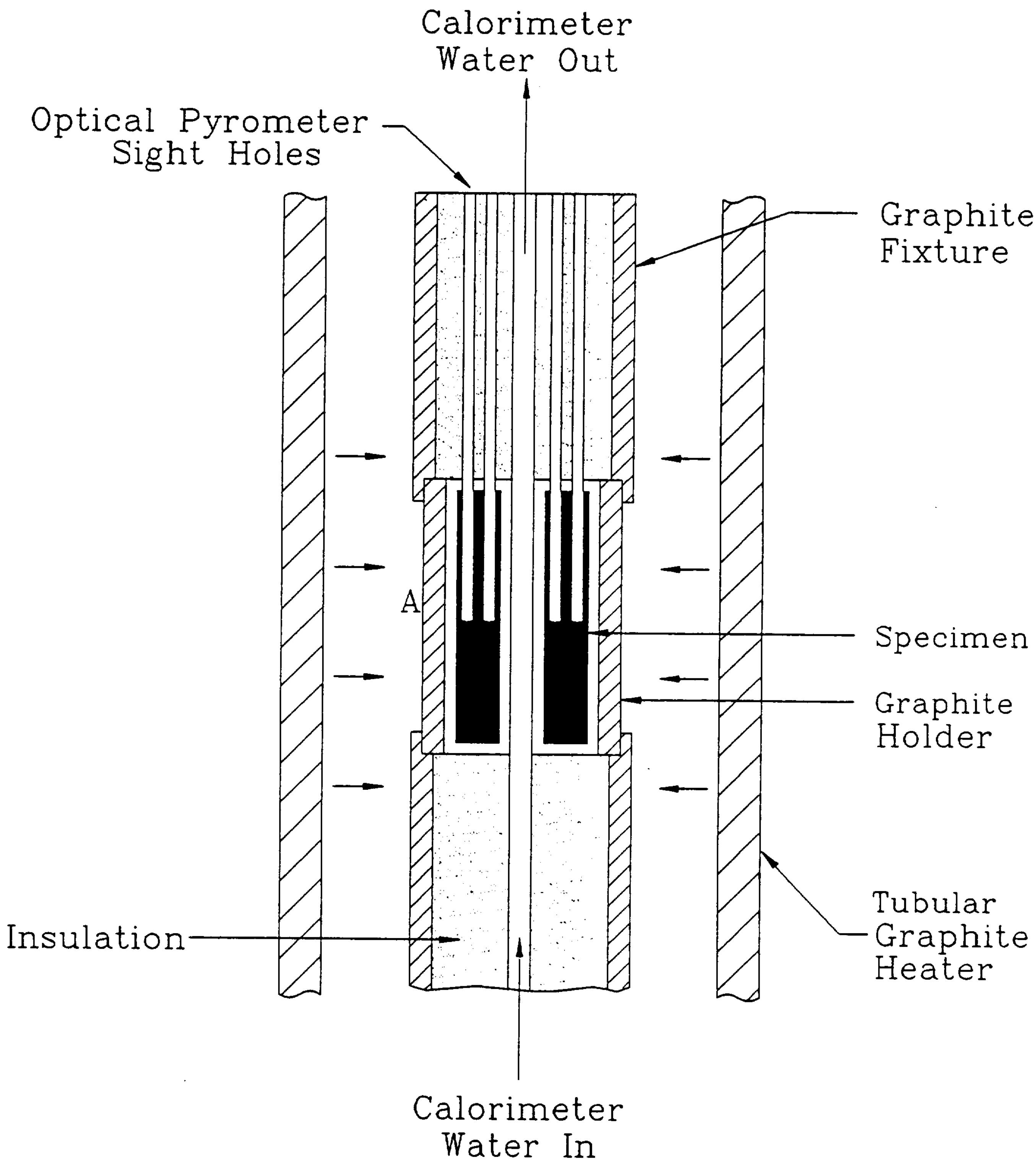

Figure 5. Cross-Sectional View of Radial Inflow Apparatus (RIA)

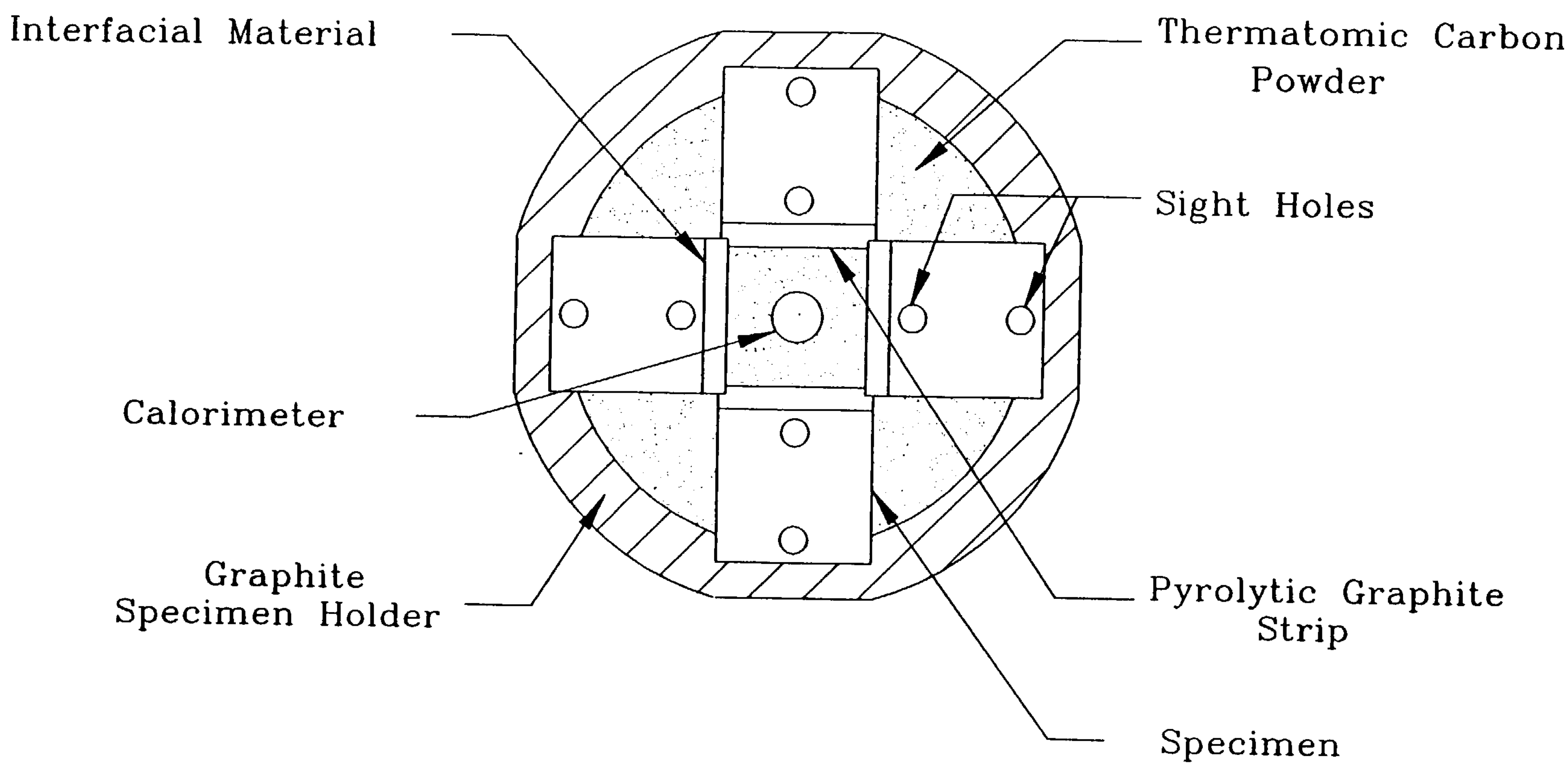

Figure 6. Top View of the Radial Inflow Apparatus Showing Specimen Configuration

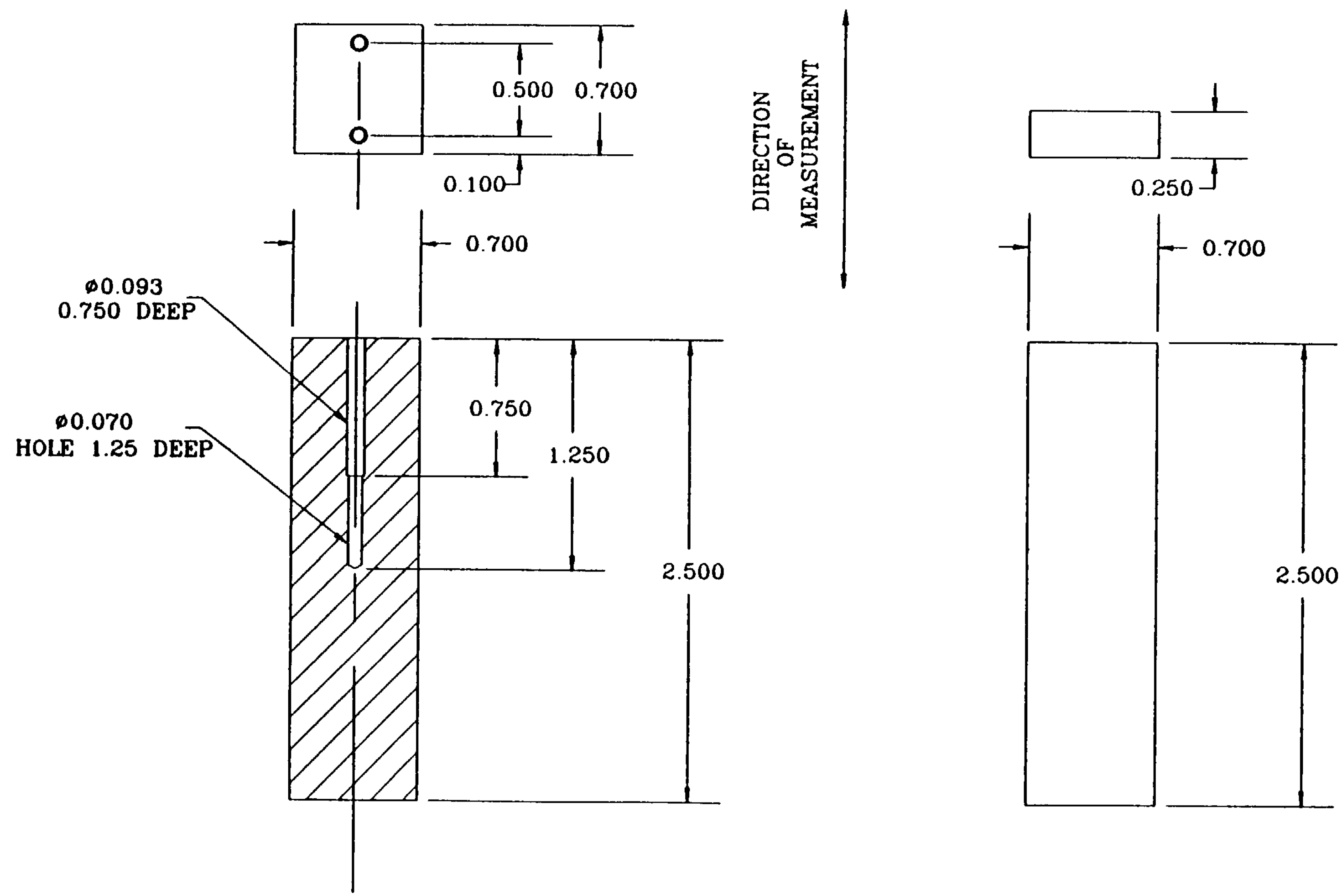

Figure 7. Typical Radial Inflow Specimens

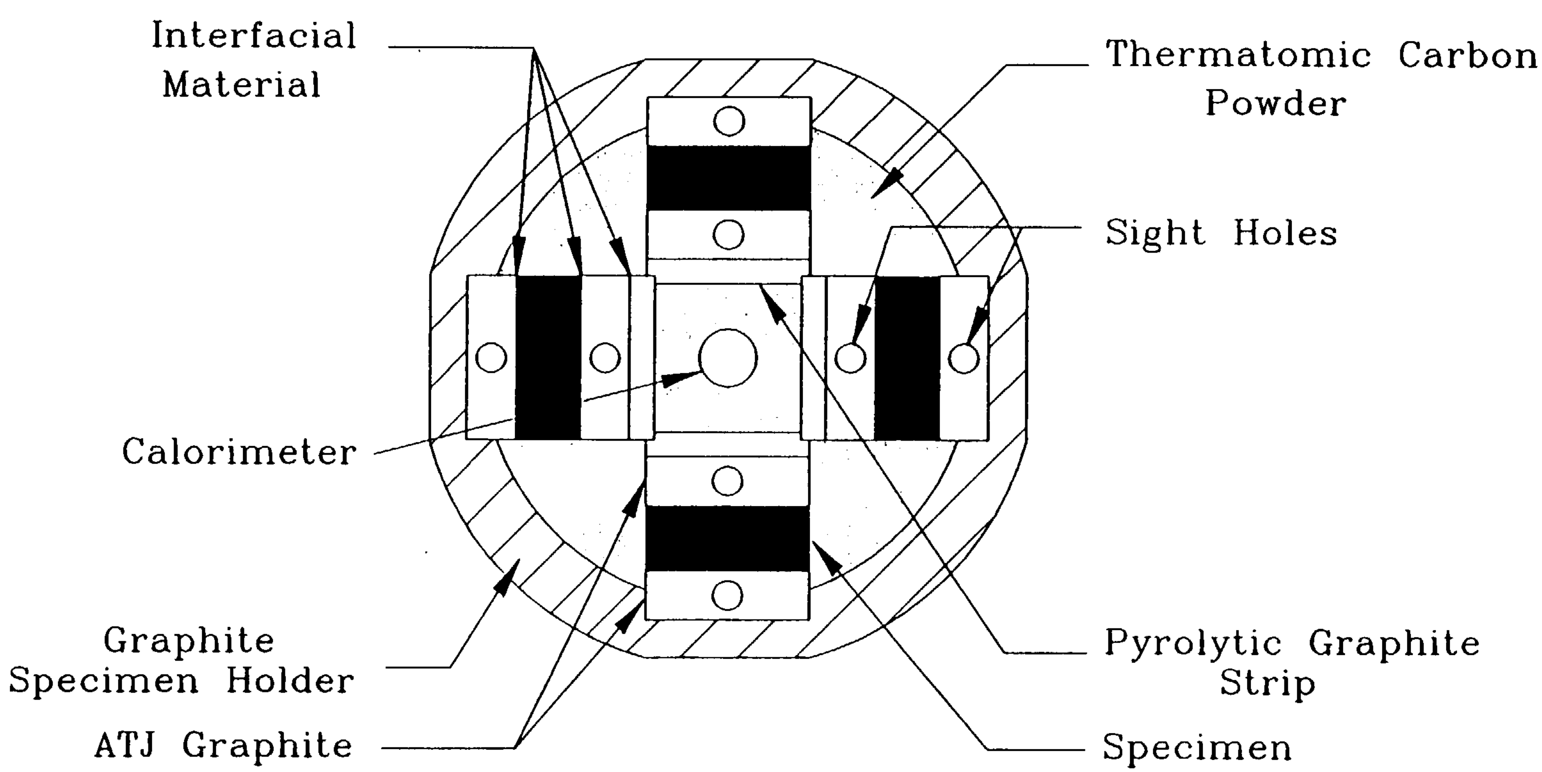

Figure 8. Configuration for 0.250" Thick Radial Inflow Specimens

APPENDIX B

DATA MEASURED IN ASTM C177 GUARDED HOT PLATE APPARATUS

Table 1

Thermal Conductivity of Angle Interlock Quartz Measured in ASTM C177 Guarded Hot Plate Apparatus

	Mean Temperature of Specimen (°F)	Thermal Conductivity of Specimen (Btu in./hr ft2°F)		
Symbol	90.10	1.236	Specimen:	ASTM-1&2
			Run No.:	F0666-125-7"Ni#1SC
	61.98	1.205	Density:	53.88 lb/ft3
	301.39	1.734		
	617.20	1.846		
	933.82	1.933		
Symbol	98.57	1.205	Specimen:	ASTM-3&4
			Run No.:	F0666-137-7"Ni#1SC
	213.23	1.427	Density:	53.88 lb/ft3
	474.92	1.660		
	785.12	1.806		

Table 2

Thermal Conductivity of Angle Interlock S-Glass Measured in ASTM C177 Guarded Hot Plate Apparatus

	Mean Temperature of Specimen (°F)	Thermal Conductivity of Specimen (Btu in./hr ft2°F)		
Symbol	88.09	1.508	Specimen:	ASTM-1&2
			Run No.:	F0666-118-7"Ni#1SC
	25.84	1.399	Density:	62.90 lb/ft3
	138.24	1.695		
	399.99	2.033		
	713.54	2.103		
	942.55	2.145		
Symbol	94.90	1.440	Specimen:	ASTM-3&4
			Run No.:	F0666-132-7"Ni#1SC
	279.01	1.877	Density:	62.90 lb/ft3
	543.61	1.976		
	845.60	2.061		

Table 3

Thermal Conductivity of Angle Interlock Kevlar Measured in ASTM C177 Guarded Hot Plate Apparatus

	Mean Temperature of Specimen (°F)	Thermal Conductivity of Specimen (Btu in./hr ft2°F)		
Symbol	87.44	1.788	Specimen:	ASTM-1&2
	153.31	2.076	Run No.:	F0666-108-7"Ni#2SC
	340.65	2.470	Density:	37.41 lb/ft3
	649.88	2.623		
Symbol	12.44	1.601	Specimen:	ASTM-3&4
	95.96	1.969	Run No.:	F0666-113-7"Ni#2SC
	260.16	2.133	Density:	37.41 lb/ft3
	447.01	2.279		

Table 4

Thermal Conductivity of Polar Weave Quartz (New) Measured in ASTM C177 Guarded Hot Plate Apparatus

	Mean Temperature of Specimen (°F)	Thermal Conductivity of Specimen (Btu in./hr ft2°F)		
Symbol	71.39	1.287	Specimen:	ASTM-1&2
	71.41	1.279	Run No.:	H036-50-7"Ni#2SC
			Density:	54.69 lb/ft3
	190.30	1.494		
	197.35	1.491		
	369.74	1.564		
	369.71	1.567		
	658.11	1.775		
	658.27	1.773		

Table 5

Thermal Conductivity of Polar Weave S-Glass (New) Measured in ASTM C177 Guarded Hot Plate Apparatus

	Mean Temperature of Specimen (°F)	Thermal Conductivity of Specimen (Btu in./hr ft2°F)		
Symbol	73.77	1.141	Specimen:	ASTM-1&2
	73.83	1.138	Run No.:	H036-60-7"Ni#1SC
			Density:	61.93 lb/ft3
	207.62	1.336		
	207.74	1.337		
	395.05	1.511		
	395.18	1.508		
	654.83	1.715		

Table 6

Thermal Conductivity of Polar Weave Kevlar (New) Measured in ASTM C177 Guarded Hot Plate Apparatus

Symbol	Mean Temperature of Specimen (°F)	Thermal Conductivity of Specimen (Btu in./hr ft2°F)		
	78.45	1.357	Specimen:	ASTM-1&2
	78.49	1.352	Run No.:	H036-55-7"Ni#1SC
			Density:	37.83 lb/ft3
	247.33	1.797		
	247.41	1.799		
	408.21	1.891		
	408.24	1.891		
	564.10	1.783		
	564.10	1.783		

APPENDIX C

DIRECTIONAL REFLECTANCE MEASUREMENTS OF POLAR WEAVE QUARTZ FABRIC

REPORT BY:

SURFACE OPTICS CORPORATION

SOC-R731-001-0692

DIRECTIONAL REFLECTANCE MEASUREMENTS ON ONE (1) SAMPLE OF PW QUARTZ FABRIC

FINAL REPORT AND APPENDIX A

Prepared for:

SOUTHERN RESEARCH INSTITUTE
Birmingham, Alabama 35205

Prepared under:

PURCHASE ORDER NUMBER BH-33087

JUNE 1992

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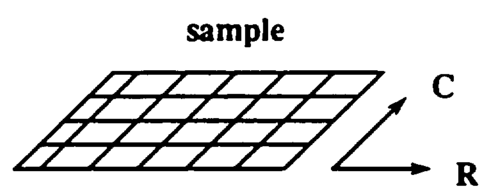
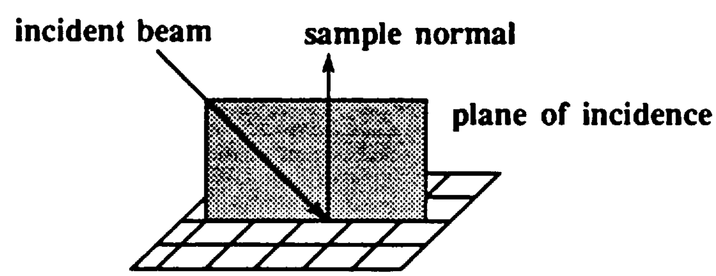
SUMMARY

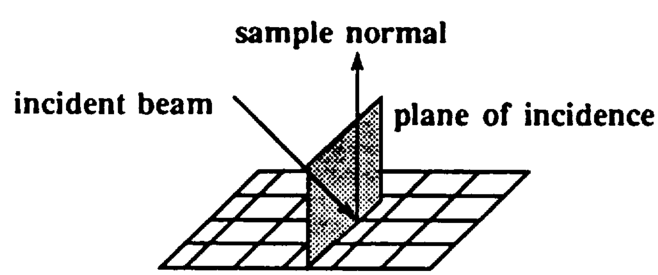
One sample of PW Quartz Fabric was measured for Southern Research Institute (SRI) by Surface Optics Corporation (SOC) under Purchase Order Number BH-33087. The measurement performed was directional reflectance (DR) from 1.6 to 26.0 µm at incident angles of 20, 45 and 75° from normal. From the DR data the directional emittance as a function of temperature and incident angle was calculated.

The sample consists of perpendicular layers of quartz fabric woven together, therefore, the DR data was measured with the plane of incidence aligned in both directions of the fabric. For ease of measurement the customer labeled one direction of the fabric as **C** and the other direction as **R** (see drawing below). The data measured for both orientations of the incident plane is reported in Appendix A.





Measurement of sample with plane of incidence aligned with R



Measurement of sample with plane of incidence aligned with C

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1.0 INTRODUCTION

This report presents directional reflectance data on one (1) sample material provided by Southern Research Institute. The work was performed under Purchase Order Number BJ-33087.

2.0 SAMPLE DESCRIPTIONS AND MEASUREMENTS REQUIRED

Table 1 is an overview of all samples and of the optical measurements performed.

3.0 DEFINITIONS AND NOMENCLATURE

3.1 Symbols and Units

Table 2 contains a listing of the symbols and units of quantities used in this investigation.

3.2 Coordinate System and Sign Convention

The quantities of reflectometry are conveniently referenced to a spherical polar coordinate system of unit radius (θ,ϕ) as shown in Figure 1.

Table 1

Sample Description and Test Parameters
Southern Research Institute

ERAS FORMAT BASIC NUMBER	MATERIAL DESCRIPTION	DIRECTIONAL REFLECTANCE Θ_i = 20,45 and 75° Φ_i = C and R (see drawing)
		1.6 – 26.0 μm
FS5675	PW Quartz	X

back of sample

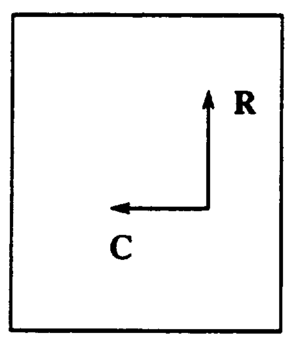

Table 2

Symbols and Units

SYMBOL			UNITS
BDR	=	Bidirectional Reflectance	$steradians^{-1}$
DR	=	Directional Reflectance	dimensionless
J_λ	=	Johnson's Solar Irradiance Function	$watts\ meter^{-2} \bullet micrometers^{-1}$
N_i	=	Source Radiance	$watts\ meter^{-2} \bullet steradians^{-1}$
N_r	=	Reflected Radiance	$watts\ meter^{-2} \bullet steradians^{-1}$
n	=	Refractive Index	dimensionless
k	=	Extinction Coefficient	dimensionless
α	=	Solar Absorptivity	dimensionless
ε_d	=	Spectral Directional Emittance	dimensionless
θ_i	=	Incident Polar Angle	degrees
θ_r	=	Reflected Polar Angle	degrees
λ	=	Wavelength	micrometers
λ_l	=	Lower Value of Wavelength	micrometers
λ_u	=	Upper Value of Wavelength	micrometers
$\|\|$	=	Parallel Polarized Light	
$\perp$	=	Perpendicular Polarized Light	
ρ_d	=	Directional Reflectance of an Unpolarized Incident Beam	dimensionless
ρ_d^u	=	Directional Reflectance Uncorrected for Instrumentation Polarization	dimensionless
ρ'	=	Bidirectional Reflectance	$steradians^{-1}$
ϕ_i	=	Incident Azimuth Angle	degrees
ϕ_r	=	Reflected Azimuth Angle	degrees
T	=	Temperature	degrees
$d\omega_i$	=	Source Solid Angle	steradians
$d\omega_r$	=	Reflected Solid Angle	steradians
h	=	Planck's Constant	$joule \bullet sec$
c	=	Speed of Light	$m \bullet sec^{-1}$
k	=	Boltzman's Constant	$joule \bullet kelvin^{-1}$

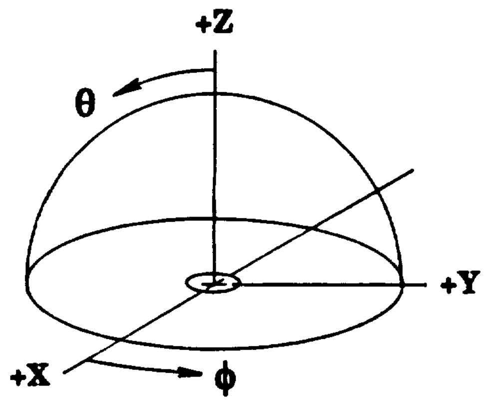

Figure 1. Coordinate System for Reflectometry Measurements.

The sample center coincides with the origin of a right-handed Cartesian coordinate system (x,y,z). The polar angle θ is measured downward from the positive z-axis, the azimuth angle ϕ counterclockwise from the positive x-axis. A fiducial mark placed at the edge of the sample serves to orient it relative to the coordinate axes. If the sample is smooth or randomly rough, the location of the mark is arbitrary and serves no other purpose than to provide the operator with a convenient reference during a set of measurements or for correlation of measurements made on more than one instrument. If the sample surface exhibits preferred orientation, such as striae resulting from machining, weaving, etc., it is SOC practice to align the fiducial mark in the direction of the striae as shown in Figure 2.

3.3 Polarization Convention

When reflectance measurements are made with polarized light, the directions of polarization are defined relative to the plane formed by the incident beam and the normal to the sample face. For an unpolarized incident beam, the reflected light (electric field vector) vibrating in the plane of incidence is called parallel polarized. The reflected light vibrating normal to the plane of incidence is said to be perpendicularly polarized (Figure 3).

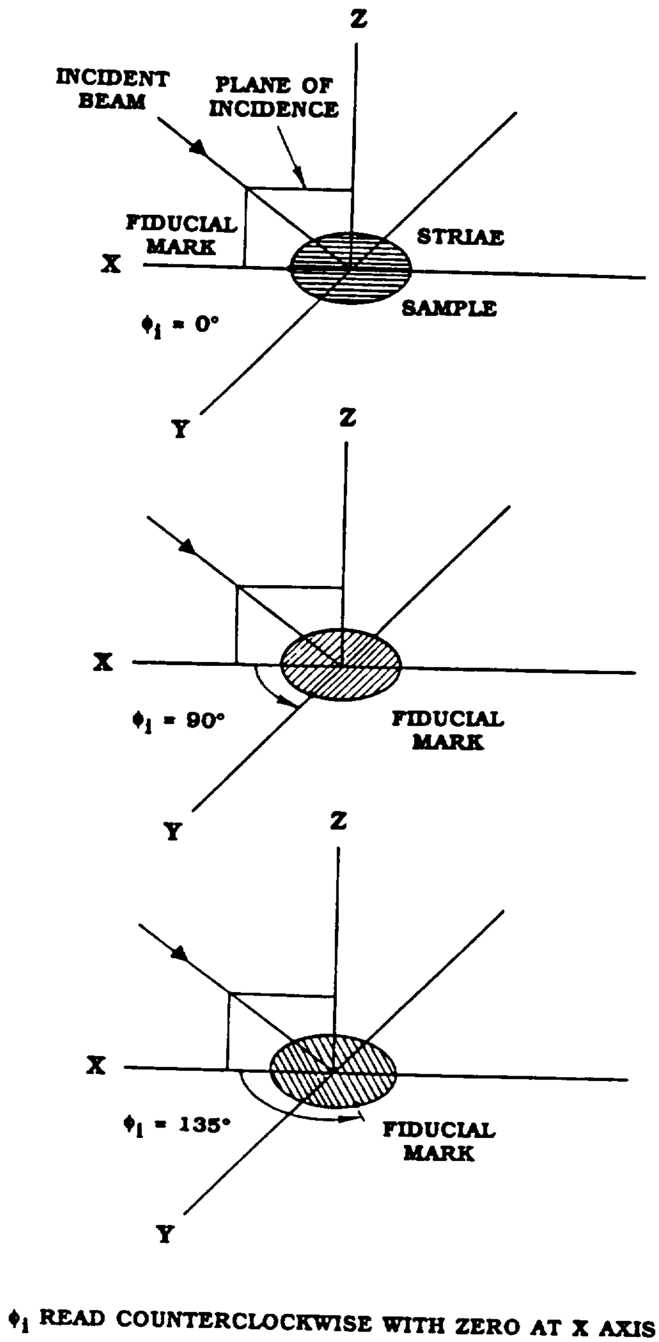

Figure 2. Definition of Striae Orientation.

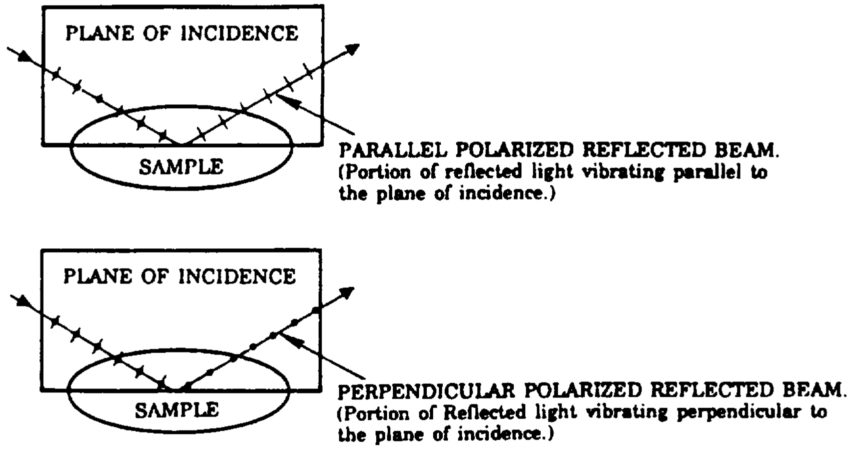

Figure 3. Convention Describing the Polarization of Reflected Light.

4.0 REFLECTANCE PROPERTIES

4.1 Directional Reflectance

The directional reflectance (DR) of a surface is defined as the ratio of the total energy reflected into the subtending hemisphere to the energy incident on the surface from the direction θ_i,ϕ_i (Figure 4).

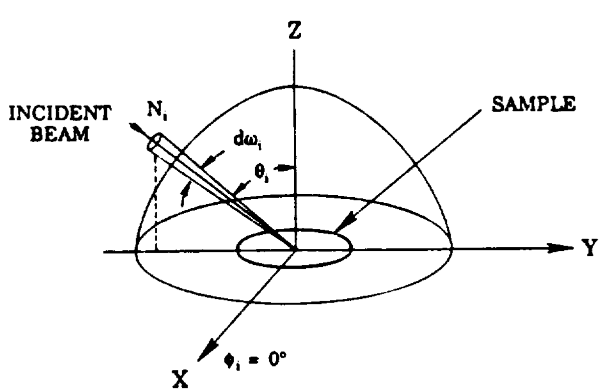

Figure 4. Diagram Illustrating Concept of Directional Reflectance.

Following the notation of Nicodemus[1], the directional reflectance may be expressed in terms of primary quantities as

$$\rho_d(\theta_i,\phi_i) = \frac{\int_0^{2\pi}\int_0^{\pi/2} N_r \sin\theta_r \cos\theta_r \, d\theta_r \, d\phi_r}{N_i \sin\theta_i \cos\theta_i \, d\theta_i \, d\phi_i} \quad . \tag{1}$$

The relation between directional and bidirectional reflectance (BDR) is given by the integral of the latter over the viewing hemisphere

$$\rho_d(\theta_i,\phi_i) = \int_0^{2\pi}\int_0^{\pi/2} \rho'(\theta_i,\phi_i;\theta_r,\phi_r) \sin\theta_r \cos\theta_r \, d\theta_r \, d\phi_r \quad . \tag{2}$$

For a perfectly diffuse isotropic reflector ($\rho'(\theta_i,\phi_i;\theta_r,\phi_r)$ = constant), integration of (2) gives

$$\rho_d = \pi\rho' \quad . \tag{3}$$

4.2 Quantities Derived from Directional Reflectance

The measured directional reflectance of a surface may be used to compute two important properties required for radiative heat transfer analysis, viz. the directional emittance and the solar absorptance.

4.2.1 Emittance

By reasons of conservation of energy, the directional emittance of an opaque surface at a given wavelength and angle of incidence may be expressed by

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[1] Nicodemus, F., "Directional Reflectance and Emissivity of an Opaque Surface", Applied Optics, Vol. 4, No. 7 (July 1965).

$$\varepsilon_d(\theta_r,\phi_r,\lambda) = 1 - \rho_d(\theta_r,\phi_r,\lambda) \qquad , \tag{4}$$

where $\rho_d(\theta_i,\phi_i,\lambda)$ is the measured directional reflectance.* From this relation, the total directional emittance of the surface at a given temperature may be found by

$$\varepsilon_t(\theta_r,\phi_r,\lambda) = 1 - \frac{\int_0^\infty \rho_d(\lambda)\, P(\lambda,T)\, d\lambda}{\int_0^\infty P(\lambda,T)\, d\lambda} \qquad , \tag{5}$$

where

$$P(\lambda,T) = \frac{8\pi hc}{\lambda^5(e^{hc}/\lambda Tk - 1)} \qquad , \tag{6}$$

is Planck's Function for the given wavelength and temperature. Substituting values for the constants h, c and k and providing the appropriate unit conversion so λ can be expressed in micrometers we have

$$P(\lambda,T) = \frac{0.000119088}{\lambda^5[e^{14388/\lambda T} - 1]} \qquad . \tag{7}$$

SOC software has been developed to provide emittance data of three types, depending on the angular coverage present in the reflectance measurements:

(1) directional, near-normal emittance, when reflectance has been measured at near-normal incidence (θ = 20°);

(2) directional angular emittance, when reflectance has been measured at any incidence angle other than near-normal;

---

* The θ_i and ϕ_i dependence of ρ_d and ε_d is dropped from the notation for reasons of brevity and is assumed for the remainder of this discussion.

(3) total hemispherical emittance, when reflectance has been measured over a sufficiently wide range of incidence angles to permit integration over the hemisphere (assuming no ϕ dependence for $\varepsilon_t(\theta_i,\phi_i)$), viz.

$$\varepsilon_H = 2\int_0^{\pi/2} \varepsilon_t(\theta)\ \sin\theta\ \cos\theta\ d\theta \quad . \tag{8}$$

4.2.2 Solar Absorptance

According to Kirchhoff's Law, the absorptance of a surface at any wavelength is equal to its emittance under equilibrium conditions

$$\alpha_\lambda = \varepsilon_\lambda \quad . \tag{9}$$

The solar absorptance of the surface may therefore be written as

$$\alpha_s = \frac{\int_{\lambda_1}^{\lambda_2} [1 - \rho_d(\lambda)]\ J(\lambda)\ d(\lambda)}{\int_{\lambda_1}^{\lambda_2} J(\lambda)\ d(\lambda)} \quad , \tag{10}$$

where $J(\lambda)$ is the solar irradiance function. The limits on the integrals (λ_1 and λ_2) are typically 0.2 μm and 7.0 μm, respectively. These limits are chosen such that the equation can be adequately calculated without significant error. SOC program SOLARAB calculates the exoatmospheric solar absorptance of a surface from the measured directional reflectance and the NASA solar spectrum SP-8005, modified to give a solar constant of 1368 (watts/m^2). The computational procedure selects points of the solar irradiance function which match the wavelengths of the measured reflectances, using interpolation where necessary. The program is capable of utilizing directional reflectance data obtained over the full range of angles of incidence.

5.0 APPARATUS AND INSTRUMENTATION

5.1 Directional Reflectometry

Surface Optics Corporation utilizes two instruments for the measurement of directional reflectance: an integrating-sphere reflectometer in the wavelength region from 0.2 to 1.6 μm, and a hemi-ellipsoidal reflectometer from 1.6 to 25.0 μm (and beyond if required).

Both instruments are employed in the "reciprocal" mode. This means that the sample is uniformly illuminated by the interior of a domed surface, and the radiation scattered by the sample in a specified direction θ_i is focused onto a detector. Measurements made in this manner are fully equivalent to those utilizing the "direct" mode, in which the source illuminates the sample from a given direction and the radiation scattered by the sample is collected and detected.

Construction details and operational features of the two instruments are presented in the following sections.

5.1.1 Cary-Integrating Sphere Reflectometer

This instrument is designed for directional reflectance measurements in the near ultraviolet, visible and near infrared region. As illustrated in Figure 5 the sample is located at the center of a hollow 9" diameter sphere which is coated with a thick layer of Halon (G-80 tetrafluoretheylene).

The source illumination for the sample is provided by a 55 watt halogen bulb mounted behind the sample in the center of the integrating sphere. A diffuse reflector physically blocks the region between the sample and the bulb such that light from the halogen bulb must bounce off the integrating sphere a minimum of two times before reflecting off the sample surface. Thus, the sample views a uniformly illuminated hemisphere of 2π steradiancy. The angle of incidence θ_i at which the DR is measured may be varied by rotating the sample about an axis in the plane of the sample, the axis being perpendicular to the spectrophotometer beam. The azimuthal angle ϕ_i of the sample may be varied by rotation of the sample about the axis perpendicular to and through the sample center.

The beam reflected by the sample and a reference beam reflected by the illuminating hemisphere enter the collection optics of a Cary Model 14 Spectrophotometer. Here a rotating chopper alternately selects energy from the sample and reference beams, which is focussed onto a dispersing prism. The resulting monochromatic signals are directed to the appropriate detectors, a

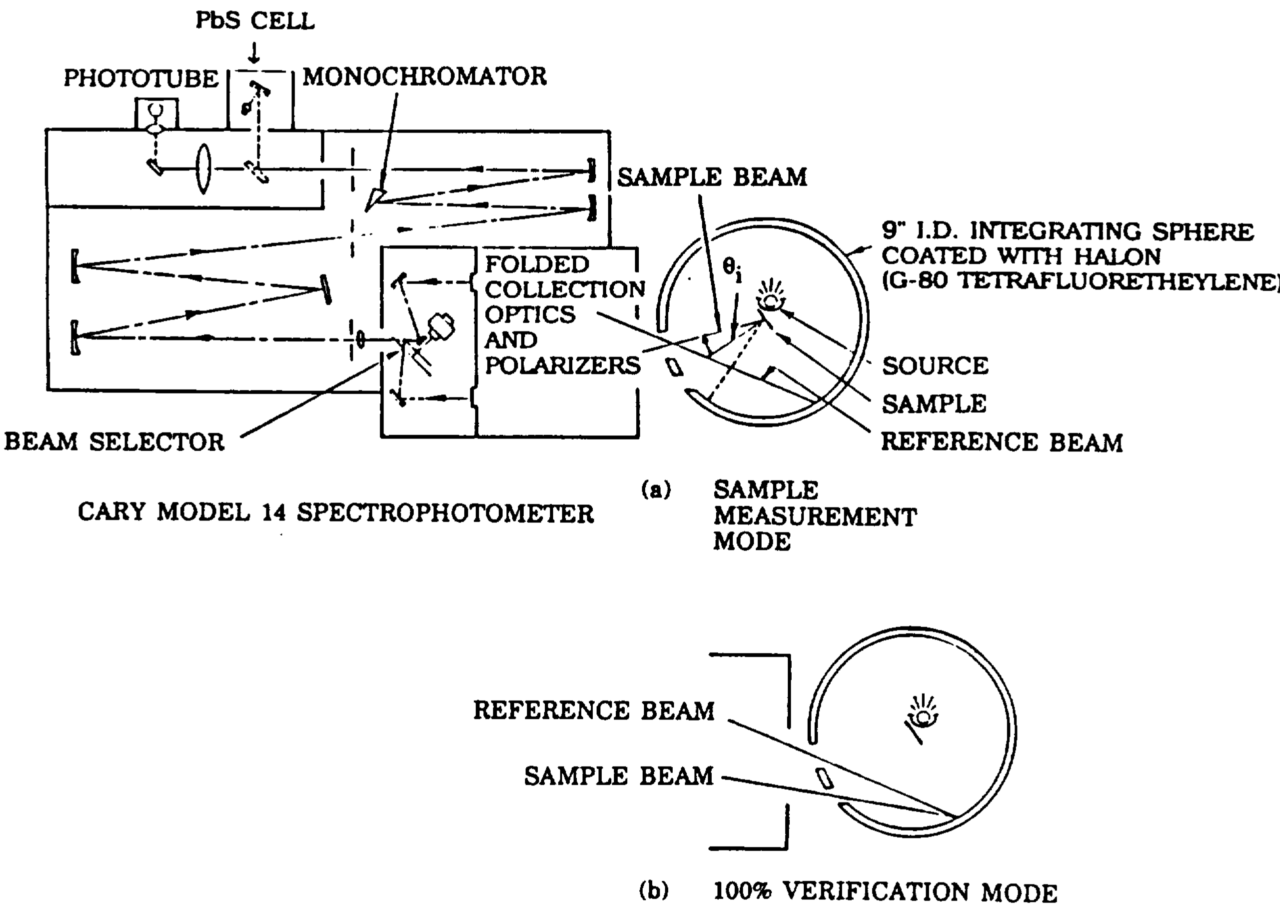

Figure 5. Schematic of Cary-Integrating Sphere Reflectometer.

photomultiplier tube for the region from 0.3 to 0.8 μm, and a lead sulphide cell for that from 0.8 to 1.6 μm when measuring polarized data. The detector circuits automatically form the difference of the two signals which is directly proportional to the directional reflectance (DR), and which is displayed as function of wavelength on a stripchart recorder. For internal calibration, the instrument is operated in the 100% or verification mode in which the two branches of the spectrophotometer collection optics view the same spot on the illuminating hemisphere. The principal features, components and performance characteristics of the instrument are shown in Table 3.

Measurements in the ultraviolet (UV) area of the spectrum can be extended from 0.3 μm down to 0.2 μm with minor modifications to the Cary spectrometer. To extend measurements farther into the UV, the 55 watt halogen bulb is replaced with a deuterium lamp that provides significantly more energy in the UV portion of the spectrum. In addition to replacement of the source, the photomultiplier tube is replaced with another photomultiplier tube with superior response in the ultraviolet portion of the spectrum. With these two modifications the directional reflectance data can be collected down to 0.2 μm unpolarized. The methods described previously to calibrate and measure the directional reflectance of a material are not affected with the change of the source and detector. Polarized UV measurements require that the Glan Thompson prism polarizers (~ 0.3 to 1.6 μm) be replaced with UV dichroic sheet polarizers (0.2 to 0.31 μm).

5.1.2 Infrared Ellipsoidal Reflectometer

From 1.6 to 25.0 μm and beyond, directional reflectance is experimentally measured using a hemi-ellipsoidal reflectometer. The features of this instrument are outlined in Table 4.

The characteristics of a hemi-ellipsoid are such that a point source of light emanating from one focus is imaged at the other focus.[2] The geometrical arrangement, in this case, of the source and sample at the foci in the plane of the ellipse, is shown in Figure 6. The source illuminates the sample uniformly over 2π steradians. The reflected radiation from the sample is viewed by a small spherical "overhead" mirror which directs the illumination in sequence to a plane mirror, a torroidal mirror, a plane mirror, thence to the monochromator slit, through the monochromator and to the detector, see Figure 6.

In the alignment process, the detector is replaced by a mercury arc source, and the Hg green line traverses the reflectometer optical path in the "reverse" direction. The monochromator entrance

[2] Brandenberg, W.M., "Focusing Properties of Hemispherical and Ellipsoidal Mirror Reflectometers", Number DGA63-1111. ERR-AN-352, General Dynamics Astronautics Report (November 1963).

Table 3

Cary-Integrating Sphere Reflectometer

Function	Determination of directional reflectance as a function of wavelength, angle of incidence, and light polarization in the near-ultraviolet, visible and near-infrared region.
Wavelength	0.2 to 1.6 μm.
Type	Integrating sphere coupled to Cary Model 14 dual beam prism-grating spectrophotometer.
Radiation Source	55 watt quartz halogen lamp, 3400° for 0.3 to 2.0 μm, and 30 watt Deuterium lamp for 0.2 to 0.3 μm.
Mode of Operation	Reciprocal: Uniform hemispherical illumination of sample. Sample viewing as a function of angle. Records traces for light polarized parallel ($\|$) and perpendicular ($\perp$). The $\|$ and $\perp$ traces are averaged to obtain reflectance for unpolarized light with effects of instrumentation polarization eliminated.
Sample Holder	Located in center of integrating sphere.
100% Value	Absolute measurement device, comparison to standard not required.
Transfer Optics	Custom design by Cary.
Polarizer	Dual Glan Thompson prisms (one in each beam) manufactured by Karl Lambrecht Corporation for ~ 0.3 to 2.0 μm, and UV dichroic sheet polarizer for 0.2 to 0.3 μm.
Viewing Angle	Near-normal (20°) to grazing (80°), with intermediate angles as required.
Detectors	Broadband response, phototube for 0.3 to 0.8 μm, lead sulfide for 0.8 to 1.6 μm, and PMT optimized for solarband region of spectrum, 0.2 to 0.3 μm.
Recording	Strip chart recorder.
Data Presentation	Graphical as a function of wavelength and incidence angle, tabular in ERAS format. Parallel and perpendicular polarized traces can be provided, with computed values of index of refraction (n) and extinction coefficient (k).

Table 4
Infrared Reflectometer

Function	Determination of directional reflectance as a function of wavelength, angle of incidence, and light polarization in the infrared region.
Wavelength	1.6 to 40 μm, coverage to 600 μm possible if required.
Type	Hemi-ellipsoidal: Ellipse cleavage plane contains semi-major and semi-minor axis. Infrared source at one focus, sample at other.
Infrared Source	High-purity, copper cavity with aerorod heater silver-soldered to outside, interior flame sprayed with a corrosion resistant alloy.
Chopper	Twin bladed, located between source and sample. Frequency, 20 Hz.
Mode of Operation	Reciprocal: Uniform illumination of sample, sample viewing as a function of angle. Records traces as $f(\lambda)$ for light polarized perpendicular ($\perp$) and parallel ($\parallel$). Average ($\perp$) and ($\parallel$) traces to obtain reflectance for unpolarized radiation, i.e. with effects of instrumentation polarization eliminated.
Sample Holder	Water cooled carousel holds eight samples, individually positionable in sample measurement position.
100% Value	Absolute, or in comparison to high-reflectance evaporated gold reference sample.
Transfer Optics	Toroidal mirror $2\theta = 60°$, FL = 125 mm, used at 1 to 1 magnification.
Polarizers	Perkin-Elmer wiregrid and thin film (over ZnSe) infrared polarizers.
Monochromator	Perkin-Elmer model 210 grating. Available gratings: 1800, 640, 240, 101, 40, 20, 10, 5, and 1.25 lines/mm.
Viewing Angle	Near-normal (20°) to grazing (80°), with intermediate angles as required.
Detectors	PbS detector, 1.6 to 2.2 μm; pyroelectric detector, 2.2 to 40.0 μm.
Signal Processing	EG&G (PAR) #124 amplifier.
Recording	Digital voltmeter.
Data Presentation	Graphical, as a function of wavelength and incidence angle; tabular in ERAS format. If required, parallel and perpendicular polarized traces and computed n and k values.

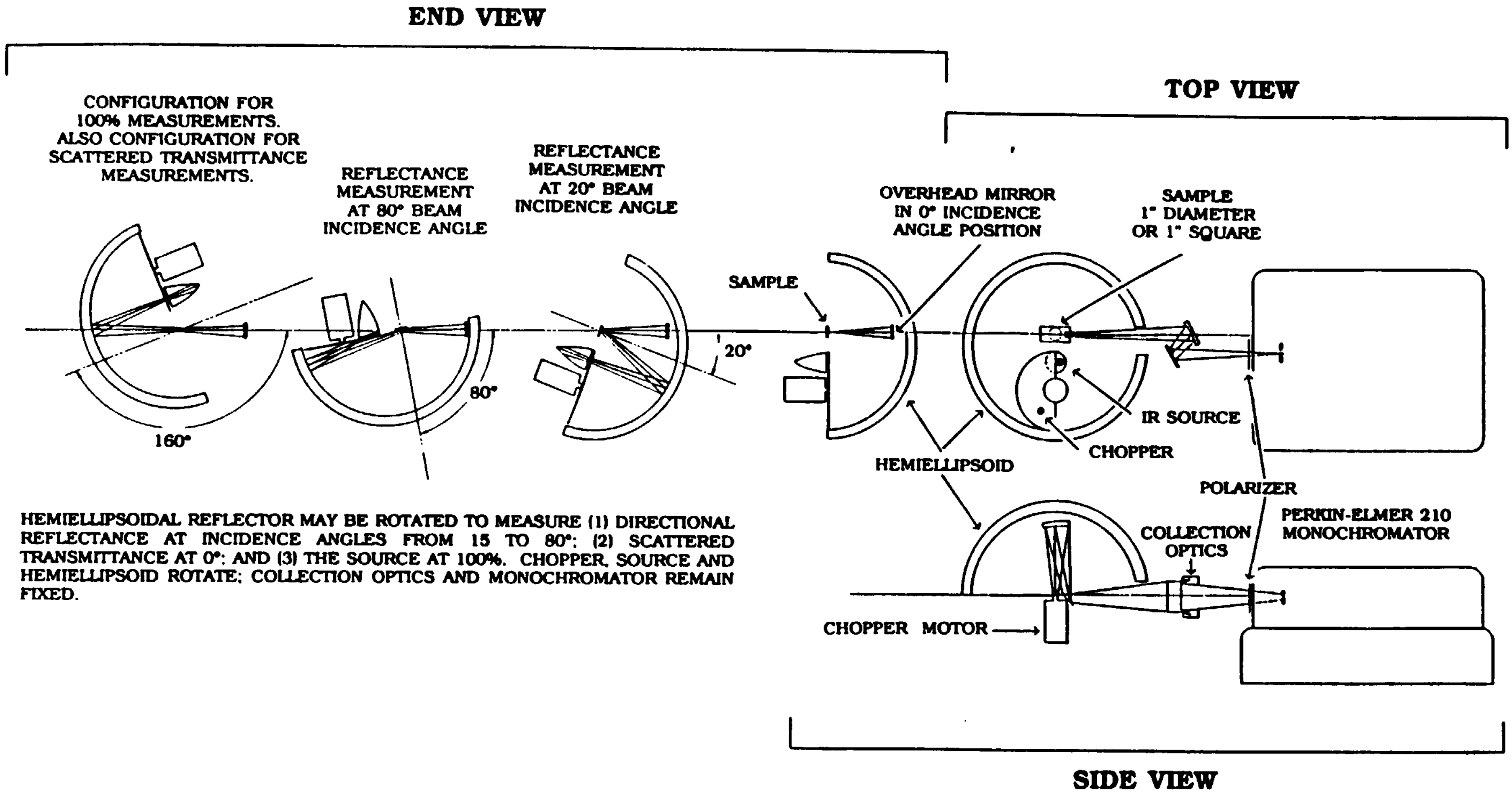

Figure 6. Schematic of Infrared Reflectometer.

slit is imaged by the collection optics on a 1" diameter sample disc. The specularly and/or diffusely reflected slit image is in turn imaged by the hemi-ellipsoid into the IR source opening. The slit image on the sample (about 1/8" x 1/2") when reimaged by the ellipsoid on the source cavity, must fall completely within the confines of the IR cavity entrance. Given a uniform radiance from the cavity, uniform illumination of the slit image on the sample over 2π steradians is provided.[3] The large diameter (12") and closely spaced foci (2" separation) of the hemi-ellipsoid used make the geometric deviation from a hemisphere minimal, but this deviation is all important in minimizing the size of the diffusely reflected slit image at the cavity entrance, see reference 2.

To allow performance of required functions, it is necessary to rotate the overhead mirror, together with the collection optics, monochromator, and detector, in relation to the source, chopper, and sample system. The rotation is performed about an axis through the sample center, in the plane of the sample and parallel to the ellipse semi-minor axis. This rotation is required (1) to allow positioning the mirror directly above the sample to measure the directional reflectance with the specular component eliminated, (2) to allow reflectance measurements as a function of angle 20 to 80°, and (3) to make a 100% measurement without use of a reference standard. The scattering or zero incidence angle measurement (specular component eliminated) is discussed below in Section 5.1.4. With this mechanism, angular measurements are routinely made for near-normal (20°), to grazing at 80° or greater.

Directional reflectance is, by definition, the ratio of the total reflected radiation to the radiation incident at a specified angle. Energy recorded when the sample is viewed by the overhead mirror gives the reflected datum. The incident datum may be measured (1) directly (so-called absolute method) or (2) derived by a replacement of the sample with a standard of known reflectance, such as evaporated gold on a smooth fused silica substrate.

The absolute 100% measurement requires removing the sample from the measurement position and rotating the overhead mirror to a location below the plane of the ellipse, see Figure 6. In this location, the overhead mirror receives the light which falls on the sample position, thus allowing measurement of the 100% datum.

The positioning of the overhead mirror in relation to the sample location is an important feature of the reflectometer. It cannot be accomplished by simply rotating the overhead mirror alone. The entire optical train, overhead mirror, torroid, monochromator and detector must remain fixed in relationship to each other; if the overhead mirror rotates, the entire train has to be rotated. This is now actually feasible with design changes recently accomplished. But for solid (non-fluid samples), the source-sample holder-chopper system is rotated, as shown in Figure 6.

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[3] Ibid.

5.1.3 Instrumentation Polarization

An unpolarized beam, after reflection from a surface, may be polarized to varying degrees, depending on the angle of incidence, the composition and roughness of the reflecting surface, and the wavelength of light. For angles of incidence near-normal (θ_i = 0 to about 20°) the reflected beam is usually only nominally polarized by reflection**, but at higher incidence angles (40 to 90°), the reflected beam from most samples shows pronounced polarization.

Grating and prism monochromators, in dispersing radiation, may introduce partial polarization to the beam. A light beam which is made up of equal components of perpendicular and parallel polarized light, upon passage through a monochromator, may emerge with unequally polarized components. The degree of polarization is highly wavelength dependent. For the instruments used, the polarization ratio (parallel/perpendicular) ranges from 0.573, (Perkin-Elmer 210) is more than 4 (Cary 14). At high angles, errors in reflectance for materials which on reflection tend to polarize light can be very large if effects of instrumentation polarization are not eliminated.

In practice, the beam (or beams in the dual beam Cary) is polarized parallel by a suitable polarizer and the reflectance of the parallel polarized trace is recorded. The operation is repeated with the polarizer rotated 90°. The trace for unpolarized incident radiation is derived by averaging the two traces. This procedure is time consuming but provides the correct results and provides additional data, i.e., at a given wavelength, the reflectance for parallel and perpendicular polarized light. From these data, *n* and *k* values may be calculated.

5.1.4 Normal (θ_i = 0°) and Grazing Incidence Measurements

The two reflectometers described above are based on similar operating principles*** and therefore share certain common characteristics. If a measurement is attempted at normal incidence, only the scattered or "non-specular" reflectance will be recorded. For the Cary-sphere device, the surface of the sphere that should provide the incident radiation for a zero incidence angle is the hole through which the reflected beam leaves the sphere. For the ellipsoidal device, the specular beam is similarly eliminated by the overhead mirror. There are instances where it is desired to measure only the diffuse reflectance and use is made of the zero incident angle.

** Multilayer stacks may produce considerable polarization, even at 20 degrees.

*** Sample subtends a dome of uniform illumination, viewing from a narrow solid angle.

Measurements at near-normal incidence are limited to angles no less than 20° from the normal. This limitation is fixed by the size of the opening in the Cary sphere and the sample mirror and geometry of the system in the ellipsoidal device..

A measurement angle at "grazing" incidence on a 1" diameter sample is limited in both instruments. The grazing incidence angle limitation is established by the size of the sample and geometric considerations. The image of the spectrometer entrance slit projected to the sample surface will ultimately fall off a finite-sized sample as the angle of incidence approaches 90°.

Angular measurements with the Cary-sphere device may be made to 80° using a 1" diameter sample; with the ellipsoidal device, measurements are possible at angles greater than 80° if narrow monochromator slits are used. The determining factor of the slit width is signal-to-noise which is in turn a function of wavelength and the use of polarizers. Polarizers must reduce signal strength at least 50% and in practice reduce it as much as 80 to 90%. For reasons already mentioned, grazing incidence measurements for polarizing samples are usually of little value without correction for instrumentation polarization.

5.1.5 Performance Verification

The principal problem in directional reflectance measurements is the availability of suitable standards. Directional reflectometers should provide a correct reflectance value for a specularly reflecting sample, a diffusely reflecting (scattering) sample, or a sample which reflects part of the light into a specular lobe and scatters the remainder. Calibration standards which may be correlated with theory are generally specular reflectors. The problem of standards has been discussed in some detail in a SAMSO report by R.J. Champetier and G.J. Friese.[4] The report compiles work done to resolve discrepancies in directional reflectance (or directional emittance) obtained on the same sample by three different laboratories. The preferred standard for the IR region is pure, highly polished (and therefore specular) fused silica. A second choice is evaporated gold on a polished glass substrate.

As already noted, SOC uses two instruments to cover the full spectral region from 0.3 to 25.0 μm. For both instruments, the error is estimated by comparison of measured reflectance with values established by the National Bureau of Standards (NBS) or with theoretical values calculated from n and k data in the literature.[4]

---

[4] Champetier, R.J., and Friese, G.J., "Use of Polished Fused Silica to Standardize Directional Polished Emittance and Reflectance Measurements in the Infrared", SAMSO Report TR-74-202, SAMSO, Los Angeles Air Force Station, Los Angeles, CA 90054 (9 August 1974).

The alternate method of error determination, viz, the summation of individual errors, is reasonably straightforward except for evaluation of the uniformity of the radiant intensity in the 2π steradians region subtended by the sample. This problem is common to both the Cary-sphere and the ellipsoid.

5.1.5.1 Cary-Sphere

Five samples which are mixtures of Halon and carbon black sintered to a solid mass were prepared and standardized by the NBS. These samples were diffuse reflectors. The reflectance ranges in the wavelength band between 0.25 and 2.5 µm for each sample are as follows:

- Sample #2 - 0.031 to 0.018;
- Sample #7 - 0.241 to 0.170;
- Sample #10 - 0.512 to 0.462;
- Sample #13 - 0.755 to 0.727;
- Sample #17 - 0.913 to 0.982.

The same five samples were measured by SOC in the region from 0.3 to 2.0 µm on the Cary-sphere. The deviation of the measured reflectance from the NBS values was in general less than 1%, excepting for sample #2, which showed values 1.3% higher than the NBS data. In operation the instrument is routinely checked against a specular gold standard. In the region from 1.0 to 2.0 µm, the standard shows reflectances of 98.5% to 99.5%, in good agreement with theoretical values.

5.1.5.2 Ellipsoidal Reflectometer

Beyond 2.5 µm, no diffuse standards exist. In this region, SOC uses a fused silica standard, i.e. a specular reflector. Reflectances at selected wavelengths between 4.0 and 25.0 µm are measured as a function of angle. Incident angles are 20, 30, 40, 50, 60, 70, 75 and 80°. The results are compared to values calculated from n and k (Reference 4). An example of experimental fused silica reflectance values is shown in Figure 7. The curves are labeled parallel ($\parallel$) and perpendicular ($\perp$) according to the usual polarization convention. Agreement between measured and theoretical data is seen to be good. The instrument is routinely checked against the fused silica sample after adjustments are made, after a new source is installed, or if no measurements have been made for more than two weeks. At 16 µm, the standard is measured at eight angles and in both perpendicular and parallel polarization modes and checked against theoretical values in Reference 4. The agreement in the average ⊥ and ∥ values is generally within 1% for angles from 20 to 70°; the 75 and 80° values may be in error by as much as 3%.

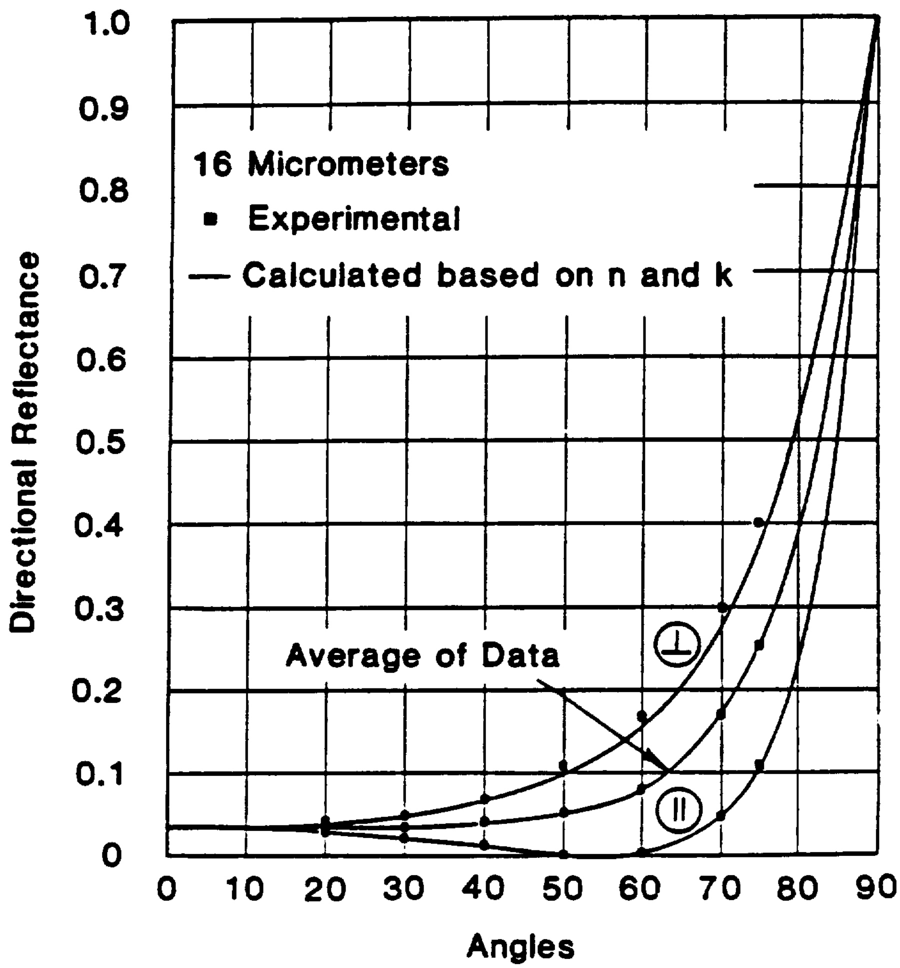

Figure 7. Directional Reflectance of Fused Silica Standard at 16 µm — Perpendicular (⊥), Parallel (∥), and Average.

6.0 DATA REDUCTION AND PRESENTATION

Data reduction is by interactive means, using a Sun 3/260 computer with a CRT terminal (CIT-101) and laser printer within the SOC laboratory facility. Current working sets of data are stored entirely within the computer where they are immediately available to the terminal display, either as print-out in report-ready format or graphical presentation. This procedure has eliminated the use of keypunch formats. Another advantage is the speed with which data on new materials can be acquired, processed and transferred. If required, the system provides computer-to-computer transfer between the SOC site and a client's facility via telephone lines.

6.1 Codes for Data Reduction

Data obtained with all incoherent source instrumentation (Cary-Integrating Sphere, Infrared Reflectometer) are processed by an interactive prompting system which eliminates the use of keypunch formats. For the directional reflectance measurements, the programs automatically merge the data collected by the Cary-Integrating Sphere and the Infrared Reflectometer.

6.1.1 Directional Reflectance Codes

Cary data (DR from 0.3 to 1.6 μm) are read from the instrument charts and entered into the computer by means of a prompting system. Infrared data (DR from 1.2 to 40.0 μm) are read from digital voltmeter printer tape and entered by prompting at each wavelength of interest. The raw data are processed into reflectance data and formatted to the standard ERAS form.[5] Two different classes of data are recognized:

1. near-normal, unpolarized data (used largely for thermal analysis calculations);

2. angular data collected in both polarizations (used as a data base for signature calculations).

[5] Earing, D., "Support Information for Target System Measurements", Willow Run Laboratories, Institute of Science and Technology, The University of Michigan (December 1967).

The following types of data may be generated, depending on requirements:

1. Solar absorptance as a function of polar incidence angle;

2. Integrated directional emittance as a function of temperature and angle, and total hemispherical emittance;

3. Directional reflectance as a function of wavelength and angle (including perpendicular and parallel polarization branches and their average);

4. "Bestfit" values of index of refraction and extinction coefficient;

5. "Bestfit" Brewster angle.

Figures 8 and 9 show the data reduction program steps involved in the two classes of reduction.

6.2 Data Presentation

Data is presented in both graphical and tabular form. In both cases special software is used. The tabular data is compiled in accordance with the ERAS format. In addition, all ERAS formatted data can be provided on tape.

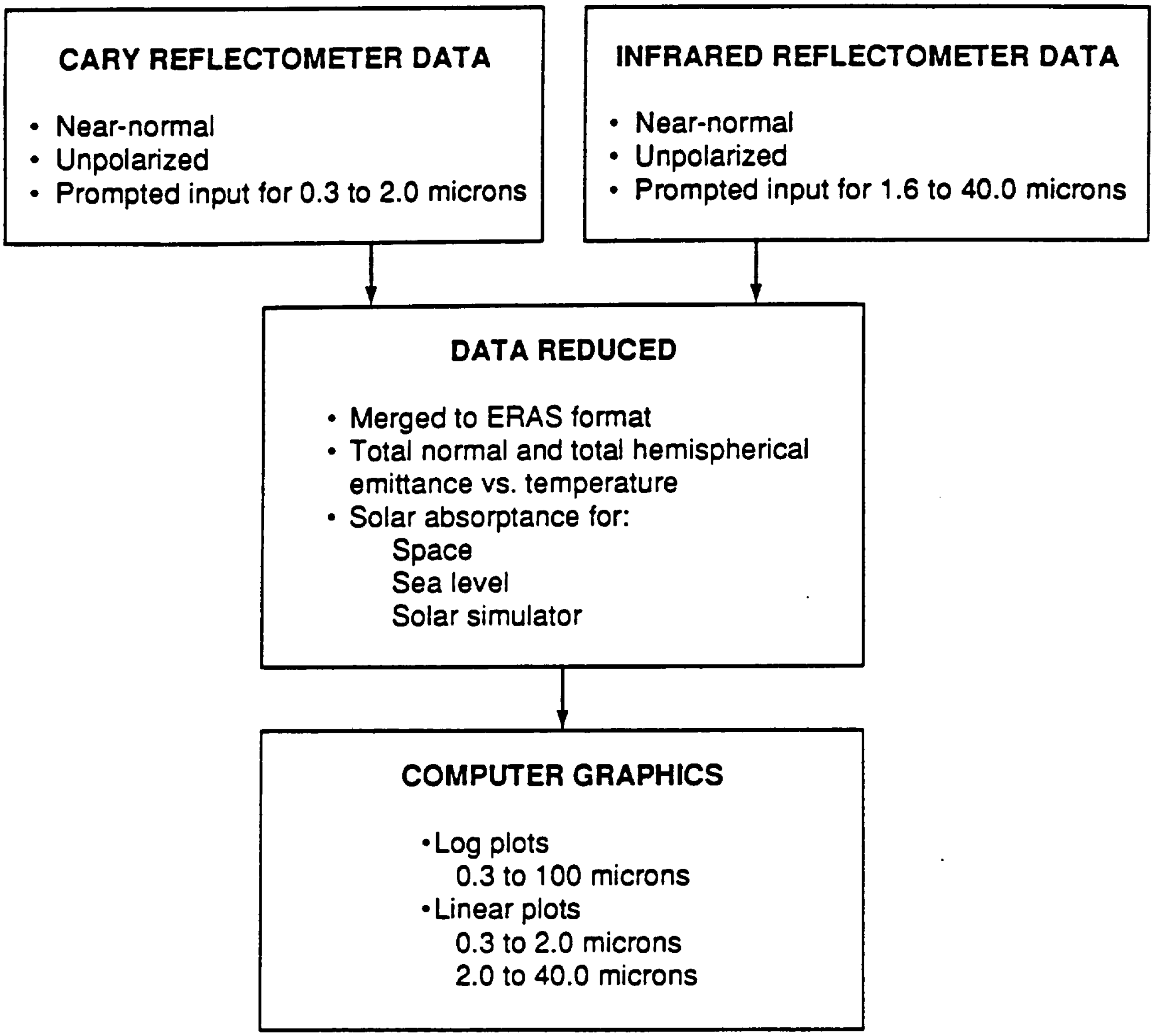

Figure 8. Directional Reflectance Data Processing for Thermal Analysis Calculations.

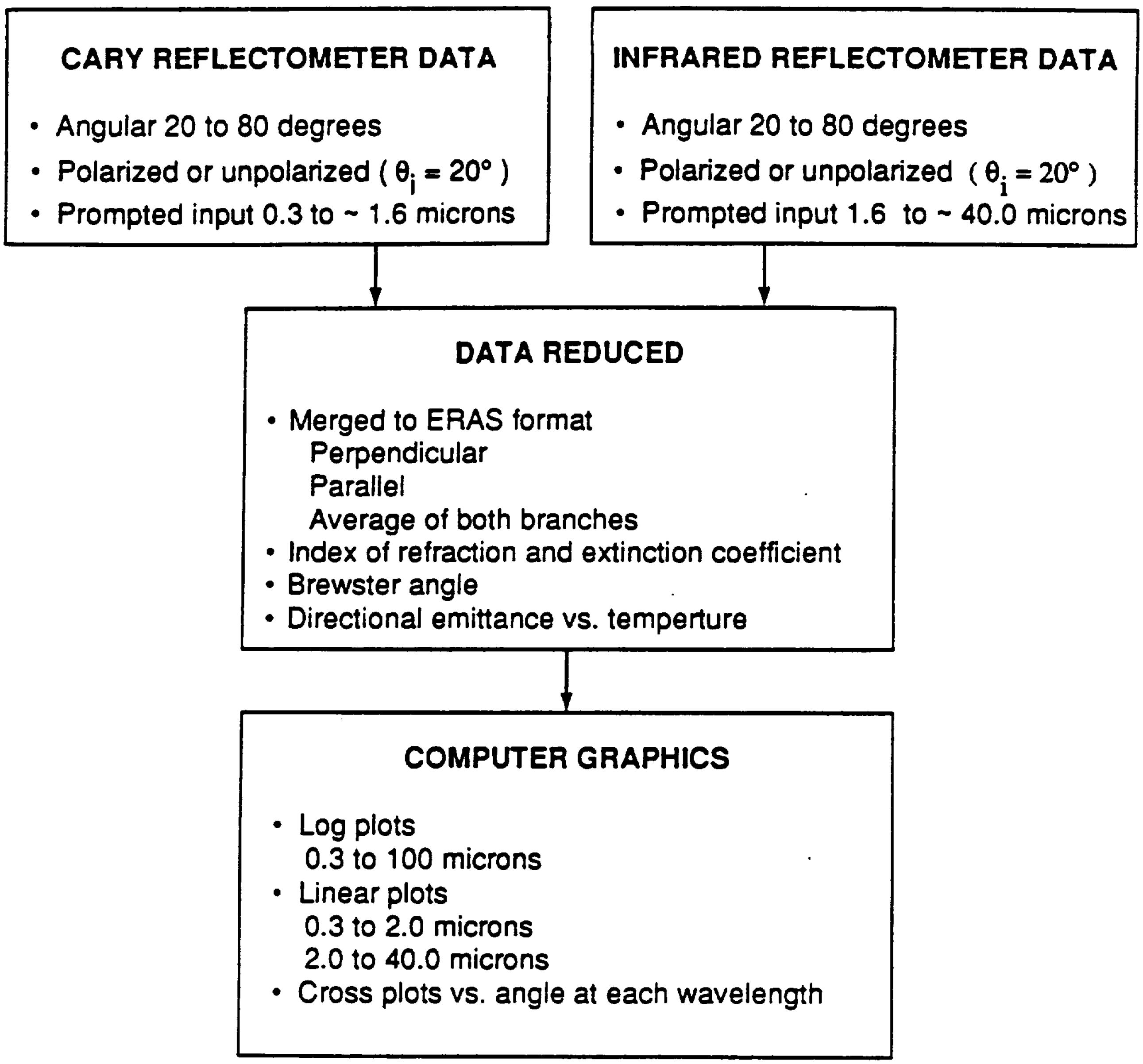

Figure 9. Directional Reflectance Data Processing for Signature Calculations.

APPENDIX A

SOUTHERN RESEARCH INSTITUTE
PW QUARTZ
FS5675:

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PAGE NO.

DIRECTIONAL REFLECTANCE

APPENDIX A

INDEX TO APPENDIX A (continued)

PAGE NO.

DIRECTIONAL REFLECTANCE

APPENDIX A

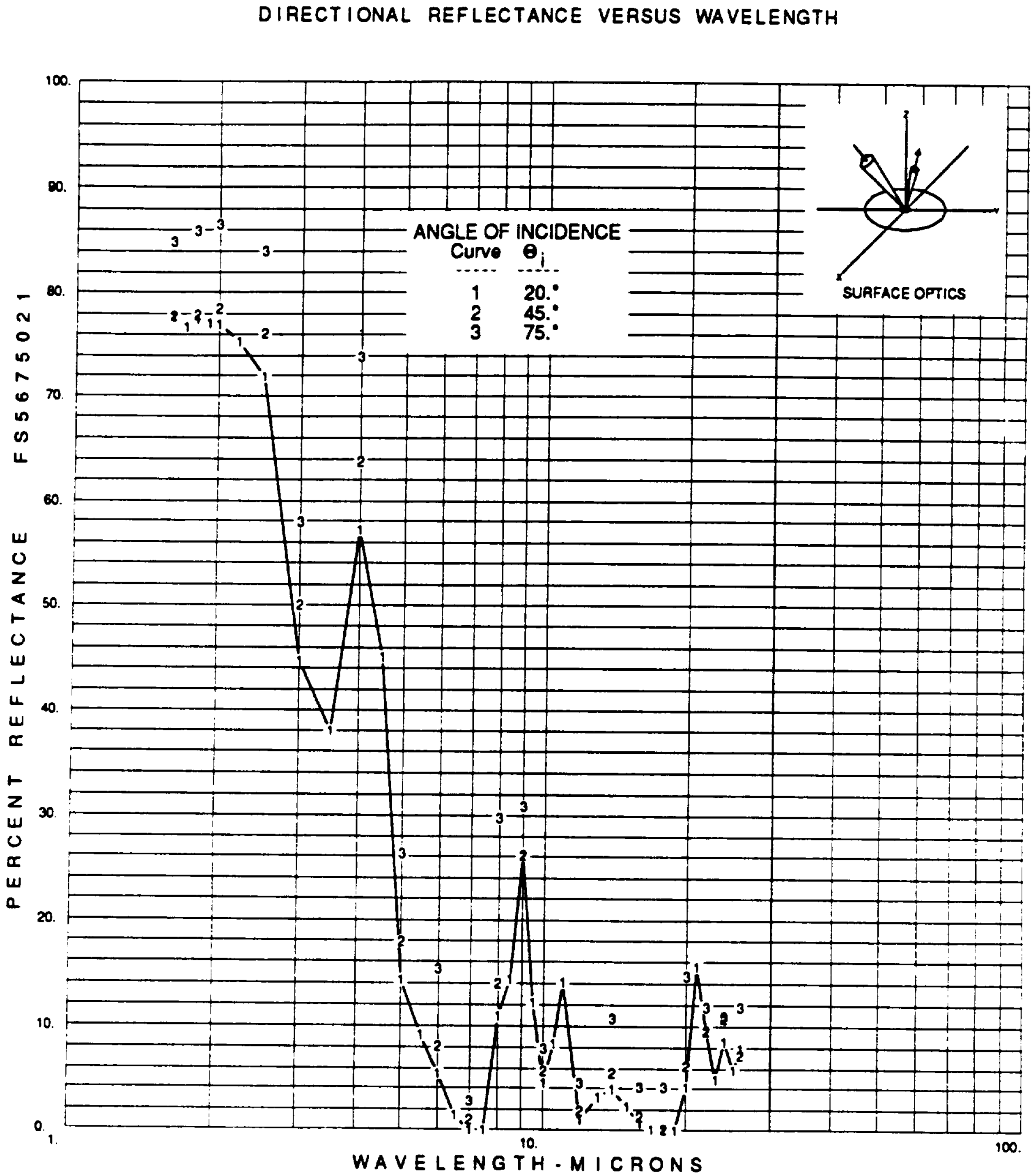

FIGURE A -1. SOUTHERN RESEARCH INSTITUTE: PW QUARTZ,
PHI = C
DIRECTIONAL REFLECTANCE VS. WAVELENGTH
BANDWIDTH 1.6 TO 26.0 MICROMETERS
DATA CORRECTED FOR INSTRUMENTATION POLARIZATION
INCIDENT AZIMUTH ALIGNED WITH C

APPENDIX A

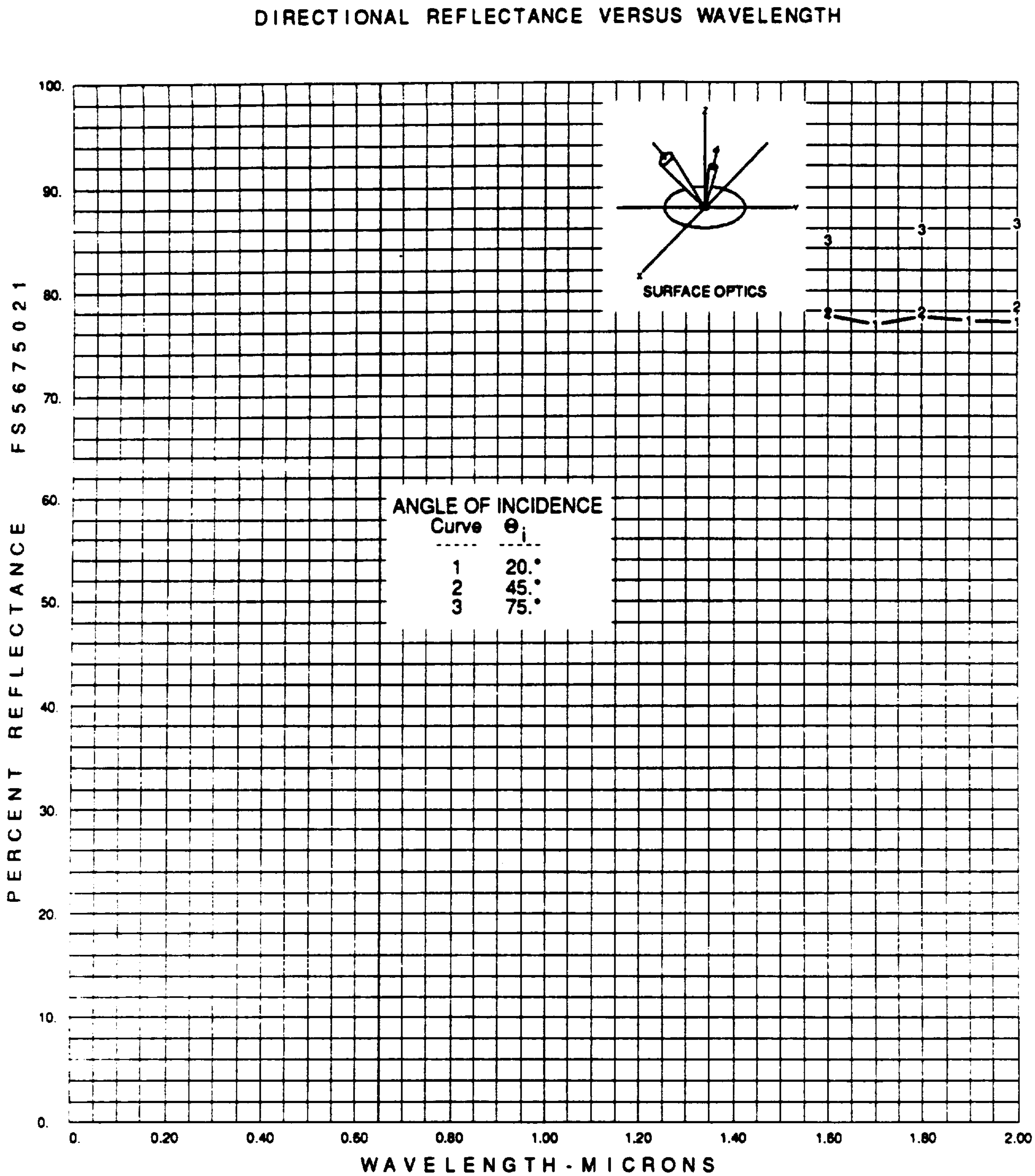

FIGURE A -2. SOUTHERN RESEARCH INSTITUTE: PW QUARTZ, PHI = C
DIRECTIONAL REFLECTANCE VS. WAVELENGTH
BANDWIDTH 1.6 TO 2.0 MICROMETERS
DATA CORRECTED FOR INSTRUMENTATION POLARIZATION
INCIDENT AZIMUTH ALIGNED WITH C

APPENDIX A

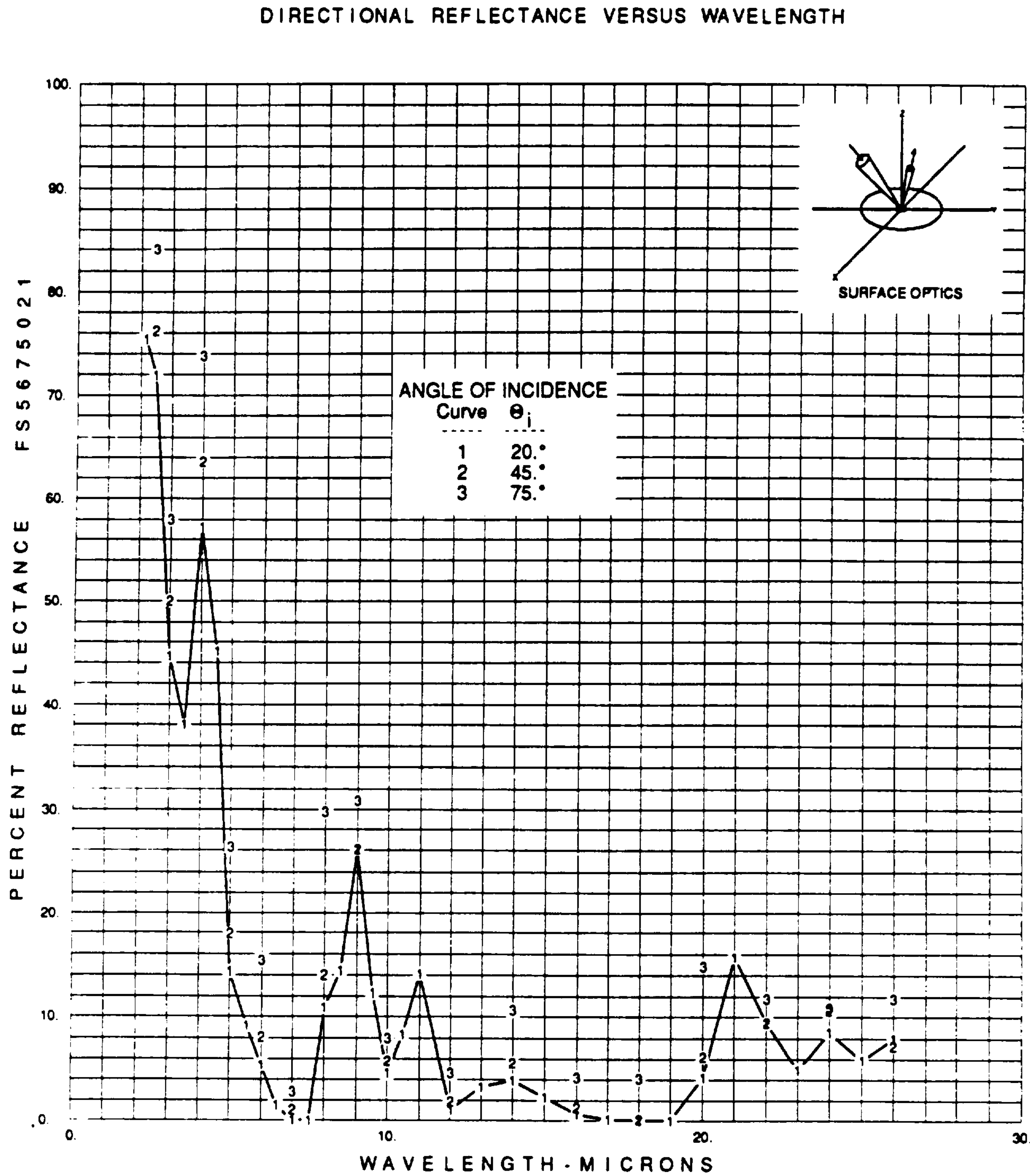

FIGURE A -3. SOUTHERN RESEARCH INSTITUTE: PW QUARTZ,
PHI = C
DIRECTIONAL REFLECTANCE VS. WAVELENGTH
BANDWIDTH 2.2 TO 26.0 MICROMETERS
DATA CORRECTED FOR INSTRUMENTATION POLARIZATION
INCIDENT AZIMUTH ALIGNED WITH C

APPENDIX A

TABLE A-1. **SOUTHERN RESEARCH INSTITUTE: PW QUARTZ, PHI = C**
DIRECTIONAL REFLECTANCE VS. WAVELENGTH - ERAS DATA
DATA CORRECTED FOR INSTRUMENTATION POLARIZATION
INCIDENT AZIMUTH ALIGNED WITH C

FS56750215001		3	1								
FS56750215101		SOUTHERN RESEARCH INSTITUTE: PW QUARTZ, PHI = C									
FS56750215102		CORRECTED FOR INSTRUMENTATION POLARIZATION EFFECTS									
FS56750217001		052192									
FS56750219001	1	001	1	1.6	26.	39				20.	0.
FS56750219201	1	1.6	77.6	1.7	76.7	1.8	77.5	1.9	77.1	2.	77.0
FS56750219202	1	2.2	75.4	2.5	71.9	3.	44.7	3.5	38.0	4.	57.2
FS56750219203	1	4.5	45.1	5.	14.3	5.5	9.2	6.	5.4	6.5	1.5
FS56750219204	1	7.	0.0	7.5	0.0	8.	10.9	8.5	14.4	9.	26.2
FS56750219205	1	9.5	12.2	10.	4.6	10.5	8.4	11.	14.1	12.	1.0
FS56750219206	1	13.	3.2	14.	3.9	15.	2.3	16.	0.7	17.	0.2
FS56750219207	1	18.	0.0	19.	0.0	20.	4.2	21.	15.6	22.	9.5
FS56750219208	1	23.	4.9	24.	8.6	25.	5.9	26.	7.9		
FS56750219001	2	001	1	1.6	26.	20				45.	0.
FS56750219201	2	1.6	77.8	1.8	77.9	2.	78.5	2.5	76.1	3.	50.1
FS56750219202	2	4.	63.7	5.	17.9	6.	8.1	7.	1.0	8.	14.0
FS56750219203	2	9.	26.1	10.	5.8	12.	1.9	14.	5.5	16.	1.3
FS56750219204	2	18.	0.2	20.	6.2	22.	9.5	24.	10.7	26.	7.3
FS56750219001	3	001	1	1.6	26.	20				75.	0.
FS56750219201	3	1.6	84.9	1.8	85.9	2.	86.5	2.5	84.0	3.	57.9
FS56750219202	3	4.	73.9	5.	26.4	6.	15.4	7.	2.8	8.	29.8
FS56750219203	3	9.	30.9	10.	7.9	12.	4.6	14.	10.7	16.	4.2
FS56750219204	3	18.	4.1	20.	14.7	22.	11.8	24.	10.9	26.	11.8

APPENDIX A

TABLE A -2. SOUTHERN RESEARCH INSTITUTE: PW QUARTZ, PHI = C DIRECTIONAL EMITTANCE AS A FUNCTION OF INCIDENT ANGLE AND TEMPERATURE DATA CORRECTED FOR INSTRUMENTATION POLARIZATION INCIDENT AZIMUTH ALIGNED WITH C

FS5675021: SOUTHERN RESEARCH INSTITUTE: PW QUARTZ, PHI = C
CORRECTED FOR INSTRUMENTATION POLARIZATION EFFECTS

Emittance tabulated as a function of zenith angle and temperature:

Zenith angle (degrees)	Wavelength range (microns)	Temperature (degrees Kelvin) 100	200	300	400	500	600
20	1.600 - 26.000	0.942	0.948	0.934	0.909	0.871	0.824
45	1.600 - 26.000	0.933	0.943	0.926	0.896	0.851	0.796
75	1.600 - 26.000	0.897	0.902	0.879	0.841	0.789	0.729

APPENDIX A

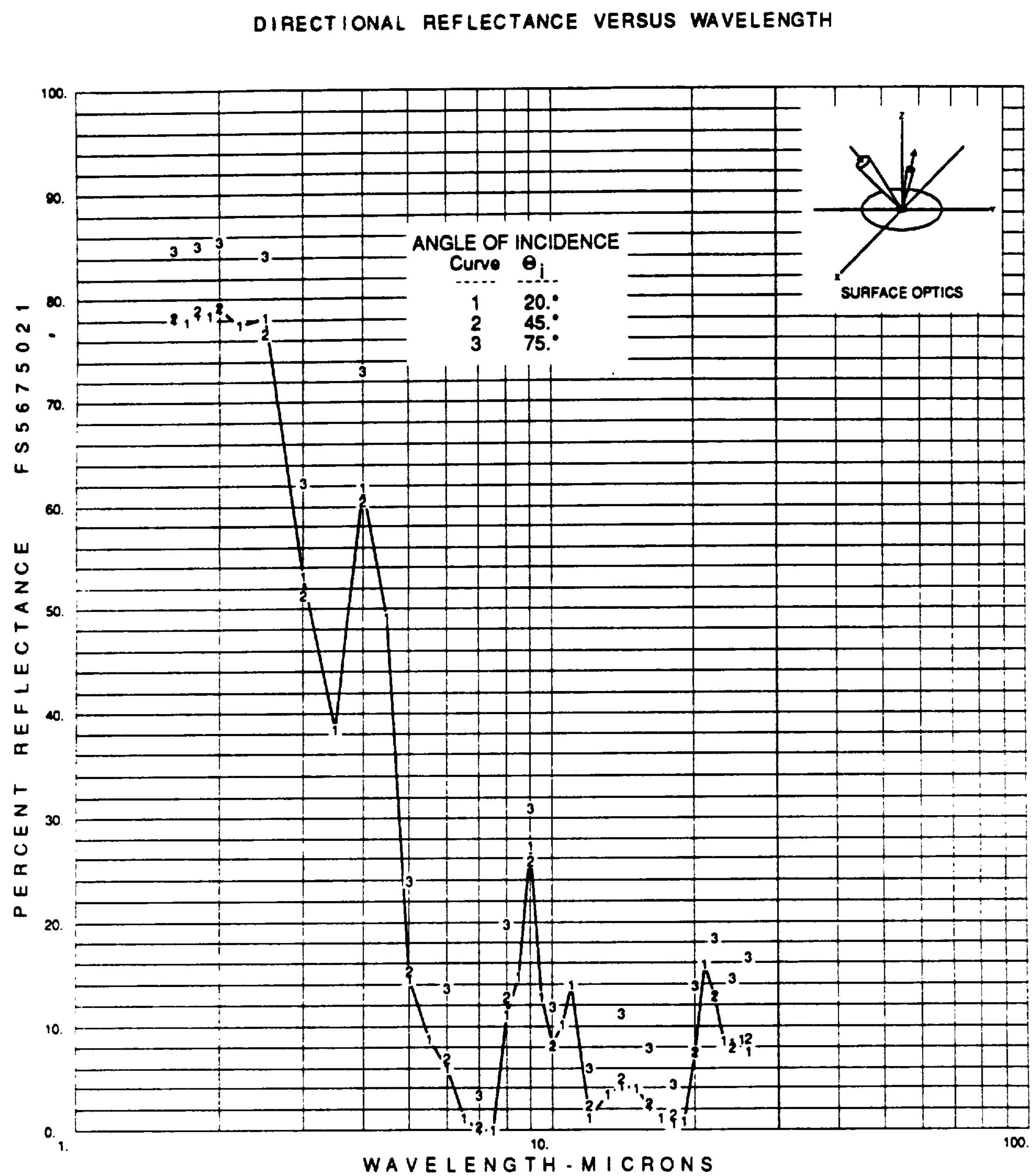

FIGURE A -4. SOUTHERN RESEARCH INSTITUTE: PW QUARTZ, PHI = R
DIRECTIONAL REFLECTANCE VS. WAVELENGTH
BANDWIDTH 1.6 TO 26.0 MICROMETERS
DATA CORRECTED FOR INSTRUMENTATION POLARIZATION
INCIDENT AZIMUTH ALIGNED WITH R

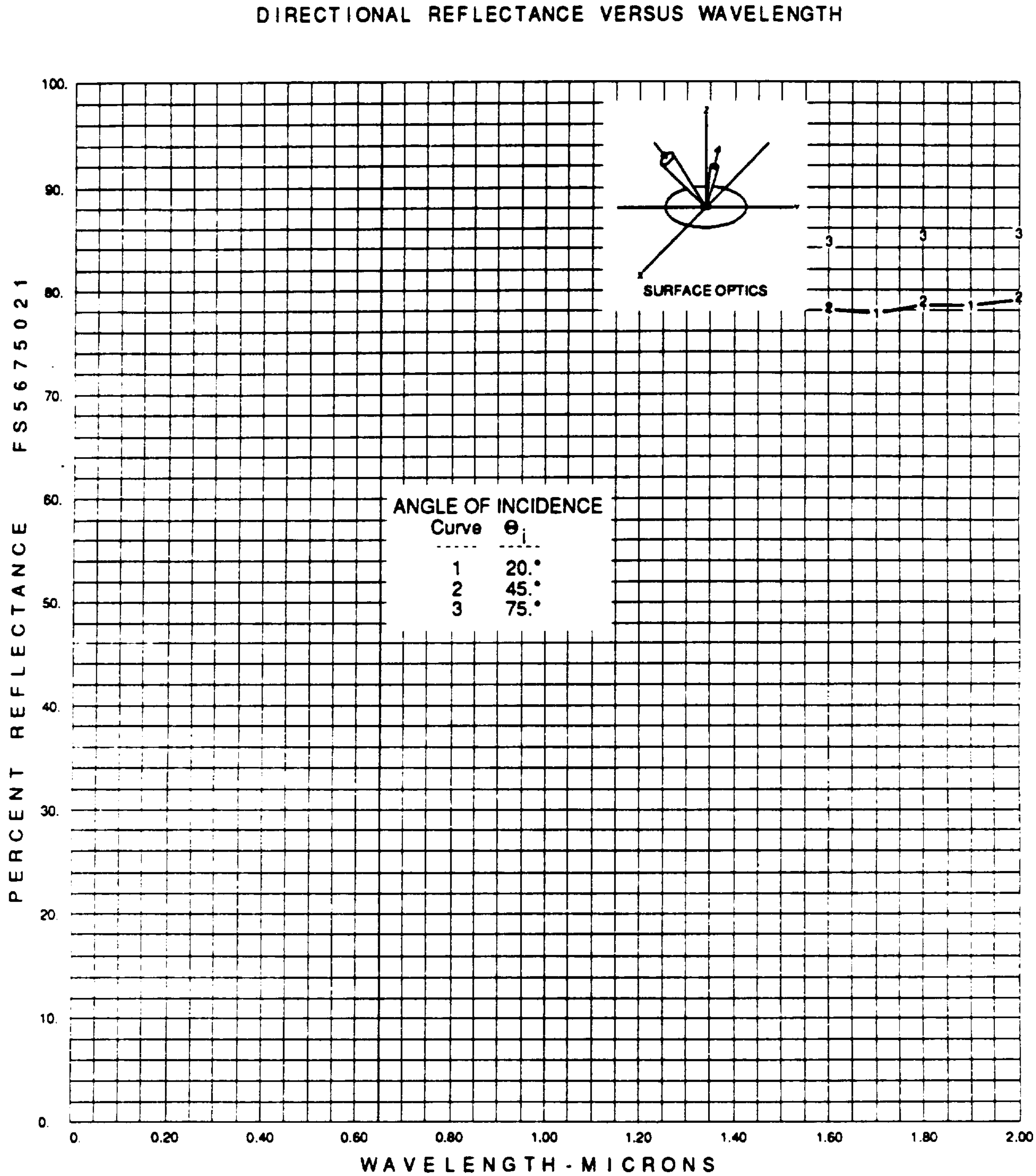

FIGURE A -5. SOUTHERN RESEARCH INSTITUTE: PW QUARTZ, PHI = R
DIRECTIONAL REFLECTANCE VS. WAVELENGTH
BANDWIDTH 1.6 TO 2.0 MICROMETERS
DATA CORRECTED FOR INSTRUMENTATION POLARIZATION
INCIDENT AZIMUTH ALIGNED WITH R

APPENDIX A

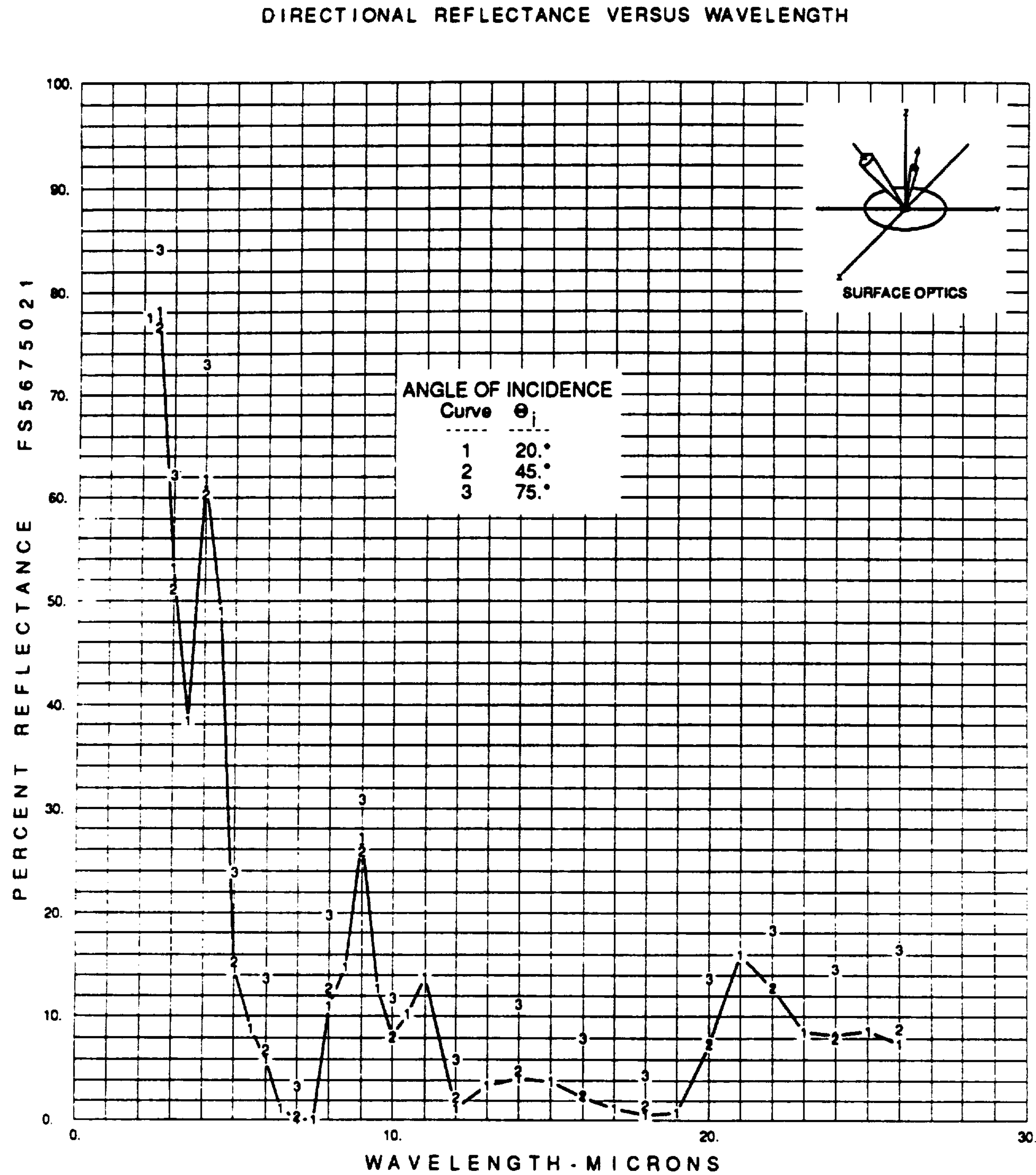

FIGURE A -6. SOUTHERN RESEARCH INSTITUTE: PW QUARTZ, PHI = R
DIRECTIONAL REFLECTANCE VS. WAVELENGTH
BANDWIDTH 2.2 TO 26.0 MICROMETERS
DATA CORRECTED FOR INSTRUMENTATION POLARIZATION
INCIDENT AZIMUTH ALIGNED WITH R

APPENDIX A

TABLE A-3. SOUTHERN RESEARCH INSTITUTE: PW QUARTZ, PHI = R
DIRECTIONAL REFLECTANCE VS. WAVELENGTH - ERAS DATA
DATA CORRECTED FOR INSTRUMENTATION POLARIZATION
INCIDENT AZIMUTH ALIGNED WITH R

FS56750215001		3	1								
FS56750215101		SOUTHERN RESEARCH INSTITUTE: PW QUARTZ, PHI = R									
FS56750215102		CORRECTED FOR INSTRUMENTATION POLARIZATION EFFECTS									
FS56750217001		052192									
FS56750219001	1	001	1	1.6	26.	39				20.	0.
FS56750219201	1	1.6	78.1	1.7	77.7	1.8	78.5	1.9	78.4	2.	79.0
FS56750219202	1	2.2	77.5	2.5	78.2	3.	53.2	3.5	38.4	4.	61.8
FS56750219203	1	4.5	49.1	5.	14.5	5.5	8.8	6.	6.0	6.5	1.1
FS56750219204	1	7.	0.0	7.5	0.0	8.	11.0	8.5	14.7	9.	27.2
FS56750219205	1	9.5	12.7	10.	8.2	10.5	10.2	11.	13.8	12.	1.1
FS56750219206	1	13.	3.4	14.	4.2	15.	3.9	16.	2.2	17.	1.1
FS56750219207	1	18.	0.6	19.	0.8	20.	7.4	21.	15.9	22.	12.7
FS56750219208	1	23.	8.6	24.	8.3	25.	8.7	26.	7.5		
FS56750219001	2	001	1	1.6	26.	20				45.	0.
FS56750219201	2	1.6	78.3	1.8	78.9	2.	79.3	2.5	76.6	3.	51.2
FS56750219202	2	4.	60.4	5.	15.3	6.	6.9	7.	0.4	8.	12.7
FS56750219203	2	9.	25.8	10.	8.1	12.	2.3	14.	4.9	16.	2.5
FS56750219204	2	18.	1.5	20.	7.5	22.	12.8	24.	7.9	26.	8.8
FS56750219001	3	001	1	1.6	26.	20				75.	0.
FS56750219201	3	1.6	84.7	1.8	85.2	2.	85.5	2.5	84.2	3.	62.2
FS56750219202	3	4.	73.0	5.	23.9	6.	13.6	7.	3.3	8.	19.8
FS56750219203	3	9.	30.9	10.	11.8	12.	6.0	14.	11.1	16.	7.9
FS56750219204	3	18.	4.4	20.	13.7	22.	18.4	24.	14.5	26.	16.5

APPENDIX A

TABLE A-4. **SOUTHERN RESEARCH INSTITUTE: PW QUARTZ, PHI = R DIRECTIONAL EMITTANCE AS A FUNCTION OF INCIDENT ANGLE AND TEMPERATURE DATA CORRECTED FOR INSTRUMENTATION POLARIZATION INCIDENT AZIMIUTH ALIGNED WITH R**

FS5675021: SOUTHERN RESEARCH INSTITUTE: PW QUARTZ, PHI = R
CORRECTED FOR INSTRUMENTATION POLARIZATION EFFECTS

Emittance tabulated as a function of zenith angle and temperature:

Zenith angle (degrees)	Wavelength range (microns)	Temperature (degrees Kelvin) 100	200	300	400	500	600
20	1.600 - 26.000	0.926	0.936	0.925	0.901	0.861	0.810
45	1.600 - 26.000	0.926	0.936	0.923	0.897	0.856	0.804
75	1.600 - 26.000	0.868	0.884	0.872	0.842	0.794	0.735

APPENDIX D

THERMAL ANALYSIS COMPUTER PROGRAM SOURCE CODE

```
C     THERMAL BLANKET ANALYSIS PROGRAM, VERSION 4.0

C     Written by:
C     Dale E. Matthews
C     119 Sunrise Drive
C     Forest, VA 24551
C     (804) 239-0221

      INTERFACE TO SUBROUTINE GETKEYF [C] (X,I)
      CHARACTER*1 X [NEAR,REFERENCE]
      INTEGER*2 I [NEAR,REFERENCE]
      END

      INTERFACE TO SUBROUTINE GETNUMF [C] (X,I)
      DOUBLE PRECISION X [NEAR,REFERENCE]
      INTEGER*2 I [NEAR,REFERENCE]
      END

      INTERFACE TO SUBROUTINE LETTER [C] ()
      END

      INTERFACE TO SUBROUTINE UD [C] (M)
      INTEGER*2 M [NEAR,REFERENCE]
      END

      INTERFACE TO SUBROUTINE Y_OR_N [C] (RESPONSE)
      CHARACTER RESPONSE [NEAR,REFERENCE]
      END

      INCLUDE 'FGRAPH.FI'
      INCLUDE 'FGRAPH.FD'

      REAL T[ALLOCATABLE](:),TMOD[ALLOCATABLE](:)
      REAL T_45[ALLOCATABLE](:),TINC,TF,tmax[allocatable](:)
      REAL K[ALLOCATABLE](:,:),C[ALLOCATABLE](:,:),P[ALLOCATABLE](:)
      REAL A[ALLOCATABLE](:,:),dx[allocatable](:)
      REAL Q45,W,Z,ad,max_time,tmp
      REAL AK[ALLOCATABLE](:,:),E
      REAL KT[ALLOCATABLE](:,:),CTT[ALLOCATABLE](:,:)

      DOUBLE PRECISION XX

      INTEGER I,J,N,N2
      INTEGER*2 CT,HFLAG,d2
      INTEGER*2 INUMK[ALLOCATABLE](:),INUMC[ALLOCATABLE](:)

      CHARACTER*30 OUTPUT,SPREAD,STR30,stats
      CHARACTER*1 ASK
      CHARACTER STR*2,STR2*12,STRA*2,STRB*6,STR3*15,hfl*4
      CHARACTER*30 MATL[ALLOCATABLE](:)
      character*10 fluxfile

      COMMON N

      RECORD/RCCOORD/CURPOS


C     Variable Initializations

      DT=1.00/3600
      DT2=2*DT
      TINC=0.00

C************************PROGRAM HEADER****************************************

      call intro()
```

```
      call oscreen(n,e,output,spread,hflag,stats)

      if(hflag.eq.1)then
      hfl='ASRM'
      fluxfile='asrm.dbx'
      max_time=450
      else if(hflag.eq.0)then
      hfl='SSRM'
      max_time=400
      fluxfile='ssrm.dbx'
      else
      end if

      d2=setvisualpage(5)

      open(6,file=fluxfile,access='sequential',form='binary')
      OPEN(12,FILE=OUTPUT)
      OPEN(13,FILE=SPREAD,ACCESS='SEQUENTIAL',FORM='BINARY')
      open(14,file=stats,access='sequential',form='binary')


:************************GET BLANKET CONFIGURATION***************************

 4    continue

      d2=setactivepage(2)

 7    D2=SETBKCOLOR(1)
      D2=SETTEXTCOLOR(3)
      CALL CLEARSCREEN($GCLEARSCREEN)
      call settextwindow(1,1,25,80)
      call clearscreen($GWINDOW)

      do 2771 i=2,24
      call settextposition(i,2,curpos)
      do 2771 j=1,78
      call outtext(char(177))
771   continue

      d2=settextcolor(14)
      call settextposition(25,12,curpos)
      call outtext('ASTC V4.0 - Developed by Southern Research Institute
     $, 1992')

      d2=setbkcolor(3)
      d2=settextcolor(1)
      call settextwindow(3,22,5,58)
      call clearscreen($GWINDOW)
      call sbox(3,22,5,58)
      call settextposition(2,6,curpos)
      call outtext('Specify Blanket Construction')

      IF(.NOT.(ALLOCATED(MATL)))THEN
      allocate(tmax(n))
      ALLOCATE(MATL(N))
      ALLOCATE(K(N,5),C(N,5),P(5),DX(I),A(N,N))
      ALLOCATE(KT(N,5),CTT(N,5),AK(N,5))
      ALLOCATE(INUMK(N),INUMC(N))
      ELSE
      END IF

      DO 2400 J=1,N
      tmax(j)=0.00
      DX(J)=0.00
      P(J)=0.00
```

```
      DO 2400 J2=1,5
      K(J,J2)=0.00
      KT(J,J2)=0.00
      C(J,J2)=0.00
      CTT(J,J2)=0.00
2400  CONTINUE

      d2=setvisualpage(2)

      DO 2501 I=1,N
      CALL SETTEXTWINDOW(7,10,23,71)
      D2=SETBKCOLOR(1)
      d2=settextcolor(15)
      CALL CLEARSCREEN($GWINDOW)
      D2=SETTEXTCOLOR(14)
      CALL DBOX(7,10,23,71)

      CALL SETTEXTPOSITION(3,2,CURPOS)
      CALL OUTTEXT(CHAR(199))

      DO 2502 J=1,58
      CALL OUTTEXT(CHAR(196))
2502  CONTINUE
      CALL OUTTEXT(CHAR(182))

      WRITE(STR,'(I2)')I
      CALL SETTEXTPOSITION(2,25,CURPOS)
      CALL OUTTEXT('Layer No. '//STR)

      CALL SETTEXTPOSITION(4,4,CURPOS)
      CALL OUTTEXT('Enter name of material: ')
            IF(I.NE.1)THEN
            CALL SETTEXTPOSITION(5,4,CURPOS)
            CALL OUTTEXT('(F1 to repeat a previous entry)')
            CALL SETTEXTPOSITION(4,28,CURPOS)
            ELSE
            END IF
      D2=SETTEXTCOLOR(15)
      CALL GETSTRNG(MATL(I),CT)

            IF(I.GT.1)THEN
            IF(CT.EQ.5)THEN
            CALL REPEAT_MATL(I,N,MATL,KT,AK,CTT,C,P,DX)
            GOTO 2501
            ELSE
            END IF
            ELSE
            END IF

      D2=SETTEXTCOLOR(14)
      CALL SETTEXTPOSITION(5,4,CURPOS)
      CALL OUTTEXT('Enter Density (lb/ft^3) of material: ')
      D2=SETTEXTCOLOR(15)
2880  CALL GETNUMF(XX,CT)
      P(I)=XX

            IF(P(I).EQ.0.00)THEN
            WRITE(*,*)CHAR(07)
            GOTO 2880
            ELSE
            END IF

      CALL SETTEXTPOSITION(6,4,CURPOS)
      D2=SETTEXTCOLOR(14)
      CALL OUTTEXT('Enter thickness (in.) of material: ')
      D2=SETTEXTCOLOR(15)
```

```
      CT=0
2881  CALL GETNUMF(XX,CT)
      DX(I)=XX
            IF(DX(I).EQ.0.00)THEN
            WRITE(*,*)CHAR(07)
            GOTO 2881
            ELSE
            END IF

      D2=SETTEXTCOLOR(14)
      CALL SETTEXTPOSITION(7,2,CURPOS)
      CALL OUTTEXT(CHAR(199))
      DO 2503 J=1,58
      CALL OUTTEXT(CHAR(196))
2503  CONTINUE
      CALL OUTTEXT(CHAR(182))

      CALL SETTEXTPOSITION(8,8,CURPOS)
      CALL OUTTEXT('Enter up to five THERMAL CONDUCTIVITY datapoints')
      CALL SETTEXTPOSITION(9,8,CURPOS)
      CALL OUTTEXT('Press F1 or enter blank temperature when complete')

      CALL SETTEXTPOSITION(11,5,CURPOS)
      CALL OUTTEXT('Temperature (øF)            k (Btuúin/ftýúsecúøR)')

      D2=SETTEXTCOLOR(15)

      DO 2505 J=1,5
2885  CALL SETTEXTPOSITION(11+J,10,CURPOS)

      CT=0
      CALL GETNUMF(XX,CT)
      KT(I,J)=XX
2889  CALL SETTEXTPOSITION(11+J,45,CURPOS)

            IF(CURPOS.COL.EQ.10)THEN
                  IF(J.EQ.1)THEN
                  WRITE(*,*)CHAR(07)
                  GOTO 2885
                  ELSE
                  KT(I,J)=0.00
                  K(I,J)=0.00
                  EXIT
                  END IF
            ELSE
            END IF

      CALL GETNUMF(XX,CT)

                  CALL SETTEXTPOSITION(11+J,45,CURPOS)
                  IF(CURPOS.COL.EQ.45)THEN
                        IF(J.EQ.1)THEN
                        WRITE(*,*)CHAR(07)
                        GOTO 2889
                        ELSE
                        KT(I,J)=0.00
                        K(I,J)=0.00
                        EXIT
                        END IF
                  ELSE
                  END IF

      IF(CT.EQ.5)EXIT
      K(I,J)=XX

2505  CONTINUE
```

```
      D2=SETTEXTCOLOR(14)

      CALL SETTEXTPOSITION(8,8,CURPOS)
      CALL OUTTEXT('  Enter up to five SPECIFIC HEAT datapoints     ')
      CALL SETTEXTPOSITION(9,8,CURPOS)
      CALL OUTTEXT('Press F1 or enter blank temperature when complete')

      CALL SETTEXTPOSITION(11,5,CURPOS)
      CALL OUTTEXT('Temperature (øF)                 Cp (Btu/lbúøF)    ')

      D2=SETTEXTCOLOR(15)

      DO 2507 J=1,5
      CALL SETTEXTPOSITION(11+J,10,CURPOS)
      CALL OUTTEXT('                                               ')
2507  CONTINUE

      DO 2506 J=1,5
2886  CALL SETTEXTPOSITION(11+J,10,CURPOS)
      CALL GETNUMF(XX,CT)
      CTT(I,J)=XX
2890  CALL SETTEXTPOSITION(11+J,45,CURPOS)

            IF(CURPOS.COL.EQ.10)THEN
                  IF(J.EQ.1)THEN
                  WRITE(*,*)CHAR(07)
                  GOTO 2886
                  ELSE
                  CTT(I,J)=0.00
                  C(I,J)=0.00
                  EXIT
                  END IF
            ELSE
            END IF

      CALL GETNUMF(XX,CT)

                  CALL SETTEXTPOSITION(11+J,45,CURPOS)
                  IF(CURPOS.COL.EQ.45)THEN
                        IF(J.EQ.1)THEN
                        WRITE(*,*)CHAR(07)
                        GOTO 2890
                        ELSE
                        CTT(I,J)=0.00
                        C(I,J)=0.00
                        EXIT
                        END IF
                  ELSE
                  END IF


      IF(CT.EQ.5)GOTO 2501    ! EXIT
      C(I,J)=XX
506   CONTINUE

      DO 3984 J=1,5
      AK(I,J)=K(I,J)
984   CONTINUE

501   CONTINUE

      d2=setvisualpage(5)

      DO 7762 I=1,N
```

```
      DO 7761 J=1,5
      K(I,J)=AK(I,J)
7761  CONTINUE
7762  CONTINUE

C**********COUNT NUMBER OF CONDUCTIVITY & SP HEAT DATA POINTS FOR MATLS

      DO 2600 I=1,N
      INUMK(I)=0.00
      INUMC(I)=0.00
2600  CONTINUE

      DO 2602 I=1,N
      DO 2601 J=1,5
      IF(K(I,J).NE.0.00)INUMK(I)=INUMK(I)+1
      IF(C(I,J).NE.0.00)INUMC(I)=INUMC(I)+1
2601  CONTINUE
2602  CONTINUE


C****************QUE USER FOR CONFIRMATION OF CONFIGURATION****************

      d2=setactivepage(3)
      d2=setbkcolor(1)
      d2=settextcolor(3)
      call settextwindow(1,1,25,80)
      call clearscreen($GWINDOW)

      do 9144 i=2,24
      call settextposition(i,2,curpos)
      do 9144 j=2,78
      call outtext(char(177))
9144  continue

      d2=settextcolor(14)
      call settextposition(25,12,curpos)
      call outtext('ASTC V4.0 - Developed by Southern Research Institute
     $, 1992')

      d2=setbkcolor(3)
      d2=settextcolor(1)
      call settextwindow(3,19,5,61)
      call clearscreen($GWINDOW)
      call sbox(3,19,5,61)
      call settextposition(2,5,curpos)
      call outtext('Verification of Blanket Construction')

      d2=setbkcolor(1)
      d2=settextcolor(14)
      call settextwindow(7,12,23,68)
      call clearscreen($GWINDOW)
      call dbox(7,12,23,68)

      CALL SETTEXTPOSITION(2,5,CURPOS)
      CALL OUTTEXT('A Thermal Curtain of the following composition')
      CALL SETTEXTPOSITION(3,5,CURPOS)
      CALL OUTTEXT('will be analyzed. Is this correct (y/n)? ')

      call settextposition(4,2,curpos)
      call outtext(char(199))
      do 4498 i=1,53
      call outtext(char(196))
 498  continue
      call outtext(char(182))

      call settextposition(4,15,curpos)
```

```
      call outtext(char(194))

      call settextposition(5,4,curpos)
      call outtext(' Layer No. ' Material')

      call settextposition(6,2,curpos)
      call outtext(char(199))
      do 4499 i=1,53
      call outtext(char(196))
4499  continue
      call outtext(char(182))

      call settextposition(6,15,curpos)
      call outtext(char(197))

      do 4533 i=1,10
      call settextposition(6+i,15,curpos)
      call outtext(char(179))
4533  continue

      call settextposition(17,15,curpos)
      call outtext(char(207))

      DO 45 I=1,N
      WRITE(STRA,'(I2)')I
      CALL SETTEXTPOSITION(6+I,7,CURPOS)
      CALL OUTTEXT(STRA)
      call settextposition(6+i,17,curpos)
      call outtext(MATL(I)(1:len_trim(matl(i))))
45    CONTINUE

      call settextposition(3,46,curpos)

      d2=setvisualpage(3)

      CALL Y_OR_N(ASK)
      IF(ASK.NE.'Y')GOTO 24
      call outtext(ask)

      d2=setbkcolor(3)
      d2=settextcolor(1)
      call settextwindow(21,15,23,65)
      call clearscreen($gwindow)
      call sbox(21,15,23,65)
      call settextposition(2,7,curpos)
      call outtext('Add these materials to database (y/n)? ')
      call y_or_n(ask)
      call outtext(ask)

      N2=N

      ALLOCATE(T_45(N))

      DO 48 I=1,N
      DO 47 J=1,N
      A(I,J)=0.000
47    CONTINUE
48    CONTINUE


      CALL SETTEXTWINDOW(12,20,18,60)
      D2=SETBKCOLOR(7)
      D2=SETTEXTCOLOR(1)
      CALL CLEARSCREEN($GWINDOW)
      CALL DBOX(12,20,18,60)
      D2=SETTEXTCURSOR(#2000)
```

```
      D2=SETTEXTCOLOR(1)
      CALL SETTEXTPOSITION(3,10,CURPOS)
      CALL OUTTEXT('Calculating Results')
      CALL SETTEXTPOSITION(4,14,CURPOS)
      CALL OUTTEXT('Please Wait')

      D2=SETTEXTCURSOR(#2000)

      ALLOCATE(T(N),TMOD(N))

C     Initialize all temperatures at 70øF

      DO 49 I=1,N
      T_45(I)=70.00
49    CONTINUE

      DO 50 I=1,N
      T(I)=70.00
50    CONTINUE

      DO 51 I=1,N
      DX(I)=DX(I)/12.00      ! Convert inches to feet
51    CONTINUE

      TF=70.00

C     *******************Begin the analysis***************************

C     Calculate Areal Density
      ad=0
      do 6681 i=1,n
      ad=ad+dx(i)*p(i)
6681  continue

      WRITE(13)N

      WRITE(12,9001)N
9001  FORMAT(//15X,'RESULTS OF HEAT TRANSFER ANALYSIS FOR A THERMAL BLAN
     $KET '
     $/15X,'CONSISTING OF ',I2,' LAYERS OF THE FOLLOWING COMPOSITIONS:'/
     $/)

      DO 7554 I=1,N
      WRITE(12,9002)I,MATL(I),DX(I)*12.0
9002  FORMAT(20X,'Layer ',I2,' is ',A,' and ',F5.3,' in thick')

7554  CONTINUE

      WRITE(12,9005)N+1
9005  FORMAT(//20X,'Temperature at node ',I2,' remains at 70øF'//)

60    TINC=TINC+1.00


      WRITE(STRB,'(F5.1)')TINC
      CALL SETTEXTPOSITION(5,7,CURPOS)
      CALL OUTTEXT('  Calculating at t =   '//STRB)

      read(6)bsvar,q45
      q45=q45*3600.00*e


45      W=TF*(2*P2(K,KT,TF,N,INUMK(N))*DT) / (( P(N-1)*P2(C,CTT,TF,
     $ N-1,INUMC(N-1)) + P(N)*P2(C,CTT,TF,N,INUMC(N)))
     $  *(DX(1)**2))
```

```
      WRITE(12,9125)TINC
9125  FORMAT(//2X,'At T = ',F5.1,' seconds:'//2X,'NODE')

C*******************************THB=45.00***********************************

      Z=(2*Q45*DT)/(P(1)*P2(C,CTT,T_45(1),1,INUMC(1))*DX(1))

      CALL COEFF(K,INUMK,P,C,INUMC,A,T_45,DX,KT,CTT)

      T_45(1)=T_45(1)+Z
      T_45(N)=T_45(N)+W
      CALL TRIDIAG(A,T_45,N,TMOD)

      DO 94 I=1,N
      T_45(I)=TMOD(I)
94    CONTINUE

      CALL SETTEXTPOSITION(5,7,CURPOS)
      CALL OUTTEXT('Writing results at t = '//STRB)

      do 8628 i=1,n
      if(t_45(i).ge.tmax(i))then
      tmax(i)=t_45(i)
      else
      end if
8628  continue


      DO 170 I=1,N
      WRITE(13)T_45(I)
170   CONTINUE

      DO 1701 I=1,N
      WRITE(12,9004)I,T_45(I)
9004  FORMAT(2X,I2,3X,F6.1)
1701  CONTINUE

      IF(TINC.LT.max_time)GOTO 60
      WRITE(*,*)char(07)

      CLOSE(12)
      CLOSE(13)

      write(14)n
      do 9558 i=1,n
      write(14)matl(i),tmax(i)
9558  continue
      write(14)output,spread
      write(14)ad,hflag

      open(13,file=spread,access='sequential',form='binary')
      read(13)kounter

      do 9721 i=1,max_time
      do 9721 j=1,n
      read(13)tmp
      if(mod(i,10).eq.0)write(14)tmp
9721  continue

      close(13)

      CALL CLEARSCREEN($GWINDOW)
      CALL DBOX(14,20,20,60)

      CALL SETTEXTPOSITION(3,12,CURPOS)
```

```
      CALL OUTTEXT('Analysis Complete')
      CALL SETTEXTPOSITION(5,10,CURPOS)
      CALL OUTTEXT('Press a key to continue')


      close(14)


      DEALLOCATE(A,T_45,tmax)
      DEALLOCATE(DX,T,TMOD,C,P,K,AK,KT,CTT,MATL,INUMC,INUMK)

      CALL LETTER()

      CALL POST(stats)

C**********************************END OF PROGRAM****************************

500   D2=SETTEXTCURSOR(#0707)
      D2=SETVIDEOMODE($DEFAULTMODE)
      CALL CLEARSCREEN($GCLEARSCREEN)
      END

C************************SUBROUTINES*****************************************
C****************************************************************************

      SUBROUTINE COEFF(K,NUMK,P,C,NUMC,A,T,DX,KT,CTT)

      INTEGER I,N
      REAL K(N,5),C(N,5),P(N),A(N,N),T(N),DX(N),DT
      REAL KT(N,5),CTT(N,5)
      INTEGER*2 NUMK(N),NUMC(N)

      COMMON N

      DT=1.00/3600.00

       A(1,1)=1.00+(2.00*P2(K,KT,T(1),1,NUMK(1))*DT)/
     $  (P(1)*P2(C,CTT,T(1),1,NUMC(1))*
     $  (DX(1))**2)

       A(1,2)= -(2.00*P2(K,KT,T(2),1,NUMK(1))*DT)/
     $  (P(1)*P2(C,CTT,T(2),1,NUMC(1))*
     $  (DX(1))**2)

       DO 155 I=2,N

C  Composite node terms.

       A(I,I-1)=-(4.00*P2(K,KT,T(I-1),I-1,NUMK(I-1))*DT)/
     $(((DX(I-1)*P(I-1)*P2(C,CTT,T(I-1),I-1,NUMC(I-1))
     $)+(DX(I)*P(I)*P2(C,CTT,T(I),I,NUMC(I))))
     $*(DX(I-1)+DX(I)))

       A(I,I)=1.00+((8.00*DT)/((DX(I-1)+DX(I))**2))*
     $((DX(I-1)*P2(K,KT,T(I),I-1,NUMK(I-1))+DX(I)*
     $P2(K,KT,T(I),I,NUMK(I)))/
     $((DX(I-1)*P(I-1)*P2(C,CTT,T(I),I-1,NUMC(I-1)))
     $+(DX(I)*P(I)*P2(C,CTT,T(I),I,NUMC(I)))))

        IF(I.LT.N)THEN

       A(I,I+1)=(-4.00*P2(K,KT,T(I+1),I,NUMK(I))*DT)/
     $(((DX(I-1)*P(I-1)*P2(C,CTT,T(I+1),I-1,NUMC(I-1))
     $)+(DX(I)*P(I)*P2(C,CTT,T(I+1),I,NUMC(I))))
     $*(DX(I-1)+DX(I)))
```

```
      ELSE
      END IF

155   CONTINUE

      RETURN
      END

C******************************************************************************

       SUBROUTINE TRIDIAG(A,S,N,X)
       REAL A(N,N),S(N),X(N)
       INTEGER I,N
       DO 20 I=1,N-1
       A(I+1,I+1)=A(I+1,I+1)-((A(I+1,I)*A(I,I+1))/A(I,I))
       S(I+1)=S(I+1)-((A(I+1,I)*S(I))/A(I,I))
20     CONTINUE
       X(N)=S(N)/A(N,N)
       DO 30 I=N-1,1,-1
       X(I)=(S(I)-A(I,I+1)*X(I+1))/A(I,I)
30     CONTINUE
       RETURN
       END

C***************External Source Code Files*******


      INCLUDE 'DBOX.FOR'

      INCLUDE 'GETSTRNG.FOR'

      INCLUDE 'GETS80.FOR'

      include 'isub.for'

      INCLUDE 'REPEAT.FOR'

      include 'oscreen.for'

      include 'post.for'
```

```
subroutine post(filename)
include 'fgraph.fd'

integer*2 d2,udpos,udinc,oldud
character*30 filename
character*27 option(4)
character*50 narr(4)
record/rccoord/curpos

common/narr/option

option(1)='Quick Summary of Results'
option(2)='View Analysis Results'
option(3)='Review a Previous Analysis'
option(4)='Exit Program'

narr(1)='Max/min temperatures, model composition, etc.'
narr(2)='View temperature vs. time graph of analysis'
narr(3)='(Reserved for future use)'
narr(4)='Exit ASTC and return to DOS'


d2=setactivepage(1)
d2=settextcursor(#2000)

d2=setbkcolor(1)
d2=settextcolor(3)
call settextwindow(1,1,25,80)
call clearscreen($GWINDOW)

do 1 i=2,24
call settextposition(i,2,curpos)
do 1 j=2,78
call outtext(char(177))
continue

d2=settextcolor(14)
call settextposition(25,12,curpos)
call outtext('ASTC V4.0 - Developed by Southern Research Institute
$, 1992')

d2=setbkcolor(3)
d2=settextcolor(1)
call settextwindow(3,25,5,55)
call clearscreen($GWINDOW)
call sbox(3,25,5,55)
call settextposition(2,7,curpos)
call outtext('ASTC Post-Processor')

d2=setbkcolor(1)
d2=settextcolor(14)
call settextwindow(7,18,18,62)
call clearscreen($GWINDOW)
call dbox(7,18,18,62)
call settextposition(2,6,curpos)
call outtext('Select one of the following options')

call settextposition(3,2,curpos)
call outtext(char(199))
do 2 i=3,43
call outtext(char(196))
continue

call outtext(char(182))

do 3 i=1,4
```

```
      call settextposition(4+i,10,curpos)
      call outtext(option(i)(1:len_trim(option(i))))
3     continue

      call settextposition(10,2,curpos)
      call outtext(char(199))
      do 4 i=3,43
      call outtext(char(196))
4     continue

      call outtext(char(182))

      call settextposition(11,9,curpos)
      call outtext(char(24)//char(25)//' to move, ENTER to select')

      d2=setbkcolor(3)
      d2=settextcolor(1)
      call settextwindow(20,12,22,68)
      call clearscreen($GWINDOW)
      call sbox(20,12,22,68)

      call settextwindow(21,14,21,66)
      call clearscreen($GWINDOW)
      call settextposition(2,27-(len_trim(narr(1)))/2,curpos)
      call outtext(narr(1)(1:len_trim(narr(1))))

      d2=setbkcolor(7)
      d2=settextcolor(1)
      call settextwindow(11,26,11,55)
      call clearscreen($GWINDOW)
      call settextposition(1,2,curpos)
      call outtext(option(1)(1:len_trim(option(1))))

      d2=setvisualpage(1)

      udinc=0
      udpos=1
      oldud=1

      do while(udinc.lt.5)
      call ud(udinc)

      if(udinc.eq.5)then
            if(udpos.eq.1)then
            d2=setvisualpage(5)
            call summary(filename)
            udinc=0
            cycle
            else
            end if

            if(udpos.eq.2)then
            call plot(filename)
            udinc=0
            cycle
            else
            end if

            if(udpos.eq.3)then
            udinc=0
            cycle
            else
            end if

            if(udpos.eq.4)call quit()
      else
```

```
      end if

      oldud=udpos
      udpos=udpos+udinc
      if(udpos.gt.4)udpos=1
      if(udpos.lt.1)udpos=4

      d2=setbkcolor(1)
      d2=settextcolor(14)
      call settextwindow(10+oldud,26,10+oldud,55)
      call clearscreen($GWINDOW)
      call settextposition(1,2,curpos)
      call outtext(option(oldud)(1:len_trim(option(oldud))))

      d2=setbkcolor(7)
      d2=settextcolor(1)
      call settextwindow(10+udpos,26,10+udpos,55)
      call clearscreen($GWINDOW)
      call settextposition(1,2,curpos)
      call outtext(option(udpos)(1:len_trim(option(udpos))))

      d2=setbkcolor(3)
      d2=settextcolor(1)
      call settextwindow(21,14,21,66)
      call clearscreen($GWINDOW)
      call settextposition(2,27-(len_trim(narr(udpos)))/2,curpos)
      call outtext(narr(udpos)(1:len_trim(narr(udpos))))

:      read(*,*)

      end do

      d2=setvideomode($DEFAULTMODE)
      end

:*****************************************************
      subroutine summary(filename)
      include 'fgraph.fd'


      real tmax[allocatable](:),ad
      integer*2 d2,hflag
      integer n
      character*8 strf
      character*2 stri
      character*4 hfl
      character*30 filename,opfile,matl[allocatable](:),spread
      record/rccoord/curpos

      open(14,file=filename,access='sequential',form='binary')

      read(14)n
      allocate(matl(n),tmax(n))
      do 500 i=1,n
      read(14)matl(i),tmax(i)
00    continue
      read(14)opfile,spread
      read(14)ad,hflag

      if(hflag.eq.1)hfl='ASRM'
      if(hflag.eq.0)hfl='SSRM'

      d2=setactivepage(2)
      d2=setbkcolor(1)
      d2=settextcolor(3)
      call settextwindow(1,1,25,80)
```

```
      call clearscreen($GWINDOW)

      do 1 i=2,24
      call settextposition(i,2,curpos)
      do 1 j=2,79
      call outtext(char(177))
1     continue

      d2=settextcolor(14)
      call settextposition(25,12,curpos)
      call outtext('ASTC V4.0 - Developed by Southern Research Institute
     $, 1992')

      call settextwindow(4,6,22,74)
      call clearscreen($GWINDOW)
      call dbox(4,6,22,74)

      call settextposition(2,25,curpos)
      call outtext('Summary of Results')

      call settextposition(3,2,curpos)
      call outtext(char(199))
      do 2 i=1,65
      call outtext(char(196))
2     continue

      call outtext(char(182))

      call settextposition(4,4,curpos)
      call outtext(char(218))
      do 3 i=1,61
      call outtext(char(196))
3     continue
      call outtext(char(191))

      call settextposition(5,6,curpos)
      call outtext('Layer   Material                                    Max
     $Temp øR')

      call settextposition(5,4,curpos)
      call outtext(char(179))
      call settextposition(5,66,curpos)
      call outtext(char(179))

      call settextposition(6,4,curpos)
      call outtext(char(195))
      do 4 i=1,61
      call outtext(char(196))
4     continue
      call outtext(char(180))

      do 5 i=1,6
      call settextposition(6+i,4,curpos)
      call outtext(char(179))
      call settextposition(6+i,66,curpos)
      call outtext(char(179))
5     continue
      call settextposition(13,4,curpos)
      call outtext(char(192))

      do 6 i=1,61
      call outtext(char(196))
6     continue
      call outtext(char(217))

      call settextposition(4,12,curpos)
```

```
      call outtext(char(194))
      call settextposition(5,12,curpos)
      call outtext(char(179))
      call settextposition(6,12,curpos)
      call outtext(char(193))


      call settextposition(4,53,curpos)
      call outtext(char(194))
      call settextposition(5,53,curpos)
      call outtext(char(179))
      call settextposition(6,53,curpos)
      call outtext(char(193))

      call settextposition(14,8,curpos)
      call outtext('Areal Density (lb/ftý):')
      call settextposition(15,8,curpos)
      call outtext('Heat flux curves used:')
      call settextposition(16,8,curpos)
      call outtext('Analysis output file:')
      call settextposition(17,8,curpos)
      call outtext('Analysis database file:')

      d2=settextcolor(15)

      do 20 i=1,n
      write(stri,'(i2)')i
      write(strf,'(f7.1)')(tmax(i)+459.60)
      call settextposition(6+i,7,curpos)
      call outtext(stri//'     '//matl(i)//'              '//strf)
20    continue

      call settextposition(14,33,curpos)
      write(strf,'(f7.1)')ad

      do 25 i=1,len_trim(strf)
      if(strf(i:i).ne.' ')call outtext(strf(i:i))
25    continue


      call settextposition(15,31,curpos)
      call outtext(hfl)
      call settextposition(16,30,curpos)
      call outtext(opfile)
      call settextposition(17,33,curpos)
      call outtext(spread)

      d2=setvisualpage(2)

      close(14)

      deallocate(tmax,matl)

      call letter()

      d2=setactivepage(1)
      d2=setvisualpage(1)

      return
      end

c*****************************************************

      subroutine plot(filename)
      include 'fgraph.fd'
      real temp[allocatable](:,:),bs,maxtemp
```

```
integer*2 d2,char_flag,hflag,yinc,color(8),xstep,ntemp
integer n
character*50 str
character*30 filename,bstring,dfile,list,matl[allocatable](:)
character*3 xstring
character*5 ystring
record/xycoord/xy
record/rccoord/curpos

if(setvideomode($ERESCOLOR).eq.0)then
      call clearscreen($GCLEARSCREEN)
      print*,'Unable to set EGA graphics mode'
      print*,'Press a key to continue'
else
end if

if(registerfonts('*.FON').lt.0)then
d2=setvideomode($DEFAULTMODE)
print*,' '
print*,'Could not locate font files.  Copy all files with a'
print*,' ''.FON'' extension from the distribution disk into'
print*,'the working directory for this program.'
print*,'Press a key to continue...'
call letter()
call reset_screen()
return
else
end if

color(1)=2
color(2)=4
color(3)=5
color(4)=6
color(5)=9
color(6)=10
color(7)=3
color(8)=1

open(6,file=filename,access='sequential',form='binary')
read(6)n

allocate(matl(n))

do 1 i=1,n
if(i.eq.1)then
read(6)matl(i),maxtemp
else
read(6)matl(i),bs
end if
continue

read(6)bstring,dfile
read(6)x,hflag

maxtemp=maxtemp+459.60

d2=setactivepage(1)

list="t'helv'"//'h15w12b'
d2=setfont(list)


call moveto(240,10,xy)

str='Temperature vs. Time'
```

```
d2=setcolor(4)
d2=settextcolor(4)
call settextposition(2,40-len_trim(str)/2,curpos)
call outgtext(str)


d2=setbkcolor($WHITE)
d2=setcolor(1)
d2=settextcolor(12)
call moveto(60,30,xy)
d2=lineto(610,30)
d2=lineto(610,320)
d2=lineto(60,320)
d2=lineto(60,30)

d2=settextcolor(1)
call settextposition(25,35,curpos)
call outtext('Time (sec)')

call settextposition(1,2,curpos)
call outtext('Temp (øR)')

list="t'helv'"//'h10w8b'
d2=setfont(list)

if(hflag.eq.1) then
tmax=450
xstep=int2(550/45)
icount=45
call moveto(60,325,xy)
call outgtext('0')
      do 2 i=1,9
      call moveto(50+(61*i),325,xy)
      write(xstring,'(i3)')int(50*i)
      call outgtext(xstring)
      continue

else if(hflag.eq.0)then
tmax=400
xstep=int2(550/40)
icount=40
call moveto(60,325,xy)
call outgtext('0')

call moveto(50,325,xy)
      do 3 i=1,8
      call moveto(50+(69*i),325,xy)
      write(xstring,'(i3)')int(50*i)
      call outgtext(xstring)
      continue

else
end if

yinc=int2(maxtemp/10)
call moveto(40,315,xy)
call outgtext('0')

do 4 i=1,10
write(ystring,'(i5)')int(yinc*i)
call moveto(20,315-(i*29),xy)
call outgtext(ystring)
continue


ntemp=int2(tmax/10)
```

```fortran
      allocate(temp(ntemp,n))

      do 7 i=1,ntemp
      do 5 j=1,n
      read(6)temp(i,j)
      temp(i,j)=temp(i,j)+459.60
5     continue
7     continue

      close(6)

      do 10 i=1,n
      d2=setcolor(color(i))

      call moveto(450,250+(i-1)*15,xy)
      call outgtext(matl(i)(1:len_trim(matl(i))))

      call moveto(60,int2(320-((70+459.6)/maxtemp)*290),xy)

      do 9 j=1,icount
      d2=lineto(60+int2(xstep*j),int2(320-(temp(j,i)/maxtemp)*290))
c      read(*,*)
9     continue
10    continue


      d2=setvisualpage(1)
      call letter()
      deallocate(temp,matl)
      call unregisterfonts()

      call reset_screen()

      return
      end

c*******************************************************

      subroutine reset_screen()
      include 'fgraph.fd'
      integer*2 d2
      character*27 option(4)
      character*50 narr(4)
      character*50 nar
      record/rccoord/curpos

      common/narr/option

      nar='View temperature vs. time graph of analysis'

      d2=setvideomode($DEFAULTMODE)

      d2=setactivepage(1)

      d2=settextcursor(#2000)

      d2=setbkcolor(1)
      d2=settextcolor(3)
      call settextwindow(1,1,25,80)
      call clearscreen($GWINDOW)

      do 1 i=2,24
      call settextposition(i,2,curpos)
      do 1 j=2,78
      call outtext(char(177))
```

```
 continue

 d2=settextcolor(14)
 call settextposition(25,12,curpos)
 call outtext('ASTC V4.0 - Developed by Southern Research Institute
$, 1992')

 d2=setbkcolor(3)
 d2=settextcolor(1)
 call settextwindow(3,25,5,55)
 call clearscreen($GWINDOW)
 call sbox(3,25,5,55)
 call settextposition(2,7,curpos)
 call outtext('ASTC Post-Processor')

 d2=setbkcolor(1)
 d2=settextcolor(14)
 call settextwindow(7,18,18,62)
 call clearscreen($GWINDOW)
 call dbox(7,18,18,62)
 call settextposition(2,6,curpos)
 call outtext('Select one of the following options')

 call settextposition(3,2,curpos)
 call outtext(char(199))
 do 2 i=3,43
 call outtext(char(196))
 continue

 call outtext(char(182))

 do 3 i=1,4
 call settextposition(4+i,10,curpos)
 call outtext(option(i)(1:len_trim(option(i))))
 continue

 call settextposition(10,2,curpos)
 call outtext(char(199))
 do 4 i=3,43
 call outtext(char(196))
 continue

 call outtext(char(182))

 call settextposition(11,9,curpos)
 call outtext(char(24)//char(25)//' to move, ENTER to select')

 d2=setbkcolor(3)
 d2=settextcolor(1)
 call settextwindow(20,12,22,68)
 call clearscreen($GWINDOW)
 call sbox(20,12,22,68)

 call settextwindow(21,14,21,66)
 call clearscreen($GWINDOW)
 call settextposition(1,27-(len_trim(nar))/2,curpos)
 call outtext(nar(1:len_trim(nar)))

 d2=setbkcolor(7)
 d2=settextcolor(1)
 call settextwindow(12,26,12,55)
 call clearscreen($GWINDOW)
 call settextposition(1,2,curpos)
 call outtext(option(2)(1:len_trim(option(2))))

 d2=setvisualpage(1)
```

```
      return
      end

*****************************************************
```

```
      SUBROUTINE INTRO()
      INCLUDE 'FGRAPH.FD'

      INTEGER*2 D2,I,J
      CHARACTER*30 LIST
      RECORD/RCCOORD/CURPOS
      RECORD/XYCOORD/XY

      IF(SETVIDEOMODE($ERESCOLOR).EQ.0)RETURN

      IF(REGISTERFONTS('*.FON').LT.0)RETURN

      d2=setactivepage(1)

      D2=SETTEXTCOLOR(14)

      CALL DBOX(1,1,25,80)

      CALL SETTEXTPOSITION(3,2,CURPOS)
      CALL OUTTEXT(CHAR(199))
      DO 5 I=1,76
      CALL OUTTEXT(CHAR(196))
5     CONTINUE
      CALL OUTTEXT(CHAR(182))


      CALL SETTEXTPOSITION(23,2,CURPOS)
      CALL OUTTEXT(CHAR(199))
      DO 10 I=1,76
      CALL OUTTEXT(CHAR(196))
10    CONTINUE
      CALL OUTTEXT(CHAR(182))

      D2=SETCOLOR(7)
      D2=RECTANGLE($GFILLINTERIOR,71,270,79,282)

      D2=SETCOLOR(8)
      D2=RECTANGLE($GFILLINTERIOR,67,250,102,266)
      D2=RECTANGLE($GFILLINTERIOR,84,270,102,285)

      D2=RECTANGLE($GFILLINTERIOR,47,267,67,282)
      D2=RECTANGLE($GFILLINTERIOR,47,285,84,301)

      D2=PIE($GFILLINTERIOR,47,250,87,282, 67,246,47,266)

      D2=PIE($GFILLINTERIOR,66,269,102,301, 84,301 ,102,284)

      LIST="t'helv'"//'h15w12b'
      D2=SETFONT(LIST)

      d2=setcolor(7)
      CALL MOVETO(120,265,XY)
      CALL OUTGTEXT('Southern Research Institute')
      CALL MOVETO(120,280,XY)
      CALL OUTGTEXT('1992')

      LIST="t'tms rmn'"//'h30w24b'
      D2=SETFONT(LIST)

      CALL MOVETO(250,80,XY)
      D2=SETCOLOR(4)
      CALL OUTGTEXT('A S T C')

      LIST="t'helv'"//'h20w12b'
      D2=SETFONT(LIST)
      d2=SETCOLOR(14)
```

```
      CALL MOVETO(100,110,XY)
      CALL OUTGTEXT('Aft Skirt Thermal Curtain Analysis Program')

      CALL SETTEXTPOSITION(12,34,CURPOS)
      CALL OUTTEXT('Version 4.0')

C       d2=setactivepage(0)

C       d2=setcolor(3)

C       DO 15 I=1,175,2
C       D2=RECTANGLE($GFILLINTERIOR,320-1.8*I,175-I,320+1.8*I,175+I)
C15      CONTINUE


      D2=SETBKCOLOR($BLUE)

      d2=setvisualpage(1)
C       D2=SETACTIVEPAGE(1)

C       call delay(int2(300))

      CALL SETTEXTPOSITION(15,30,CURPOS)
      CALL OUTTEXT('Press a key to begin')

      call letter ()
      call unregisterfonts()

      D2=SETVIDEOMODE($DEFAULTMODE)
      RETURN
      END
```

```
      SUBROUTINE REPEAT_MATL(I,N,MATL,KT,AK,CTT,C,P,DX)
      INCLUDE 'FGRAPH.FD'

      INTEGER N,I
      REAL KT(N,5),AK(N,5),CTT(N,5),C(N,5),P(N),DX(N)
      CHARACTER*30 MATL(N)
      INTEGER*2 D2,ARPOS,OLDARROW,ARINC
      CHARACTER*2 S2
      CHARACTER YN

      RECORD/RCCOORD/CURPOS

      D2=SETACTIVEPAGE(1)
      D2=SETVISUALPAGE(1)
      D2=SETBKCOLOR(1)
      D2=SETTEXTCOLOR(15)
      CALL SETTEXTWINDOW(1,1,25,80)
      CALL CLEARSCREEN($GCLEARSCREEN)
      CALL DBOX(1,1,25,80)
      CALL SETTEXTPOSITION(4,18,CURPOS)
      WRITE(S2,'(I2)')I
      CALL OUTTEXT('Select material for blanket layer number '//S2)
      CALL SETTEXTPOSITION(5,18,curpos)
      CALL OUTTEXT('Use arrow keys to move cursor, ENTER to select')

      D2=SETBKCOLOR(7)
      D2=SETTEXTCOLOR(4)
      CALL SETTEXTWINDOW(8,20,11+I,60)
      CALL CLEARSCREEN($GWINDOW)
      CALL DBOX(8,20,12+I,60)

      D2=SETTEXTCOLOR(1)
      DO 10 J=1,I-1
      CALL SETTEXTPOSITION(2+J,6,CURPOS)
      CALL OUTTEXT(MATL(J))
 0    CONTINUE


      D2=SETBKCOLOR(1)
      D2=SETTEXTCOLOR(15)
      CALL SETTEXTWINDOW(10,24,10,26+LEN_TRIM(MATL(1)))
      CALL CLEARSCREEN($GWINDOW)
      CALL SETTEXTPOSITION(1,2,CURPOS)
      CALL OUTTEXT(MATL(1)(1:LEN_TRIM(MATL(1))))

      ARPOS=1
      ARINC=0

      DO WHILE(ARINC.LT.5)
      D2=SETBKCOLOR(1)
      D2=SETTEXTCOLOR(15)
      OLDARROW=ARPOS

      CALL SETTEXTWINDOW(9+ARPOS,24,9+ARPOS,26+LEN_TRIM(MATL(ARPOS)))
      CALL CLEARSCREEN($GWINDOW)
      CALL SETTEXTPOSITION(1,2,CURPOS)
      CALL OUTTEXT(MATL(ARPOS)(1:LEN_TRIM(MATL(ARPOS))))

      CALL UD(ARINC)
      IF(ARINC.EQ.5)EXIT
      ARPOS=ARPOS+ARINC
      IF(ARPOS.GT.I-1)ARPOS=1
      IF(ARPOS.LT.1)ARPOS=I-1

      D2=SETBKCOLOR(7)
      D2=SETTEXTCOLOR(1)
```

```
      CALL SETTEXTWINDOW(9+OLDARROW,24,9+OLDARROW,26+LEN_TRIM(MATL(OLDAR
     $ROW)))
      CALL CLEARSCREEN($GWINDOW)
      CALL SETTEXTPOSITION(1,2,CURPOS)
      CALL OUTTEXT(MATL(OLDARROW)(1:LEN_TRIM(MATL(OLDARROW))))
      END DO

      D2=SETBKCOLOR(4)
      CALL SETTEXTWINDOW(18,15,23,65)
      CALL CLEARSCREEN($GWINDOW)
      CALL DBOX(18,15,23,65)
      CALL SETTEXTPOSITION(2,9,CURPOS)
      CALL OUTTEXT('Selected material for layer '//s2//' is')
      CALL SETTEXTPOSITION(3,9,CURPOS)
      CALL OUTTEXT(MATL(ARPOS)(1:LEN_TRIM(MATL(ARPOS)))//'.')
      CALL SETTEXTPOSITION(4,9,CURPOS)
      CALL OUTTEXT('Is this correct (Y/N)?')
      CALL Y_OR_N(YN)
      IF(YN.EQ.'N')GOTO 1

      MATL(I)=MATL(ARPOS)
      DX(I)=DX(ARPOS)
      P(I)=P(ARPOS)

      DO 50 JJ=1,5
      CTT(I,JJ)=CTT(ARPOS,JJ)
      C(I,JJ)=C(ARPOS,JJ)
      KT(I,JJ)=KT(ARPOS,JJ)
      AK(I,JJ)=AK(ARPOS,JJ)
50    CONTINUE

      D2=SETACTIVEPAGE(0)
      D2=SETVISUALPAGE(0)
      RETURN
      END
```

```
subroutine OSCREEN(n,e,file1,file2,hflag,file3)
include 'fgraph.fd'
integer*2 d2,ct,hflag
integer n
double precision xx
real e
character*30 file1,file2,file3
character*1 a_s
record/rccoord/curpos

d2=setactivepage(1)

d2=setbkcolor(1)
d2=settextcolor(3)
call clearscreen($GCLEARSCREEN)

do 1 i=2,24
call settextposition(i,2,curpos)
do 1 j=2,79
call outtext(char(177))
continue
d2=settextcolor(14)
call settextposition(25,12,curpos)
call outtext('ASTC V4.0 - Developed by Southern Research Institute
$, 1992')



d2=setbkcolor(3)
d2=settextcolor(1)
call settextwindow(4,15,6,65)
call clearscreen($GWINDOW)
call sbox(4,15,6,65)
call settextposition(2,10,curpos)
call outtext('Input the following information')


d2=setbkcolor(1)
d2=settextcolor(15)
call settextwindow(9,15,19,65)
call clearscreen($GWINDOW)
d2=settextcolor(14)
call dbox(9,15,19,65)

call settextposition(3,5,curpos)
call outtext('Name of output file: ')
call settextposition(5,5,curpos)
call outtext('Number of blanket layers: ')
call settextposition(7,5,curpos)
call outtext('Emittance (0 < e < 1): ')
call settextposition(9,5,curpos)
call outtext('Heat Flux (ASRM/SSRM): ')
d2=settextcolor(15)
call settextposition(9,16,curpos)
call outtext('A')
call settextposition(9,21,curpos)
call outtext('S')
d2=settextcolor(14)
call settextposition(9,26,curpos)
call outtext(':')

d2=setvisualpage(1)

d2=settextcolor(15)
call settextposition(3,26,curpos)
```

```
      call getstrng(file1,ct)

10    call settextposition(5,31,curpos)
      if(curpos.col.eq.26)then
            write(*,*)char(07)
            goto 5
      else
      end if
      call getnumf(xx,ct)
      n=int2(xx)
      if(n.eq.0)then
            write(*,*)char(07)
            goto 10
      else
      end if

12    call settextposition(7,28,curpos)
      if(curpos.col.eq.31.and.n.eq.0)then
            write(*,*)char(07)
            goto 10
      else
      end if
      call getnumf(xx,ct)
      e=xx
      if(e.lt.0.00.or.e.gt.1.00)then
            write(*,*)char(07)
            goto 12
      else
      end if

15    call settextposition(9,29,curpos)
      if(curpos.col.eq.28)then
            write(*,*)char(07)
            goto 12
      else
      end if

      call settextposition(9,30,curpos)
      if(curpos.col.eq.28)then
            write(*,*)char(07)
            goto 15
      else
      end if


      call getstrng(a_s,ct)
      if(a_s.eq.'a'.or.a_s.eq.'A')then
      hflag=1
      else if(a_s.eq.'s'.or.a_s.eq.'S')then
      hflag=0
      else
      write(*,*)char(07)
      goto 15
      end if


      k=0
      do 20 i=1,len_trim(file1)
      if(file1(i:i).eq.'.')then
      k=i
      exit
      else
      end if
20    continue

      if(k.eq.0)then
```

```
      file2=file1(1:len_trim(file1))//'.dbs'
      file3=file1(1:len_trim(file1))//'.db$'
      else
      file2=file1(1:k-1)//'.dbs'
      file3=file1(1:k-1)//'.db$'
      end if


c      read(*,*)
c      d2=setvideomode($DEFAULTMODE)

c      print*,file1,n,e,a_s,hflag
c      print*,file2


      return

      end

      include 'sbox.for'
```

```
      SUBROUTINE GETS80(NAME,CTRL)
      INCLUDE 'FGRAPH.FD'

      CHARACTER*1 X
      CHARACTER*80 NAME
      INTEGER*2 CTRL,ROW,COL
      RECORD/RCCOORD/CURPOS

      CTRL=0
      I=0

      DO WHILE(CTRL.NE.100)
      CALL GETKEYF(X,CTRL)
      IF(CTRL.EQ.0)THEN
      I=I+1
      NAME(I:I)=X
      CALL OUTTEXT(X)
      ELSE
      END IF
            IF(CTRL.EQ.-25)THEN
            IF(I.GT.0)THEN
            NAME(I:I)=' '
            I=I-1
            CALL GETTEXTPOSITION(CURPOS)
            COL=CURPOS.COL-1
            ROW=CURPOS.ROW
            CALL SETTEXTPOSITION(ROW,COL,CURPOS)
            CALL OUTTEXT(' ')
            CALL SETTEXTPOSITION(ROW,COL,CURPOS)
            ELSE
            END IF
            ELSE
            END IF


      IF(CTRL.EQ.-50.OR.CTRL.EQ.5)RETURN

      END DO

      DO 20 K=I+1,80
      NAME(K:K)=' '
20    CONTINUE

      RETURN
      END
```

```
      SUBROUTINE GETSTRNG(NAME,CTRL)
      INCLUDE 'FGRAPH.FD'

      CHARACTER*1 X
      CHARACTER*50 NAME
      INTEGER*2 CTRL,ROW,COL
      RECORD/RCCOORD/CURPOS

      CTRL=0
      I=0

      DO WHILE(CTRL.NE.100)
      CALL GETKEYF(X,CTRL)
      IF(CTRL.EQ.5)RETURN
      IF(CTRL.EQ.0)THEN
      I=I+1
      NAME(I:I)=X
      CALL OUTTEXT(X)
      ELSE
      END IF
            IF(CTRL.EQ.-25)THEN
            IF(I.GT.0)THEN
            NAME(I:I)=' '
            I=I-1
            CALL GETTEXTPOSITION(CURPOS)
            COL=CURPOS.COL-1
            ROW=CURPOS.ROW
            CALL SETTEXTPOSITION(ROW,COL,CURPOS)
            CALL OUTTEXT(' ')
            CALL SETTEXTPOSITION(ROW,COL,CURPOS)
            ELSE
            END IF
            ELSE
            END IF

      IF(CTRL.EQ.-50)RETURN

      END DO

      DO 20 K=I+1,50
      NAME(K:K)=' '
0     CONTINUE

      RETURN
      END
```

```
      SUBROUTINE DBOX(X11,Y11,X22,Y22)

      X1,X2,Y1,Y2 ARE THE CORNERS OF THE CURRENT TEXTWINDOW

      INCLUDE 'FGRAPH.FD'
      INTEGER X11,X22,Y11,Y22
      INTEGER*2 X1,X2,Y1,Y2
      RECORD/RCCOORD/CURPOS

      X1=INT2(X11)
      X2=INT2(X22)
      Y1=INT2(Y11)
      Y2=INT2(Y22)

      CALL SETTEXTPOSITION(1,2,CURPOS)
      CALL OUTTEXT(CHAR(201))
      DO 5 I=1,(Y2-Y1)-3
      CALL OUTTEXT(CHAR(205))
      CONTINUE
      CALL OUTTEXT(CHAR(187))

      DO 10 I=1,(X2-X1)-1
      CALL SETTEXTPOSITION(1+I,2,CURPOS)
      CALL OUTTEXT(CHAR(186))
      CALL SETTEXTPOSITION(1+I,(Y2-Y1),CURPOS)
      CALL OUTTEXT(CHAR(186))
0     CONTINUE

      CALL SETTEXTPOSITION((X2-X1)+1,2,CURPOS)
      CALL OUTTEXT(CHAR(200))
      DO 15 I=1,(Y2-Y1)-3
      CALL OUTTEXT(CHAR(205))
5     CONTINUE
      CALL OUTTEXT(CHAR(188))

      RETURN
      END
```

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15. Supplementary Notes

16. Abstract

Improvements in SRB Thermal Curtain were identified by Thermal Design featuring:

a) selection of materials capable of thermal protection (insulation) and service temperatures by tri-layering, quartz, S2 glass/ Kevlar, in thinner (lighter) cross section

b) weaving in single piece (instead of 24 sections) to achieve improved strength (resist aero loads)

c) weaving to reduce mfg. (labor) cost with angle interlock construction

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