8/11/95

D0 Engineering Note

No. 3823-112-EN-443
D0 Silicon Upgrade

Thermal Conductivity Measurements
of Adhesives and Metal Strips

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Approved

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Table of Contents

- 1.0 Introduction
- 2.0 Design Parameters
- 3.0 Products Tested
- 4.0 Measurement Method
- 5.0 Calibration
- 6.0 Results
- 7.0 Conclusions
- 8.0 Error Analysis
- 9.0 Future Work
- 10.0 References

Figures

- Figure 1. Fixture for Adhesive Thermal Conductivity Tests
- Figure 2. Fixture for Strip Thermal Conductivity Tests
- Figure 3. Calibration Graph of Thermistor #2
- Figure 4. Aluminum Strip End Correction Graph
- Figure 5. Copper Strip End Correction Graph

Tables

- Table 1. Summary of Adhesive Thermal Conductivity Values
- Table 2. Summary of Adhesive Thermal Conductivity Values
- Table 3. Summary of Ablefilm 563K Adhesive Thermal Conductivity Values
- Table 4. Summary of Strip Thermal Conductivity Values
- Table 5. Summary of Aluminum Strip Convection Test
- Table 6. Summary of Copper Strip Convection Test
- Table 7. Summary of Copper End Correction Comparison
- Table 8. Summary of Aluminum End Correction Comparison
- Table 9. Summary of Standard Deviations
- Table 10. Summary of Measured vs Published k Values

1.0 Introduction

This note is a followup to previous work done relating to thermal conductivity tests for the D0 Silicon Upgrade¹. The testing of adhesives described here was done as outlined in the above mentioned note; therefore, the experimental setup and design for testing adhesives is marginally described here. However, some strips were tested to determine their thermal conductivity which utilized a different testing setup. That setup is described here as well.

The measured thermal conductivities of the adhesives show Ablefilm 563K to have the highest thermal conductivity value of 0.89 W/m-K. The strip tests also showed that a consistent thermal conductivity value can be obtained for a strip within 5%.

2.0 Design Parameters

The goal of the D0 Silicon Upgrade is to limit the temperature rise through any one bond or through any one material. In the analysis of this situation the following equation was used to analyze the thermal behavior:

$$Q = kA \frac{\Delta T}{\Delta X}$$

where: ΔT = Temperature between 2 points (°C)
 Q = Heat Input (W)
 ΔX = joint thickness (cm)
 k = thermal conductivity (W/cm-°C)
 A = joint area (cm²)

The testing equipment was designed to measure k by controlling Q , A and ΔX and measuring ΔT .

3.0 Products Tested

The adhesives and strip materials tested are listed below:

Adhesives:

1. Ablefilm 563
2. Ablefilm 563K
3. Ablefilm 539IA
4. Hexcel 5313, Deh 24
5. Hexcel 5313, HV 953
6. Hexcel 5313, HV 953 & CGE
7. Tra-Duct, BA 2902
8. Araldite AW 106

Strips:

1. Aluminum
2. Beryllium
3. Silicon
4. Copper

4.0 Measurement Method

Figure 1 shows the adhesive test setup as already detailed in the note referenced previously. The cylinders are made from aluminum T6061 with a 0.75" diameter and 0.75" height. The adhesive is sandwiched between the two identical cylinders. Triangular wedges of Kapton tape are used to establish 0.003" and 0.006" thick adhesive gaps if the adhesive is nonsolid. The Ablefilm adhesives don't require the Kapton wedges to maintain their thickness during curing. The "thin" samples use nonsolid adhesives which are allowed to "float" by putting the appropriate curing weight on top of the aluminum cylinders during the cure process without any thickness wedges involved.

A 50 or 60 ohm resistor is inserted into a cross-drilled hole in the top cylinder and the other cylinder is screwed down to a large aluminum heat sink. The voltage across the resistor is generally set at 20 volts. Heat flows from the powered resistor to the heat sink. Aluminum temperature is sampled at four points along this path by thermistors. They are inserted into holes drilled in the aluminum until they reach the center of the fixture. This is assumed to measure an average cross-section temperature of the fixture. Thermistors are used to monitor temperature because of their accuracy (6% change per °C), quick response time and small size (1mm dia.).

The results of the thermal conductivity tests are also expressed in one other way for the adhesives; it is called "joint resistance". It is calculated by dividing the temperature difference across the gap by the power density input to the resistor. It is a useful number to predict performance of such joints. It has historically been found to be a good proportionality of the thermal resistance to bond thickness. Surface effects were found to be insignificant in the previous work with this setup; therefore, they have been ignored in this case up to this point.

The setup for measuring the thermal conductivity of the strips is shown in Figure 2. It works in the same way as the cylinders described above. The resistor is powered to send heat through the aluminum fixture, past the thermistors and through the strip. Temperatures are recorded at the four thermistor positions and the values are used in generating thermal conductivity values.

5.0 Calibration

These thermistors are originally calibrated to a known temperature by heating up an insulated solid aluminum block and measuring the temperature at different points. A heat source (in this case, a soldering iron) is put into the far end of the block and is allowed to heat the block from approximately 20°C below room temperature to approximately 20°C above room temperature. Three LM342 temperature converter IC's are used to record the exact temperature of the block at different locations throughout the block while the thermistors also take data readings as the block heats up. The average temperature of the three IC's were plotted versus the log of the thermistor readings. An example of this type of graph is shown in Figure 3. The best fit 3rd order polynomial was used to determine the temperature readings of the thermistors at any one point in time.

Notes:

1. Aluminum 6061 cylinders
2. End faces flat to 0.0002"

Glue or Grease Joint under Study
+ Shim

Drill and tap for 1/4"-28

Very Large Aluminum Heat Sink

Aluminum Cylinders,

FIGURE 1: ADHESIVE FIXTURE

Hans Jostein 12/21/93

FIGURE 2: FIXTURE FOR TESTING STRIP THERMAL CONDUCTIVITIES

Figure 3: 6/28/95; Calibration of Thermistor #2

6.0 Results

The results for the adhesives is presented in Tables 1 thru 3. Besides bulk thermal conductivity of the adhesives, other relevant values are calculated to give an idea of the reliability of the numbers. Adhesives are cured as to provided data sheets.

The initial data using the strip fixture is shown in Table 4. Because of many inconsistent values in runs 1-6 using an aluminum strip, convection was considered in this table. Two ways were attempted to determine convection's role in this procedure. In the first case the test setup was run without any strip in the fixture. After reaching a steady state condition(constant temperature), all of the heat into the block is being taken away from the block. This situation resulted in a value of $6 \text{ W/m}^2\text{-K}$ for the convection coefficient for this physical setup. The amount of heat using this convection coefficient value is subtracted from the heat generated by the resistor that is flowing through the test fixture.

The second way to test whether convection played a role in the strip tests is to simply attempt to put insulation all around the fixture in order to eliminate any heat loss effects. A comparison of the test setup with and without insulation is shown in Tables 5 and 6.

Table 5: Aluminum Strip

Run	Uncorrected Length (cm)	Voltage (Volts)	$\Delta T_{\text{joint}}(^{\circ}\text{K})$	k (W/m-K)
7-not insulated	0.9652	20	19.6	133
8-insulated	0.95	20	20.4	128
9-insulated	0.95	15	11.3	132
10-insulated	0.95	10	4.5	137

Table 6: Copper Strip

Run(s)	Corrected Length (cm)	Voltage (Volts)	$\Delta T_{\text{joint}}(^{\circ}\text{K})$	k (W/m-K)
1-6-not insulated	Varies	20	Varies	419
7-insulated	2.305	20	8.7	421
8-insulated	3.788	20	14	430

The results of these two different ways to consider convection do not agree at all. In the case where the fixture was heated without a strip, the value of $6 \text{ W/m}^2\text{-K}$ indicates a significant loss of heat due to convection. On the other hand, completing runs with insulation placed around the fixture wherever possible gives very similar conductivity values to when there is no insulation, thus indicating very little convection loss.

Schmidgall/Jostlein-July10,1995

Table 2: Summary of Adhesive Thermal Conductivities

Date	Joint Material	Thickness (mils)	Run #	Al Cond (W/cm-K)	Al Equiv Length(cm)	Joint Resistance (K-cm ² /W)	Bulk Cond (W/m-K)	Power Source Voltage(Volts)
7/5	Hexcel 5313 Hardener	3	1	1.99	10.94	5.51	0.14	20
7/6			2	1.96	10.69	5.45	0.14	20
7/5		6	1	2.02	15.65	7.77	0.20	20
7/6			2	2.00	15.55	7.76	0.20	20
7/5		thin	1	2.03	1.65	0.81	??	20
7/5	Hexcel CGE	thin	1	2.11	2.22	1.05	??	20
7/7	BA 2902	3	1	2.02	3.02	1.5	0.51	20
7/10		6	1	2.18	3.91	1.80	0.85	20
7/7		thin	1	2.03	0.29	0.14	??	20
7/10	Araldite	3	1	2.01	9.80	4.88	0.16	20
7/10		6	1	2.08	17.15	8.26	0.18	20
7/10		thin	1	2.29	2.77	1.21	??	20

Summary of All Ablefilm 563K Adhesive Thermal Conductivities

Date	Sample #	Thickness (mils)	Run #	Al Cond (W/cm-K)	Al Equiv Length(cm)	Joint Resistance (K-cm ² /W)	Bulk Cond (W/m-K)	Power Source Voltage(Volts)
6/28	1	2	1	4.92	2.84	0.58	0.88	10
6/28			2	2.11	1.23	0.58	0.87	20
6/30			3	2.15	1.27	0.59	0.86	20
7/31	2	2	1	1.96	1.10	0.56	0.91	20
8/1			2	2.04	1.16	0.57	0.90	20
7/6	3	2	1	1.74	1.09	0.63	0.81	20
8/2			2	2.22	1.50	0.67	0.75	20
8/2			3	2.19	1.45	0.66	0.77	20
7/5	4	2	1	2.13	1.09	0.51	0.99	20
8/2			2	2.09	1.07	0.51	0.99	20
8/2			3	2.06	1.04	0.50	1.02	20

Table 4: Summary of Strip Thermal Conductivities

Date	Strip Material	Length (cm)	Run #	Source Power (Watts)	Strip Power less Fixture Heating (Watts)	Conductivity (W/m-K)	Strip Power less Convection (Watts)	Conductivity (W/m-K)	Remarks
7/12	Aluminum	0.9652	7	5.18	4.8	131	3.8	103	
7/12	Beryllium-long direction	1.356	1	4.4	4.1	211	1.8	94	
7/12	Beryllium-short direction	0.404	1	4.4	4.37	114	3.6	93	
7/13	Silicon	0.489	2	5.16	4.7	90.8	2.7	51.4	
7/14	Silicon*	0.489	3	5.17	4.5	89.3	2.5	49.5	
7/14	Silicon**	0.522	4	5.17	4.3	46.9	2.1	23.2	Broken Strip
7/17	Silicon**	0.5207	5	5.18	5.05	79.1	3.1	49.0	

*Test was run without insulating support below heat source.

**Test was done on the silicon with heat flowing in a direction perpendicular to silicon runs 2&3.

There was also great variation in thermal conductivity values when the different lengths of the same strip were tested. Because of this fact and the feeling that the end capture of the strips generated "special" end effects, a decision was made to attempt to incorporate the end effects into an additional length. This additional length would be added to each run of a certain material in order to give a truer picture of the actual length that the heat input is affecting.

For both aluminum and copper strips the joint temperature was graphed versus the strip length between blocks and a linear equation was derived. These graphs are shown in Figures 4 and 5. By considering the effective length when $\Delta T = 0$, the equations gave the additional strip lengths required to add on to the actual strip length between blocks. The additional strip length differed for copper and aluminum. In each case however, when the additional strip length was included, there was an agreement on the thermal conductivity for all runs for each material as shown in Tables 7 and 8.

7.0 Conclusions

The results for thermal conductivity have been shown in the preceding graphs and tables. It is worth noting that Ablefilm 563K outperformed the other adhesives as predicted by available vendor data.

The test setup showed good consistency over several trials. When testing the same sample more than once the greatest difference in thermal conductivities was Ablefilm 563K, sample #3, which had a variation of 5%. The test setup also showed good consistency over several trials of the same strip material but of a different strip length. The ability of the tester to obtain a good consistency of the Ablefilm 563K over several samples was not as high as the strip results as seen in Table 9.

Table 9: Standard Deviations

Material	No. of Values	Avg k (W/m-K)	Std Dev(W/m-K)
Ablefilm 563K	4	0.89	0.107
Al strip (corr)	6	241	4.34
Cu strip (corr)	6	419	3.16

In testing the Ablefilm 563 shown in Table 1 over a power supply range from 10-20 volts, it was apparent that the input power did not play a significant role since thermal conductivity values were similar.

The thermal conductivities measured for the film adhesive Ablefilm 539IA were extremely low compared to the other adhesives. Upon doing a melt test which began around 70°C and ended at 125°C, it was found that the 539IA does not melt in this range of temperatures.

Figure 4: 7/28/95; Alum End Correction, Runs 1-5

Figure 5: 7/31/95; Copper End Correction, Runs 1-6

Table 7: End Correction Data(Copper)

Run #	Calculated k (W/m-K)	ΔT_{joint} (K)	Length between blocks (cm)	Corrected Length (cm)*	Corrected k (W/m-K)
1	160	5.05	0.5029	1.309	416
2	233	6.96	1.010	1.816	419
3	273.5	8.78	1.494	2.300	421
4	302.4	10.6	1.9964	2.802	424
5	314.2	12.74	2.500	3.306	415
6	330	14.57	2.997	3.803	419
Avg. k-->					419

*Length from graph added to measured length between fixture blocks is 0.806 cm.

Table 8: End Correction Data(Aluminum)

Run #	Calculated k (W/m-K)	ΔT_{joint} (K)	Length between blocks(cm)	Corrected Length (cm)*	Corrected k (W/m-K)
1	80	12.4	0.514	1.584	247
2	117	16.5	1.010	2.080	241
3	140	20.3	1.519	2.589	239
4	153	24.3	1.977	3.047	236
5	170	28.2	2.527	3.597	242
6	176	29.7	3.007	4.077	239
Avg. k-->					241

*Length from graph added to measured length between fixture blocks is 1.07 cm.

8.0 Error Analysis

It is of some concern that the results from the adhesive tests are not always in high agreement with the published values of these materials. Table 10 below shows the % difference from the published values of thermal conductivity for the three materials mentioned above.

Table 10: Measured vs Published k Values

Material	Measured k (W/m-K)	Published k (W/m-K)	% difference
Ablefilm 563K	0.89	1.12	20.5
Al Strip	241	240*	0.4
Cu Strip	419	403*	4.0

*Depends on the source of your value and the alloy.

It is reasonable that the strips would be the most accurate given that they are most easily held to material consistency and physical constraints. The large percent difference for the adhesive and its substantial standard deviation however, suggest that a great amount of care is required to consistently apply this material. Since its position in the design of the detector is thermally vitally important, it is of utmost importance that storage, handling and curing procedures are properly followed.

There are two areas of concern regarding these tests. They are the power being input and flowing through the adhesive or strip and the large standard deviation for the film adhesive Ablefilm 563K.

The possible errors due to adhesive control, both area and thickness, were addressed in the note mentioned previously. Errors around 4% for the area and 17% for the thickness were suggested. Using the film adhesive should reduce the thickness error value. The biggest question in the area value is whether there are a substantial number of air pockets in nonsolid adhesives or voids in the film adhesives. When curing the film adhesive under the appropriate conditions and examining its area coverage after completion, it is apparent to the naked eye that a possibly significant percentage of area contact is lost due to these voids. In this analysis no quantification of such data for either nonsolid adhesives or film adhesives was attempted.

The film adhesive thickness is reliable depending on the provider of the films. As long as they are not doubled over on application to the cylinders, they seem to give highly reliable thickness values. Also any air pockets that develop on application should be smoothed out before curing. Another consideration would be to cure the 563K under vacuum conditions to eliminate air pockets; potential voids could remain however. The Kapton wedges used to determine gap thickness using nonsolid adhesives does not seem as reliable. However, given the appropriate weight during curing, it is reasonable to believe that with great care, these desired thicknesses can be consistently achieved.

The measured area for the strips does seem highly reliable. The strips can be easily measured and result in very similar values over many runs.

The error in the ΔT value was considered in the previous note. A possible 16% error was suggested due to physical placement of the thermistor in the actual fixture holes. This is somewhat contradicted by the fact that multiple readings for the same setup are generally very consistent. Also, because each thermistor was calibrated using the average temperature of three IC's at different positions within an aluminum block, it is conceivable that a single temperature measurement might be suspect.

The strip length was highly suspect during the initial stages of the strip testing. With the inclusion of the additional length due to end effects however, the thermal conductivity values were impressively close, giving extremely low standard deviations. This result adds to the reliability of the achieved strip values and their believability.

This leaves the power put into the fixture and transferred through the adhesives and strips as the most suspect cause of improper results. But the simplistic test of covering the testing apparatus with insulation revealed no significant deviation in any of the results.

From the above results it appears that the strip test values are highly reliable and when the length correction is added, they are fairly accurate. These results seem to indicate that there is not a significant heat loss due to convection.

9.0 Future Work

For the film adhesives such as Ablefilm 563K it seems that the most important factor in obtaining consistency is to reduce the voids in the film. This may not be under the control of the applicator of these adhesive films however.

For the strips it seems that performing more tests on known samples will substantiate the low percent differences that were achieved in this study. It would also be valuable to test other materials used in the design of the detector such as the diamond and beryllium strip.

10.0 References

¹ D0 Engineering Note No. 3823.112-EN-408

Diamond End Correction Data Using Runs 5-8 (10 Volts)

Run #	Calculated k (W/m-K)	ΔT_{joint} (K)	Length between blocks (cm)	Corrected Length (cm)*	Corrected k (W/m-K)
5	476	2.9	0.745	2.27	1450
6	433	2.535	0.5918	2.1168	1549
7	291	2.248	0.3531	1.8781	1548
8	630	3.05	1.0389	2.5639	1555
				Avg. k-->	1525

* Length from graph added to measured length between fixture blocks is 1.525 cm.

Diamond End Correction Data Using Runs 5-7

Run #	Calculated k (W/m-K)	ΔT_{joint} (K)	Length between blocks (cm)	Corrected Length (cm)*	Corrected k (W/m-K)
5	476	12.4	0.745	1.7592	1124
6	433	16.5	0.5918	1.60	1175
7	291	20.3	0.3531	2.589	1127
8	630	24.3	1.0389	3.047	1245
				Avg. k-->	1168

* Length from graph added to measured length between fixture blocks is 1.0142 cm.

Aluminum?

No page 19.

8/11;Diamond End Corr, R's 5-8

(corr length
Addition

$$\frac{-1.8539}{1.2157} = -1.525$$

8/11; Diamond End Corr Effect, Runs 5-7

Correlation added
 $\frac{-1.6465}{1.6235} = -1.014$